Asian megacity heat stress under future climate scenarios: impact of air-conditioning feedback


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Asian megacity heat stress under future climate scenarios: impact of air-conditioning feedback

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Supplementary material for this article is available online

Abstract

Future heat stress under six future global warming (ΔTGW) scenarios (IPCC RCP8.5) in an Asian megacity (Osaka) is estimated using a regional climate model with an urban canopy and air-conditioning (AC). An urban heat ‘stress’ island is projected in all six scenarios (ΔTGW = +0.5 to +3.0 °C in 0.5 °C steps). Under ΔTGW = +3.0 °C conditions, people outdoors experience ‘extreme’ heat stress, which could result in dangerously high increases in human body core temperature. AC-induced feedback increases heat stress roughly linearly as ΔTGW increases, reaching 0.6 °C (or 12% of the heat stress increase). As this increase is similar to current possible heat island mitigation techniques, this feedback needs to be considered in urban climate projections, especially where AC use is large.

Abbreviations and notation used

AC Air-conditioning
AC→FB Simulation with AC feedback (FB)
AC≠FB Simulation without AC FB (no-QF, AC)
BEP+BEM Building effect parameterisation and building energy model
C Commercial and office
Cg Sensible heat flux from the globe surface (W m⁻²)
Cp Specific heat at constant pressure (J K⁻¹ kg⁻¹)
CM-BEM Urban canopy model and building energy model
CMIP Climate model intercomparison project
COP Coefficient of performance
COST Cooperation in science and technical development
D Diameter of the globe (m)
FB Feedback
GCM Global climate model
GHG Greenhouse gas
GIAJ Geospatial Information Authority of Japan
GIS Geospatial information system
IPCC Intergovernmental Panel for Climate Change

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1. Introduction

In 2018, Japan had the second hottest July on record (since 1883, Japan Meteorological Agency (JMA) official home page: https://www.data.jma.go.jp), with a mean monthly temperature in Osaka 1.63 °C higher than the 11 year (July 2000–2010) mean. These elevated temperatures resulted in the highest on record hospitalisations (54,220) and heat stroke deaths (133) (Ministry of Internal Affairs and Communications, Japan 2018). This period was designated a ‘heat wave natural disaster’ (Nikkei 2018), similar to disasters from typhoons, heavy rainfall and snowfall, and floods.

Heat waves are expected to become more common and more intense with greenhouse gas (GHG)–induced global warming (e.g. IPCC 2013), exacerbated in cities by the urban heat island effect (e.g. IPCC 2014). With cities being home to more than 66% of the population by 2050 (United Nations 2014), the impact of urban...
climate on public health and energy supply/demand is critical. Already 30% of the world’s population are exposed to deadly heat thresholds on at least 20 days per year, and this may increase to ~74% by 2100 if GHG emissions increase (Mora et al 2017).

To prepare for future heat waves, it is critical to understand how urban heat stress will change and to identify potential feedbacks from GHG-induced global warming and human activities. Although future urban air temperatures have been explored both globally and locally (e.g. Adachi et al 2012, Kusaka et al 2016, Hamdi et al 2014, Grossman-Clarke et al 2016, Conlon et al 2016, Krayenhoff et al 2018, Tewari et al 2019, Darmanto et al 2019, Takane et al 2019, Lipson et al 2019), few studies have examined the impact on human heat stress in cities. As global climate model (GCM) simulations (e.g. Delworth et al 1999, Willett and Sherwood 2012, Coffel et al 2018) still do not resolve most cities, it is difficult to predict urban heat stress.

A GCM (1° horizontal resolution) with an Urban Canopy Model (UCM) calculated the wet-bulb globe temperature (WBGT) heat stress metric (Fischer et al 2012), but this is too coarse for within-city variations. High resolution simulations using dynamical downscaling with a regional climate model (RCM) have allowed heat stress studies at 20 km (e.g. Mediterranean Diffenbaugh et al 2007) and 3 km resolution (e.g. Japan Kusaka et al 2012). Higher-resolution (a few kilometres) heat stress studies have addressed cities in Asia (Takane et al 2015, Suzuki-Parker and Kusaka 2015, 2016, Yang et al 2016, Kikumoto et al 2016, Doan et al 2016, Doan and Kusaka 2018, Yamamoto et al 2018), Europe (Altinsoy and Yildirim 2014), North America (Oleson et al 2015), and Oceania (Argüeso et al 2015).

