

## ARTICLE OPEN

## Urban warming and future air-conditioning use in an Asian megacity: importance of positive feedback

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The impact of feedback between urban warming and air-conditioning (AC) use on temperatures in future urban climates is explored in this study. Pseudo-global warming projections are dynamically downscaled to 1 km using a regional climate model (RCM) coupled to urban canopy and building energy models for current and six future global warming ( $\Delta T_{\text{GW}}$ ) climates based on IPCC RCP8.5. Anthropogenic heat emissions from AC use is projected to increase almost linearly with  $\Delta T_{\text{GW}}$ , causing additional urban warming. This feedback on urban warming reaches 20% of  $\Delta T_{\text{GW}}$  in residential areas. This further uncertainty in future projections is comparable in size to that associated with: a selection of emission scenarios, RCMs, and urban planning scenarios. Thus this feedback should not be neglected in future urban climate projections, especially in hot cities with large AC use. The impact of the feedback during the July 2018 Japanese heat waves is calculated to be 0.11 °C.

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## INTRODUCTION

With the global proportion of people living in cities expected to exceed two-thirds by 2050,<sup>1</sup> the urban climate affects many aspects of human life, including energy demand, health and the economy. Therefore, urban climate projections that include extreme weather events, such as heat waves from climate change, are of interest, given the potentially wide range of social and scientific impacts on human activities. These projections are also important when producing strategies to mitigate urban heat and for adapting to urban climate change. For example, given that US urban temperatures are predicted to increase by 1–2 °C due to climate change, energy demand is predicted to increase by 5–25%. Therefore, effective adaptation strategies that include measures to cool the urban climate and built environment that do not result in further emissions of heat or greenhouse gases (GHGs) will need to be produced and assessed.<sup>2</sup>

Of the two main methods to obtain fine horizontal resolution projections of climate, the dynamical (rather than statistical) downscaling is used here. Several previous dynamical downscaling studies of future urban climate have used regional climate models (RCMs) with a coupled urban canopy model (UCM) (hereafter RCM/UCM). For example, Kusaka et al.<sup>3</sup> predicted the 2070s summertime climate for three Japanese megacities using the Weather Research and Forecasting (WRF) model<sup>4</sup> with the single-layer UCM,<sup>5,6</sup> assuming pseudo-global warming (PGW),<sup>7,8</sup> at a 3-km resolution. This future climate projection (dynamical downscaling) method uses reanalysis data with the climatic change component from global climate models (GCMs; see ‘Methods’ section). Similar methods have been used for cities in Asia,<sup>9–11</sup> Europe,<sup>12,13</sup> North America<sup>14,15</sup> and Oceania.<sup>16</sup> In these RCM/UCM studies, anthropogenic heat ( $Q_F$ ) is an important term in the urban surface heat balance but is assumed to have a constant diurnal pattern (e.g. Fig. 3 of Kusaka et al.<sup>17</sup>). Thus  $Q_F$  impact on future urban temperatures is kept the same as current climate if all other factors (e.g. urban structure and human activities) do not change. This assumption may be reasonable

in cities with little air-conditioning (AC) use (e.g. northern European cities); however, where AC use is already common (e.g. Asian cities), it may not.

If cities experience positive feedback from interactions between urban warming and AC use,<sup>18–21</sup> this assumption would not hold. When air temperatures increase, energy consumption associated with AC use surges (Fig. 1a, Path 1) (i.e. increase in  $Q_F$  from AC use ( $Q_{F,AC}$ )). In turn, the energy released outdoors will enhance urban warming (Fig. 1a, Path 2).<sup>22</sup> Using a simple one-dimensional mixing-layer model, Ohashi et al.<sup>23</sup> estimated the increase in summertime air temperature from AC waste heat in Osaka City to be +0.36 to +0.72 °C. Previous studies focus on only one side of this process. Most consider impacts of urban warming on energy consumption (Fig. 1a, Path 1).<sup>24–27</sup> Effects of  $Q_F$  on urban temperature (Fig. 1a, Path 2) have been studied with limited-area models.<sup>28–33</sup> However, the amount of ‘additional warming’ from urban warming–AC feedback has yet to be assessed. Hence, the impact of this feedback process on future urban climate remains unknown.

