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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 ($\Delta T_{GW}$) 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 ($\Delta T_{GW} = +0.5$ to $+3.0$ °C in 0.5 °C steps). Under $\Delta T_{GW} = +3.0$ °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 $\Delta T_{GW}$ 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
$C_g$: Sensible heat flux from the globe surface (W m$^{-2}$)
$C_p$: 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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JMA Japan Meteorological Agency
LULC Land use and land cover
MGDSST Merged satellite and in situ global daily sea surface temperature
MYJ Mellor-Yamada-Janji
NCEP-NCAR National Center for Environmental Prediction—National Center for Atmospheric Research
PGW Pseudo global warming
QF Anthropogenic heat flux (W m$^{-2}$)
QF, AC $Q_F$ from AC use (W m$^{-2}$)
RCM Regional climate model
RCP Representative concentration pathway
Re Reynolds number (–)
Rg Longwave radiation emitted from a globe surface averaged by surface area (W m$^{-2}$)
Rr Residential area with predominantly concrete fireproof apartments
RRTMG Updated rapid radiation transfer model
Rw Residential area with predominantly detached wooden dwellings
$S_0$ Incoming shortwave radiation (W m$^{-2}$)
SLUCM Single-layer UCM
SOLWEIG Solar and longwave environmental irradiance geometry-model
$T_g$ Black globe temperature (°C)
TEB + BEM Town energy balance and building energy model
$T_{mrt}$ Mean radiant temperature (°C)
$U$ Wind speed (m s$^{-1}$)
UCM Urban canopy model
UCLEM Urban climate and energy model
UTCI universal thermal climate index
$v$ Kinematic viscosity of air (m$^2$ s$^{-1}$)
WBGT Wet-bulb globe temperature
WRF Weather research and forecasting
WSM3 WRF single-moment three-class
$\gamma$ Viscosity coefficient of air (Pa s$^{-1}$)
$\Delta T_{GW}$ Global warming (°C)
$\Delta UTCl_{AC\rightarrow FB}$ UTCI difference between the current and future climate for AC→FB
$\Delta UTCl_{AC\rightarrow FB}$ UTCI difference between the current and future climate for AC→FB
$\delta UTCl_{AC\rightarrow FB}$ UTCI difference between the AC →FB and the AC→FB
$\varepsilon_g$ Emissivity of the globe thermometer (–)
$\varepsilon_h$ Emissivity of human clothing (–)
$\lambda$ Thermal conductivity of air (W m$^{-1}$ K$^{-1}$)

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, Błážejczyk et al. 2013) is derived from human physiology experiments (Bröde et al. 2012a), physiological modelling, meteorology, and climatology (Błážejczyk et al. 2013). It has been applied in a range of climate conditions (Błážejczyk et al. 2012, Schreier et al. 2013, Błážejczyk 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 megacities 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\textsubscript{AC}, i.e. Q\textsubscript{E, AC}). With warmer temperatures, Q\textsubscript{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\textsubscript{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., \(\Delta\)UTC\(\textsuperscript{I}\)) is the UTCI difference between AC→FB and AC\(\neq\)FB).

Feedback from AC use (\(\Delta\)UTC\(\textsuperscript{I, AC→FB}\)) on future urban climates under future global warming scenarios (\(\Delta T\textsubscript{GW}\)) and changes in \(\Delta\)UTC\(\textsuperscript{I, AC→FB}\) related to \(\Delta T\textsubscript{GW}\) 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, $Q_{FB,AC}$ 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 $\times$ 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 (Rr) 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 (MGSST) (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 $\rightarrow$ FB) (figure 2, red arrow).

The non-$Q_{FB,AC}$ (feedback) simulation (case AC $\neq$ FB) differs from the control simulation as $Q_{FB,AC}$ is assumed to be 0 W m$^{-2}$ (figure 2, blue arrow); i.e. the larger difference in UTCI between AC $\neq$ FB and AC $\rightarrow$ FB is the $Q_{FB,AC}$ feedback effect ($\delta$UTCIC $\rightarrow$ FB). Additionally, six future climates are simulated (section 2.2). We estimate $\delta$UTCIC $\rightarrow$ FB from $\Delta$UTCIC $\rightarrow$ FB $-$ $\Delta$UTCICAC $\rightarrow$ FB (figure 2), with $\delta$UTCICAC $\rightarrow$ 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
\[ \Delta UTCl_{AC-FB} \text{ and } \Delta UTCl_{AC-FB} \text{ are } 0 \, ^\circ C. \] To determine \( \Delta UTCl_{AC-FB} \), 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 \( \Delta T_{GW} = +0.5, +1.0, +1.5, +2.0, +2.5, \) and \( +3.0 \, ^\circ C \)) 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 \( \Delta T_{GW} \) 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. Hara 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. UTCl calculation

The hourly UTCl 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 computationally 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 \( (T_g) \), and wind speed (within the urban canopy layer) (figure 3). The mean radiant temperature \( (T_{mrt}) \) is estimated from \( T_g \), air temperature, and wind speed (Kinouchi 2001):

\[
\varepsilon_h \sigma (T_{mrt} + 273.15)^4 = C_p + R_g \tag{1}
\]

\[
R_g = \varepsilon_d \sigma (T_g + 273.15)^4 \tag{2}
\]

where \( C_p \) 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 \( \varepsilon_d \) are the emissivities of the globe thermometer (assumed to be 1.0) and human clothing (0.98), respectively. \( C_p \) is a function of globe temperature and air
\[ C_g = h_g (T_g - T_a) \]  
(3)

\[ \frac{h_g D}{\lambda} = 2 + 0.55 \text{Re}^{0.5} \left( \frac{c_p \mu}{\lambda} \right)^{\frac{1}{3}} \]  
(10 < Re < 1.8 \times 10^3)  
(4)

\[ \frac{h_g D}{\lambda} = 2 + 0.34 \text{Re}^{0.566} \left( \frac{c_p \mu}{\lambda} \right)^{\frac{1}{3}} \]  
(1.8 \times 10^3 < Re < 1.5 \times 10^5)  
(5)