In Japan, WBGT is the official thermal stress index (since 2006, Ministry of the Environment, http://www.wbgt.env.go.jp/en/). Although it is correlated with both the number of heatstroke patients (heat disorder risk) (Ohashi et al 2014, Yamamoto et al 2018) and excess deaths (Takaya et al 2014), it does not have a clear relationship with human physiological responses (Yaglou and Minard 1957). However, the Universal Thermal Climate Index (UTCI) (Fiala et al 2012, Blażejczyk et al 2013) is derived from human physiology experiments (Bröde et al 2012a), physiological modelling, meteorology, and climatology (Blażejczyk et al 2013). It has been applied in a range of climate conditions (Blażejczyk et al 2012, Schreier et al 2013, Blażejczyk et al 2014) and applications (Fiala et al 2010, 2012). Heat stress also depends on micro-scale variations in urban morphology (e.g. shading) and differences in individuals (e.g. age, size, movement, activity). Hence, local-scale grid globe temperatures do not capture micro-scale variability or range of values from shading, but rather the mean for the area (section 2.3). However, grid mean heat stress can indicate the most dangerous conditions that outdoor workers will be exposed to, helping risk assessments for human health.

Japan’s many megalopolises have high population densities (e.g. Tokyo and Osaka) where people are exposed to both high temperature and humidity. Hence, there is high risk of both heat stress and heatstroke during heat waves. Additionally, Japanese cities already use air-conditioning (AC) extensively with the associated release of anthropogenic heat ($Q_A$, i.e. $Q_{E, AC}$). With warmer temperatures, $Q_{E, AC}$ can increase causing a positive feedback leading to additional urban warming and energy consumption (e.g. Ashie et al 1999, Kikegawa et al 2003, Sailor 2011, Li et al 2014, Kikegawa et al 2014, Salamanca et al 2014, Takane et al 2017, Ginzburg and Demchenko 2019, Takane et al 2019). In Osaka, this positive feedback is predicted to cause 0.6 °C additional warming in early morning August temperatures (based on a four-GCM ensemble for +3.0 °C cf to current) global warming scenario, ~2070 s. Given this is a similar size to differences or uncertainties within GHG emission scenarios, RCMs, and urban planning scenarios, this feedback need to be considered (Takane et al 2019).

Our objectives are to predict the impacts on heat stress from future climate at 1-km horizontal resolution, considering the feedbacks from $Q_{E, AC}$. We focus on Osaka, the second largest city in Japan (figure 1), as it has experienced the hottest mean summer temperatures in Japan in the past 30 years (Takane et al 2013). Osaka’s humid climate results in greater daytime urban heat island intensities than cities with drier climates (Zhao et al 2014). Moreover Osaka, already a major tourist destination, will host the 2025 World Expo, thus thermal stress is of concern to both local citizens and global visitors.

2. Methods

In this study we indicate differences between the current and future climate as $\Delta$ (e.g., $\Delta T$) and with ($\rightarrow$) and without ($\neq$) air-conditioning (AC) feedback (FB) as $\delta$ (e.g., $\delta$UTCI is the UTCI difference between AC→FB and AC$\neq$FB).

Feedback from AC use ($\delta$UTCI$\rightarrow$FB) on future urban climates under future global warming scenarios ($\Delta T_{GW}$) and changes in $\delta$UTCI$\rightarrow$FB related to $\Delta T_{GW}$ are estimated. All methods (numerical model, model setup, and climate projections) are as in Takane et al (2019), except for the UTCI and WBGT calculations. The latter are described within the Supplemental Materials.
2.1. Model settings

Following Takane et al (2017, 2019) dynamic downscaling is undertaken using the Advanced Research WRF model (ver. 3.5.1) (Skamarock et al. 2008) with model parameters as indicated in table S1 (Supplemental Material) and the following physics schemes: updated Rapid Radiation Transfer Model (RRTMG) short-wave and longwave radiation (Iacono et al. 2008); WRF single-moment three-class (WSM3) cloud microphysics (Dudhia 1989, Hong et al. 2004); Mellor–Yamada–Janjic (MYJ) atmospheric boundary-layer (Mellor and Yamada 1982, Janjic 1994, 2002); Noah land surface model (Chen and Dudhia 2001); and BEP + BEM urban canopy parameterisation (Martilli et al. 2002, Salamanca and Martilli 2010, Salamanca et al. 2010). At each time step, \( Q_{U_{AC}} \) is calculated from electricity consumption using BEP+BEM for each 1 km grid. Summertime near surface air temperature and AC electricity consumption skill have been assessed for Osaka considering diurnal and spatial variations (Takane et al. 2017, 2019).