In this study, we define the temperature difference caused by AC use as  $\delta T_{AC}$  (Fig. 1b, orange):

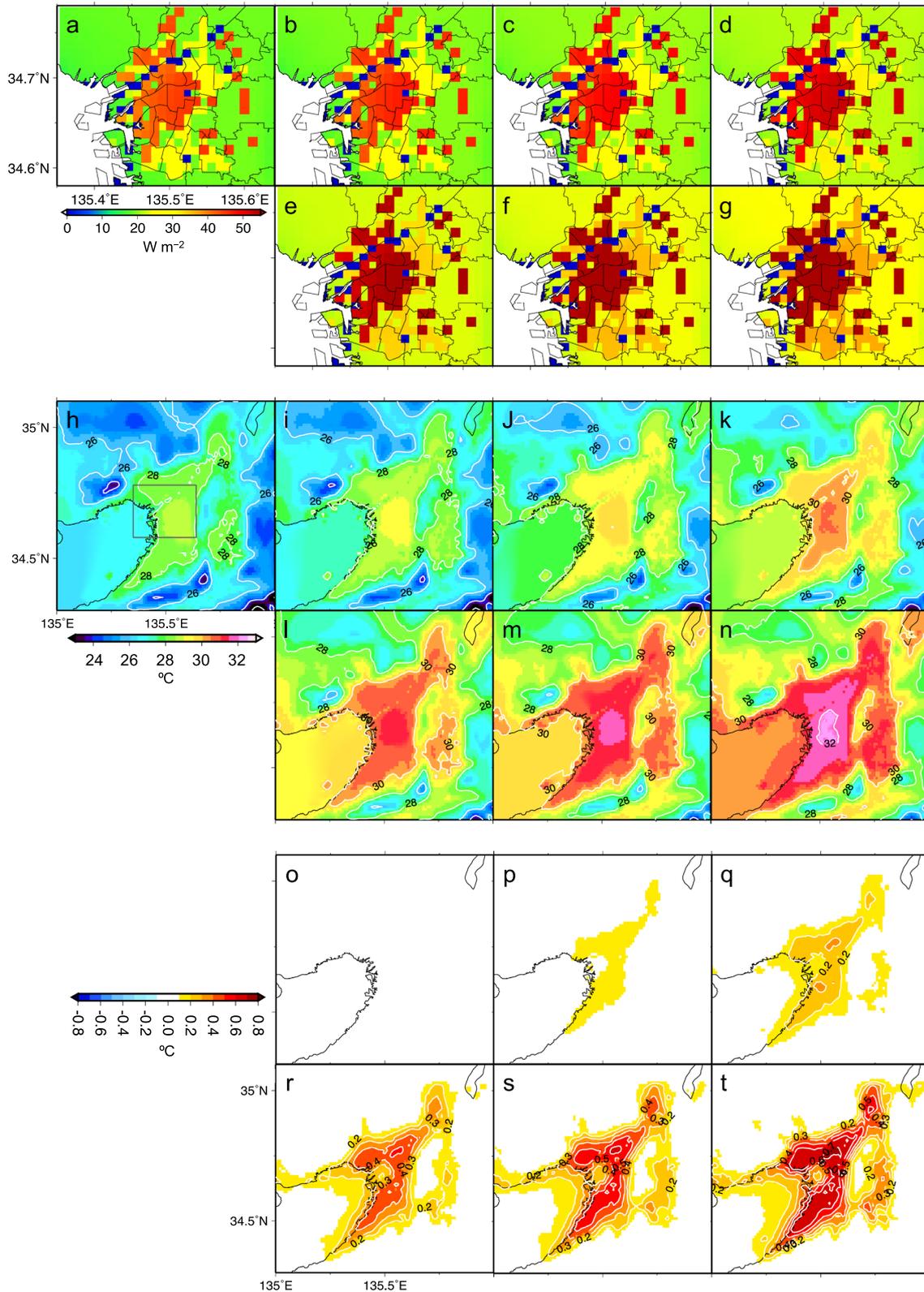
$$\delta T_{AC} = \delta T_{AC \neq FB} + \delta T_{AC \rightarrow FB} \quad (1)$$