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

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

\[ T_g = \frac{(S_0 - 38.5)}{(0.0217S_0 + 4.35U + 23.5)} + T_a \]  
(6)

where \( S_0 \) is the incoming shortwave radiation \((\text{W} \cdot \text{m}^{-2})\). 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 (RMSE (root mean square error) = 2.15 °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 ~8 °C (WBGT by ~1.5 °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) verificiation 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 $\Delta T_{GW} = +1.5 \, ^{\circ}C$ (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 $\Delta T_{GW} = +1.5 \, ^{\circ}C$, 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 $\Delta T_{GW} = +2.0 \, ^{\circ}C$, an extreme heat stress area is projected inland from Osaka, covering Kyoto and Nara (black lines, figure 4(l)). When

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) $+0.5 \, ^{\circ}C$; (c), (j) $+1.0 \, ^{\circ}C$; (d), (k) $+1.5 \, ^{\circ}C$; (e), (l) $+2.0 \, ^{\circ}C$; (f), (m) $+2.5 \, ^{\circ}C$; and (g), (n) $+3.0 \, ^{\circ}C$. All times are local (UTC + 9 h); Japan does not use daylight saving time. For WBGT see supplemental material.
$\Delta T_{GW} = +3.0 \, ^\circ \text{C}$, 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 $\Delta T_{GW} = +0.5 \, ^\circ \text{C}$) (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 $\Delta T_{GW} = +2.0 \, ^\circ \text{C}$. Under $\Delta T_{GW} = +3.0 \, ^\circ \text{C}$, 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 $\Delta T_{GW} = +2.5 \, ^\circ \text{C}$, 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 ($\delta UTCI_{AC\rightarrow FB}$)

The feedback effects of air-conditioning on UTCI ($\delta UTCI_{AC\rightarrow FB}$) 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, $\delta UTCI_{AC\rightarrow FB}$ 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, $\delta UTCI_{AC\rightarrow FB}$ 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, $Q_{F,AC}$ is large, but the deeper mixed layer reduces its impact on UTCI. At night, although $Q_{F,AC}$ is smaller, the mixed layer is much smaller. Consequently, $Q_{F,AC}$ enhances the mixed depth, and there is a greater impact on UTCI.

Increased temperature from the nocturnal feedback causes an increase in $T_{net}$, which could contribute to an UTCI increase. The contribution of $\delta UTCI_{AC\rightarrow FB}$ to $\Delta UTCI_{AC\rightarrow FB}$ (figure 6(c)) is influenced by the $\delta UTCI_{AC\rightarrow FB}$ 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 $\Delta T_{GW} = +3.0 \, ^\circ \text{C}$. These results suggest that one reason for the relatively higher $\Delta UTCI_{AC\rightarrow FB}$ at night (figure 6(a)) is the feedback process. The spatial distribution of the contribution of $\delta UTCI_{AC\rightarrow FB}$ to $\Delta UTCI_{AC\rightarrow FB}$ (figures 7(g)–(i)) is similar to that of $\delta UTCI_{AC\rightarrow FB}$ (figures 7(a)–(i)).
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 ΔTGW = +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 ΔTGW = 0.0 to +2.0 °C are similar to the mean for ΔTGW = +1.0 to +3.0 °C (figure 8(b), solid blue rectangle). Similarly, the cold summer (figure 8(c)) UTCI patterns for ΔTGW = +0.5 to +3.0 °C are similar to the mean for ΔTGW = 0.0 to +2.5 °C (figure 8(b), solid green rectangle). Therefore, the hot summer UTCI patterns for ΔTGW = +2.5 and +3.0 °C provide some insight into more extreme mean climate (e.g. ΔTGW = +3.5 and +4.0 °C, dashed blue rectangle). Similarly, the cold summer UTCI pattern at ΔTGW = 0.0 °C reflects the impact of an urban heat island mitigation of about 0.5 °C using current techniques for the current climate (ΔTGW = 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 ΔTGW.

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 ΔTGW = 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 ΔTGW = 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 (ΔUTCI_{AC→FB}) simulated when ΔT_{CW} = +3.0 °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

Figure 7. Impact of AC use in Osaka on the August monthly mean (11 years) at 05:00 (a–g) ΔUTCI_{AC→FB} and (h–n) contribution of ΔUTCI_{AC→FB} to ΔUTCI_{AC→FB} for increases of (a, g) +0.5 °C, (b, h) +1.0 °C, (c, i) +1.5 °C, (d, j) +2.0 °C, (e, k) +2.5 °C, and (f, l) +3.0 °C. For WBGT see supplemental material.
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 ($\Delta \text{UTCI}_{AC}$) roughly linearly with $\Delta T_{GW}$. At $\Delta T_{GW} = +3.0\, ^\circ C$, this reaches $0.6\, ^\circ C$ (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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