Two model domains (d01 and d02, figure 1(a)) have 126 × 126 grid points (x, y) at 5- and 1-km resolution, respectively. Vertically, the 35 sigma levels go up to 50 hPa. Land use, land cover (LULC) and topography data are from the Geospatial Information Authority of Japan (GIAJ). In d02, the GIAJ LULC and Osaka geographical information system (GIS) building footprint (polygon) data (figures 1(c), (d)) are used to classify the urban grids into (i) commercial and business (C); and residential with predominantly (ii) concrete fireproof apartments (Rt) or (iii) detached wooden dwellings (Rw). In d01, all urban areas are assumed to be Rw.

Initial and boundary conditions use NCEP–NCAR (National Centers for Environmental Prediction–National for Atmospheric Research) reanalysis (Kalnay et al. 1996) and merged satellite – in situ global daily sea surface temperature (MGDST) (Kurihara et al. 2006) data. As 11 Augusts are sufficient for climatological impacts and effects to be considered (Takane et al. 2017, 2019), the time integration for each year is from 00:00 UTC July 27 to September 1, with model spin-up. The 2000–2010 period is treated as the control simulation (case AC→FB) (figure 2, red arrow).

The no-\( Q_{U_{AC}} \) (feedback) simulation (case AC≠FB) differs from the control simulation as \( Q_{U_{AC}} \) is assumed to be 0 W m\(^{-2}\) (figure 2, blue arrow); i.e. the larger difference in UTCI between AC≠FB and AC→FB is the \( Q_{U_{AC}} \) feedback effect (\( \Delta \text{UTC}I_{AC→FB} \)). Additionally, six future climates are simulated (section 2.2). We estimate \( \Delta \text{UTC}I_{AC→FB} \) from \( \Delta \text{UTC}I_{AC→FB} = \Delta \text{UTC}I_{AC→FB} \) (figure 2), with \( \Delta \text{UTC}I_{AC→FB} \) for the current climate being 0 °C as we assume no long-term climate change (decades) (i.e., no increase in forcing temperature, and...
ΔUTCIAF−FB and ΔUTCIAFB are 0 °C. To determine ΔUTCIAF−FB, we assume that all conditions (e.g. urban structures and human activities) remain constant except for background climate change. Although unrealistic, this allows the specific impact of interest to be investigated.

2.2. Climate projection

Six future climates with background temperature increases (global warming with ΔTGW = +0.5, +1.0, +1.5, +2.0, +2.5, and +3.0 °C) relative to the current climate are simulated. The ensemble mean from four global climate models (GCMs) that participated in the Climate Model Intercomparison Project (CMIP5) (Taylor et al 2012): CCSM4 (Gent et al 2011), CESM1 (CAM5) (Meehl et al 2013), GFDL-CM3 (Donner et al 2011), and INM-CM4 (Volodin et al 2010); simulations for the representative concentration pathway [RCP] 8.5 are used. These are the highest Intergovernmental Panel on Climate Change (IPCC) greenhouse gas emissions scenario.

The climate variables (i.e. wind components, geopotential height, and temperature) differences between the current and future scenarios are estimated (figure 3). For each ΔTGW case, the climate difference for each variable is added to the NCEP–NCAR and MGDST data (figure 3) but with the relative humidity kept the same as the current climate. Advantages of this regional climate projection (so-called pseudo-global warming (PGW)) method (Kimura and Kitoh 2007, Sato et al 2007) is that it bias-corrected (e.g. Xu and Yang 2012, Bruyère et al 2014, 2015), widely used (e.g. Haral et al 2008, Kawase et al 2009, Rasmussen et al 2011, Kusaka et al 2012, 2016, Doan and Kusaka 2018, Takane et al 2019), and a verified (Kawase et al 2008, 2009, Yoshikane et al 2012) method.