where  $\delta T_{AC \neq FB}$  is the temperature difference caused by AC use but without AC feedback (Fig. 1b purple, without Path 2 Fig. 1a [no- $Q_{F,AC}$  simulation], see ‘Methods’ [Model settings]). The ‘additional temperature difference’ caused by the feedback process is  $\delta T_{AC \rightarrow FB}$  (Fig. 1b, green, with Path 2 Fig. 1a). In this study, we use model simulations to determine the different components (Fig. 1b and ‘Methods’ provide more details).

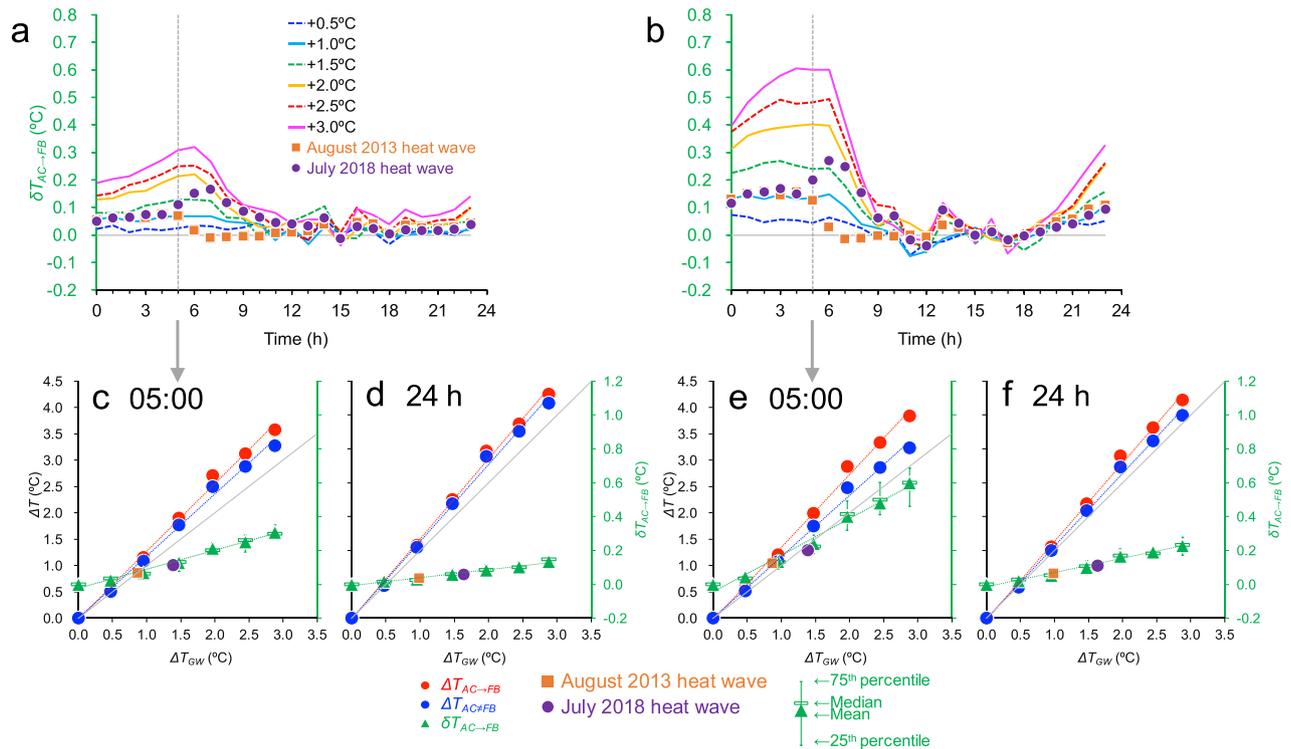
The Salamanca et al.’s<sup>22</sup> WRF/BEP+BEM (building effect parameterisation and building energy model)<sup>34–36</sup> simulations, with and without  $Q_{F,AC}$  release, allows  $\delta T_{AC}$  to be estimated (Fig. 1b, reference (R) Salamanca et al.,<sup>22</sup>  $R_{S14}$ ). The 10-day Phoenix heat wave study obtained an extreme  $\delta T_{AC}$  of 1.0 °C at night. However, as they did not separate  $\delta T_{AC}$ ,  $\delta T_{AC \rightarrow FB}$  remains unknown. Given that  $\delta T_{AC \rightarrow FB}$  may enhance electricity consumption (hereafter