2.3. UTCI calculation

The hourly UTCI is calculated for 11 years for each climate scenario using the Fiala et al (2012) human physiology polynomial parameterisation (Bröde et al 2012a, Blažejczyk et al 2013) as it is computational efficient (e.g. Bröde et al 2012b, Blažejczyk et al 2013, Provençal et al 2016, Ohashi et al 2018). It is forced with the near surface air temperature (2-m simulations or 1.5-m observations), relative humidity, black globe temperature (Tg) and wind speed (within the urban canopy layer) (figure 3). The mean radiant temperature (Tmrt) is estimated from Tg, air temperature, and wind speed (Kinouchi 2001):

\[ \varepsilon_h \sigma (T_{mrt} + 273.15)^4 = C_g + R_g \]  
\[ R_g = \varepsilon_s \sigma (T_g + 273.15)^4 \]

where \( C_g \) is the sensible heat flux from the globe surface (W m\(^{-2}\)), \( R_g \) is the longwave radiation emitted from the globe surface averaged for the surface area (W m\(^{-2}\)), and \( \varepsilon_h \) and \( \varepsilon_s \) are the emissivities of the globe thermometer (assumed to be 1.0) and human clothing (0.98), respectively. \( C_g \) is a function of globe temperature and air
temperature (Yuge 1960):

\[ C_T = h_g (T_T - T_a) \]  

\[ \frac{h_g D}{\lambda} = 2 + 0.55 R e^{0.55} \left( \frac{c_p \mu}{\lambda} \right)^{\frac{1}{3}} \]  

\[ (10 < Re < 1.8 \times 10^3) \]  

\[ \frac{h_g D}{\lambda} = 2 + 0.34 R e^{0.566} \left( \frac{c_p \mu}{\lambda} \right)^{\frac{1}{3}} \]  

\[ (1.8 \times 10^3 < Re < 1.5 \times 10^5) \]  

where \( Re \) is the Reynolds number \((U D/\nu)\), \( U \) is the wind speed, \( D \) the diameter of the globe (\(=0.15 \text{ m}\)), \( \nu \) is the kinematic viscosity of air \((\text{m}^2 \text{s}^{-1})\), \( \gamma \) the viscosity coefficient of air \((\text{Pa} \text{s})\), \( \lambda \) the thermal conductivity of air \((\text{Wm}^{-1} \text{K}^{-1})\), and \( c_p \) the specific heat at constant pressure \((\text{K}^{-1} \text{kg}^{-1})\).

\( T_T \) is estimated using the (Okada and Kusaka 2013, Okada et al 2013) improvement:

\[ T_T = \frac{(S_0 - 38.5)}{(0.0217S_0 + 4.35U + 23.5)} + T_a \]  

where \( S_0 \) is the incoming shortwave radiation \((\text{Wm}^{-2})\). Okada et al (2013) determined the equation (6) parameters from hourly observations (June-August 2006–2012, all weather conditions) at a Osaka site surrounded by office buildings \((\text{RMSE (root mean square error)} = 2.15 ^\circ \text{C})\).

The grid average UTCI and WBGT calculated provide information on exposure for outdoor workers allowing risk assessment for human health. Heat stress metrics for within shadow conditions (e.g. Ohashi et al 2014) can reduce UTCI by \(\sim 8 ^\circ \text{C}\) (WBGT by \(\sim 1.5 ^\circ \text{C}\)) in summer daytime in Tokyo (Honjo et al 2018). However, most regional scale heat stress studies use mean radiative conditions (as we do) they allow the regional scale distribution of heat stress or the heat ‘stress’ island (section 3.1) to be identified, and its change with climate change to be assessed. Regional scale values provide useful initial and/or boundary conditions for higher resolution building resolving models with street level shade and flows around building and trees.

**2.4. Verification**

The model setup (this section) verifiﬁcation is presented in Supplementary material (S1). As the urban charactistics of Osaka (ﬁgure 1(d)) do not produce a large difference between the two types of residential area (wooden detached dwellings and ﬁreproof apartments), we only present the results for the area of wooden detached dwellings (hereafter residential) and the commercial and ofﬁce buildings (commercial).
3. Results

The $\Delta T_{GW}$ changes the temperature, wind, humidity, and radiation in WRF. In the results, wind speed and $T_{mrt}$ increase a small amount with $\Delta T_{GW}$ at night but do not change during the day. Hence, their $\Delta T_{GW}$ impact on the UTCI could be small. Relative humidity changes a little from the temperature and specific humidity increases.

3.1. UTCI increase ($\Delta UTCI$) with global warming ($\Delta T_{GW}$)

The UTCI is greater in Osaka than in the surrounding land areas at 05:00 under all seven climates (current and six future scenarios, figures 4(a)–(g)), we refer to these as urban heat ‘stress’ islands. In the current climate, Osaka (white line, figure 4(a)) has moderate heat stress but with greater urban warming ($\Delta T_{GW}$), this area expands to cover the entire plain when $\Delta T_{GW} = +1.5 \degree C$ (figure 4(d)), and extends to the low-mountain area (figure 4(g)) with additional warming. People outdoors in this moderate heat stress area will sweat (sweat rate >100 g h$^{-1}$) and experience wet skin (Bröde et al 2012a). The relatively higher heat stress area is in the coastal parts of Osaka and Kobe (black line, figure 4(g)).

At 12:00, UTCI increases with $\Delta T_{GW}$ and feedback effects of AC are projected (figures 4(h)–(n)), but with inland values expected to be higher than those in the coastal area. Under current climate conditions, the entire area, except the high mountains, experiences very strong heat stress (figure 4(h)). When $\Delta T_{GW} = +1.5 \degree C$, the mountain area is included in that description (figure 4(k)). Under such conditions, the human body core temperature of people outdoors for 30 min can increase (Bröde et al 2012a). When $\Delta T_{GW} = +2.0 \degree C$, an extreme heat stress area is projected inland from Osaka, covering Kyoto and Nara (black lines, figure 4(l)).

Figure 4. Eleven-year (2000–2010) mean UTCI for August at (a)–(g) 05:00 and (h)–(n) 12:00 under different climates: (a), (h) current and $\Delta T_{GW}$ (b), (i) $+0.5 \degree C$; (c), (j) $+1.0 \degree C$; (d), (k) $+1.5 \degree C$; (e), (l) $+2.0 \degree C$; (f), (m) $+2.5 \degree C$; and (g), (n) $+3.0 \degree C$. All times are local (UTC + 9 h); Japan does not use daylight saving time. For WBGT see supplemental material.
$\Delta T_{GW} = +3.0$ °C, it covers most of the plain (figure 4(n)). Under these conditions, people will sweat at more than 650 g h$^{-1}$, show large increases in their core temperature, and have a lower net heat loss (Bröde et al. 2012a).

The changes in the diurnal range of UTCI projected for the current and six future temperature scenarios are similar, but the individual mean values of UTCI differ (figure 5(a)). In the current climate, there is 1 h with no thermal stress (~05:00), but this disappears with only a small amount of warming (after $\Delta T_{GW} = +0.5$ °C) (yellow, figure 5(b)). The midnight-to-morning period of moderate heat stress remains almost constant with $\Delta T_{GW}$ unlike the evening-to-midnight period, which decreases with $\Delta T_{GW}$ from (orange, figure 5(b)). Notably, the latter becomes a strong heat stress (red, figure 5(b)) period once $\Delta T_{GW} = +2.0$ °C. Under $\Delta T_{GW} = +3.0$ °C, the period is projected to persist until midnight. The very strong heat stress daytime period increases with $\Delta T_{GW}$ (dark red, figure 5(b)). Under $\Delta T_{GW} = +2.5$ °C, extreme heat stress conditions are expected by 12:00, persisting longer with $\Delta T_{GW}$ (black in figure 5(b)).

### 3.2. Impact of AC induced feedback on UTCI ($\delta UTCI_{AC→FB}$)

The feedback effects of air-conditioning on UTCI ($\delta UTCI_{AC→FB}$) are much greater at night than during the day in residential areas (figure 6(b)), with changing climate expected to have greater influence in the early morning. The size of this feedback increases roughly linearly with the global temperature increases (figures 6(d), (e)). At 05:00, $\delta UTCI_{AC→FB}$ increases with $\Delta T_{GW}$ (figures 7(a)–(f)) but is smaller in the centre of Osaka (figures 7(b)–(f)). However, at 12:00, $\delta UTCI_{AC→FB}$ does not change with $\Delta T_{GW}$ (figures 6(b), (e)). These differences are probably caused by the difference in mixed layer depth, as Takane et al. (2019) proposed. In the middle of the day, $Q_{AC}$ is large, but the deeper mixed layer reduces its impact on UTCI. At night, although $Q_{AC}$ is smaller, the mixed layer is much smaller. Consequently, $Q_{AC}$ enhances the mixed depth, and there is a greater impact on UTCI.

Increased temperature from the nocturnal feedback causes an increase in $T_{ntr}$ which could contribute to an UTCI increase. The contribution of $\delta UTCI_{AC→FB}$ to $\Delta UTCI_{AC→FB}$ (figure 6(c)) is influenced by the $\delta UTCI_{AC→FB}$ diurnal pattern (figure 6(b)), with the contribution for the night-to-morning period being larger than that in the daytime. The early morning contribution is about 12% when $\Delta T_{GW} = +3.0$ °C. These results suggest that one reason for the relatively higher $\Delta UTCI_{AC→FB}$ at night (figure 6(a)) is the feedback process. The spatial distribution of the contribution of $\delta UTCI_{AC→FB}$ to $\Delta UTCI_{AC→FB}$ (figures 7(g)–(i)) is similar to that of $\delta UTCI_{AC→FB}$ (figures 7(a)–(f)).
4. Discussion

4.1. Hot and cold summers: consideration of heat waves
Differences in UTCI diurnal pattern are expected in a warmer summer climate. From the 11 current summers, we identify a hot (2010, figure 8(a)) and cold (2003, figure 8(c)) summer to compare to the mean (figure 8(b)). The hot and cold summer temperatures are 30.5 °C and 28.3 °C, respectively, or 1.52 °C warmer and 0.68 °C cooler than the 11-year mean. The August 2010 temperature roughly corresponds to the conditions expected when \( \Delta T_{GW} = +1.5 \) °C (i.e. above the summer mean). These individual summers were selected for each of the future climates for comparison (figure 8).

The patterns of the hot summer (figure 8(a)) diurnal UTCI classes when \( \Delta T_{GW} = 0.0 \) to +2.0 °C are similar to the mean for \( \Delta T_{GW} = +1.0 \) to +3.0 °C (figure 8(b), solid blue rectangle). Similarly, the cold summer (figure 8(c)) UTCI patterns for \( \Delta T_{GW} = +0.5 \) to +3.0 °C are similar to the mean for \( \Delta T_{GW} = 0.0 \) to +2.5 °C (figure 8(b), solid green rectangle). Therefore, the hot summer UTCI patterns for \( \Delta T_{GW} = +2.5 \) and +3.0 °C provide some insight into more extreme mean climate (e.g. \( \Delta T_{GW} = +3.5 \) and +4.0 °C, dashed blue rectangle). Similarly, the cold summer UTCI pattern at \( \Delta T_{GW} = 0.0 \) °C reflects the impact of an urban heat island mitigation of about 0.5 °C using current techniques for the current climate (\( \Delta T_{GW} = 0.0 \) °C, dashed green rectangle). Comparing these, the need to respond to or modify the future UTCI pattern caused by global warming and urban heat island mitigation techniques can be considered, in addition to the inter-annual summer variability within \( \Delta T_{GW} \).

The August 2013 and July 2018 Japanese heat waves had monthly mean temperatures in Osaka of 30.0 °C (0.99 °C warmer than the 11-year August mean (2000–2010)) and 29.5 °C (0.45 °C warmer), roughly corresponding to \( \Delta T_{GW} = 1.0 \) and 0.5 °C, respectively (figure 8(b), dashed pink rectangle). The observed diurnal UTCI class patterns for the two heat waves (figure 8(d)) are similar to those of \( \Delta T_{GW} = 1.0 \) and 0.5 °C (figure 8(b), dashed pink rectangle).

This approach provides a rough estimate of the future climate UTCI for specific heat and cold waves using past hot and cold summers for comparison.

4.2. Heat stress metrics
Two heat-related physiological responses, sweat production and human body core temperature, increase non-linearly once UTCI exceeds 40 °C (very strong and extreme heat stresses), whereas human thermal sensation does not (Bröde et al 2012a). In Osaka, daytime UTCI is projected to exceed 40 °C during current and future climates (figure 5(b), table S2). The impact of the feedback on core temperature is estimated to be less than 0.05 °C (not shown) and is regarded as not significant in terms of heat stroke vulnerability.

As human thermal sensation does not continue to change with an increase in UTCI, there is the danger that people will not feel the increasing heat stroke vulnerability. The critical UTCI range is 30 °C–36 °C (moderate to
strong, Bröde et al. (2012a), suggesting that awareness of the changes from early evening to morning (Figure 5(b), Table S2) is critical for heat stroke prevention.

The diurnal variation and spatial patterns of UTCI in Osaka (Figures 4–7) are similar to WBGT (Supplementary material), as others have noted (Zare et al. 2018). This suggests the widely available WBGT maps can be roughly used to infer probable UTCI spatial patterns.

As the grid average heat stress metrics calculated in this study do not capture the intra-grid variability (e.g. from shade), the values are more applicable to outdoor workers than to individuals who can seek shade outdoors or go indoors to AC areas.

4.3. Relative impact of the AC feedback and thermal mitigation to heat stress metrics
The impact of the AC feedback (\(\delta_{\text{UTCI}_{\text{AC} \rightarrow \text{FB}}}\)) simulated when \(\Delta T_{\text{GW}} = +3.0\, ^\circ\text{C}\) reached 0.6 °C for UTCI and 0.4 °C for WBGT (Supplementary Material) with 24-h means 0.23 and 0.15 °C, respectively. These are of similar size to some proposed thermal mitigation strategies. For example, the estimated decreases in UTCI with
different strategies for residential Lyon in summer include 0.2 °C–0.4 °C from water aspersion and 0.4 °C–0.7 °C from vegetation (Morille and Musy 2017). Similarly, facade greening (roofs and walls) are estimated to be able decrease the August daytime maximum WBGT by 0.02 °C–0.03 °C, and the relocation of AC heat release from walls to roofs by 0.03 °C–0.06 °C for the 23 wards of Tokyo (Ohashi et al 2016). However, our estimated feedbacks would negate the mitigation benefits from these techniques in future climates, especially where AC use is high.

4.4. Future work
Our results the impact of AC on future temperatures suggest is of sufficient importance that future work is warranted:

(1) Here heat stress metrics are calculated at 1 km scale but more detailed micro-scale variations (e.g. accounting for shadow patterns from building and vegetation such as by SOLWEIG Lindberg et al 2008) would allow human behaviour (e.g. movement) to be considered (e.g. Honjo et al 2018).

(2) Our estimates of the feedback on heat stress metrics may be low as a constant coefficient of performance (COP) is assumed. A variable COP would be more realistic and should be considered in future studies (e.g. CM-BEM Kikegawa et al 2014; TEB+BEM Bueno et al 2012; UCLEM Lipson et al 2018, 2019).

(3) Our focus has been on building energy emissions from AC but Qf sources from traffic, cooling towers, non-work day energy use variation, and electric and gas AC in office areas should all be considered.

(4) Analysis of other regions using the same methods to generalise the feedback impact, as the impacts may depend on climate, building type/materials, AC performance and human behaviours (e.g. how AC is used).

(5) The UTCI heat stress and physiological response is based on Europeans. Other regions and conditions need to be studied: e.g. Asian city residents.

5. Conclusions
Effects of GHG-induced global warming on heat stress are considered by analysing RCM (with urban canopy and building energy models) dynamically downscaled simulations for current and six future climate scenarios (global warming: ΔTGW). For the latter, CMIP5 global climate model (GCM) simulations with the highest IPCC greenhouse gas emissions scenario (RCP 8.5) are used. Two heat stress indices are calculated for Osaka during August, when air conditioning (AC) use (hence energy consumption) is greatest. From this we conclude:

(i) Heat stress (e.g. UTCI) increases with ΔTGW and with AC feedback. At night, an urban heat stress island (i.e. higher UTCI in the urban area compared with the surroundings) is simulated in Osaka for the current and six future climates. In the current climate, only 1 h of no thermal stress occurs near 05:00, but this disappears with ΔTGW = +0.5 °C and warmer climates. Moderate heat stress extends across the entire Osaka plain.
when $\Delta T_{GW} = +1.5 ^\circ C$. People outside under these conditions begin to sweat, and their skin wetness increases.

(ii) Daytime UTCI tends to be greater inland than in coastal areas. An extreme heat stress area appears when $\Delta T_{GW} = +2.0 ^\circ C$ inland, affecting Kyoto and Nara. This extends over most of the plain when $\Delta T_{GW} = +3.0 ^\circ C$. These are dangerous conditions for people outdoors, as they may experience large increases in sweating and human body core temperature, and lose the ability to shed heat unless they seek opportunities to reduce heat stress (e.g. shade outdoors, AC indoors).

(iii) The impact of AC-induced feedback on UTCI increases ($\delta UTCI_{AC \rightarrow FG}$) roughly linearly with $\Delta T_{GW}$. At $\Delta T_{GW} = +3.0 ^\circ C$, this reaches 0.6 °C (12% of UTCI increase). This size is comparable to the suggested benefits of thermal mitigation techniques reported in the literature. Hence, the feedback is significant and could potentially cancel other mitigation benefits in the future, especially where AC use is large. This feedback must not be neglected in future urban climate projections.

(iv) UTCI and WBGT, two independent heat stress metrics, have similar diurnal variation and spatial patterns. As the latter is the official Japanese metric, it may be possible to roughly estimate diurnal variations in UTCI from existing maps of WBGT.

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References

Altınsöz H and Yıldırım H A 2014 Labor productivity losses over western Turkey in the twenty-first century as a result of alteration in WBGT International Journal of Biometeorology 59 463–71
Błażejczyk K, Jendritzky G, Bröde P et al 2013 An introduction to the universal Thermal Climate Index (UTCI) Geographia Polonica 86 5–10
Bröde P, Kruger L E, Rossi A F and Fiala D 2012b Predicting urban outdoor thermal comfort by the universal Thermal Climate Index (UTCI) — a case study in southern Brazil Int. J. Biometeorol. 56 471–80

Chen F and Dudhia J 2001 Coupling an advanced land–surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model description and implementation Mon. Weather Rev. 129 569–85

Darmanto N S, Varquez A C G, Kawano N and Kanda M 2019 Future urban climate projection in a tropical megacity based on global climate change and local urbanization scenarios Urban Climate 29 100462


Doan V Q and Kusaka H 2018 Projections of urban climate in the 2050s in a fast-growing city in Southeast Asia: the greater Ho Chi Minh City metropolitan area, Vietnam Int. J. Climatol. 38 4155–71

Doan V Q, Kusaka H and Ho Q B 2016 Impact of future urbanization on temperature and thermal comfort index in a developing tropical city: Ho Chi Minh City Urban Climate 17 20–31

Donner L J et al 2011 The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component of the GFDL global coupled model CM3 J. Clim. 24 3484–518

Dudhia J 1989 Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model J. Atmos. Sci. 46 3077–107


Janjic Z 2002 Nonsingular implementation of the Mellor–Yamada level 2.5 scheme in the NCEP Meso model NCEP Office Note 436 61


Lindberg F, Thorsson S and Holmer B 2008 SOLWEIG 1.0—Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. Int. J. Biometeorol. 52 697–713


Meehl G A et al 2013 Climate change projections in CESM1(CAM5) compared to CCSM4 J. Clim. 26 6287–308


Ministry of Internal Affairs and Communications, Japan 2018 (https://www.fdma.go.jp/disaster/heatstroke/item/heatstroke003_houdou04.pdf)


Morille B and Mussy M 2017 Comparison of the impact of three climate adaptation strategies on summer thermal comfort—case study in Lyon France Environ. Procedia Science 38 619–26


Provençal S, Bergeron O, Leduc R and Barrette N 2016 Thermal comfort in Quebec City, Canada: sensitivity analysis of the UTCI and other popular thermal comfort indices in a mid-latitude continental city Int. J. Biometeorol. 60 591–603


Sato T, Kimura F and Kitoh A 2007 Projection of global warming onto regional precipitation over Mongolia using a regional climate model J. Hydrol. 333 144–54


Suzuki-Parker A and Kusaka H 2016 Future projections of labor hours based on WBGT for Tokyo and Osaka, Japan, using multi-period ensemble dynamical downscale simulations Int. J. Biometeorol. 60 307–10


Takane Y, Ohashi Y, Kusaka H, Shigeta Y and Kikegawa Y 2013 Effects of synoptic-scale wind under the typical summer pressure pattern on the mesoscale high–temperature events in the Osaka and Kyoto urban areas by the WRF model Journal of Applied Meteorology and Climatology 52 1704–78


Volodin E M, Diansky N A and Gusev A V 2010 Simulating present-day climate with the INMCM4.0 coupled model of the atmospheric and oceanic general circulations Izv. Atmosph. and Oceanic Phys. 46 414–51

Willett K M and Sherwood S 2012 Exceedance of heat index thresholds for 15 regions under a warming climate using the wet-bulb globe temperature Int. J. Climatol. 32 161–77
Yoshikane T, Kimura F, Kawase H and Nozawa T 2012 Verification of the performance of the pseudo-global-warming method for future climate changes during June in East Asia SOLA 8 133–6
Yuge T 1960 Experiments on heat transfer from sphere including combined natural and forced convection Journal of Heat Transfer C82 214–20
Zare S, Hasheminejad N, Shirvan H E, Hemmatjo R, Sarebanzadeh K and Ahmadi S 2018 Comparing universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year Weather and Climate Extremes 19 49–57
Zhao L, Lee X, Smith R B and Oleson K 2014 Strong contribution of local background climate to urban heat island Nature 511 216