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**Fig. 2** Horizontal variation of August monthly mean (11 years) **(a–g)** anthropogenic heat flux ( $Q_{F, AC}$ ), **(h–n)** 2 m air temperature and **(o–t)**  $\delta T_{AC \rightarrow FB}$ : **a–g** at 14:00 local time with city administrative boundaries (lines) of Osaka City (grey square in **h**) for **a** current climate and  $\Delta T_{GW}$ , **b** +0.5°C, **c** +1.0°C, **d** +1.5°C, **e** +2.0°C, **f** +2.5°C and **g** +3.0°C. **h–n** As **a–g**, daily mean with contour intervals of 2°C (white lines). **o–t** At 05:00 local time with contour interval 0.2°C (white lines) for **o** +0.5°C, **p** +1.0°C, **q** +1.5°C, **r** +2.0°C, **s** +2.5°C and **t** +3.0°C



**Fig. 3** Impact of the feedback process on air temperature ( $\delta T_{AC \rightarrow FB}$ ). **a, b** Diurnal variations of the  $\delta T_{AC \rightarrow FB}$  for current climate (grey line, i.e. 0 °C), six future climates simulated via  $\Delta T_{GW}$  and for heat waves in July 2018 (purple circles) and August 2013 (orange squares) in Japan estimated by linear relation between  $\Delta T_{AC \rightarrow FB}$  and  $\delta T_{AC \rightarrow FB}$  for each time (Table 2a) for **a** office and **b** residential areas. **c–f** Relation between  $\Delta T_{GW}$  and  $\Delta T$  ( $\delta T_{AC \rightarrow FB}$ , green triangles) calculated from the AC  $\rightarrow$  FB (red) and AC  $\neq$  FB (blue) simulations for **c, d** office and **e, f** residential areas. **c, e** August 05:00 mean and **d, f** 24 h mean air temperatures. Regression lines (dotted). Error bars indicate 25th and 75th percentiles

The mean  $Q_{F,AC}$  at 14:00 local time (LT) (i.e. close to a daily maximum of air temperature) in August is larger for office than residential areas for all seven control simulations (hereafter AC  $\rightarrow$  FB) (Fig. 2a–g and ‘Methods’).  $Q_{F,AC}$  increases from current to future climates ( $\Delta Q_{F,AC}$ ) as  $\Delta T_{GW}$  increases, which is associated with additional AC use (Fig. 2a–g) causing a close to linear increase in both the office ( $\Delta Q_{F,AC}/\Delta T_{GW} = 1.76 \text{ W m}^{-2} \text{ °C}^{-1}$ ) and residential areas ( $3.32 \text{ W m}^{-2} \text{ °C}^{-1}$ ). When  $\Delta T_{GW}$  is +3.0 °C,  $\Delta Q_{F,AC}$  is 1.37 (office) to 1.81 (residential) times larger than for current climate conditions (Supplementary Table 1).

The mean August 2 m air temperature (24 h, 11 years) in Osaka is warmer than the surrounding areas in both current and future climates (Fig. 2h–n). The temperature difference between the AC  $\rightarrow$  FB and the no- $Q_{F,AC}$  case (AC  $\neq$  FB) simulations increases along with  $\Delta T_{GW}$  (Fig. 3), indicating that urban heat will increase over time. This is caused by  $\Delta Q_{F,AC}$  with larger differences in the residential than in the office areas.

The differences between simulations with ( $\Delta T_{AC \rightarrow FB}$ ) and without ( $\Delta T_{AC \neq FB}$ ) anthropogenic heat fluxes allows the  $\delta T_{AC \rightarrow FB}$  to be determined (Figs. 1a 2o–t and 3). The  $\delta T_{AC \rightarrow FB}$  (05:00, 11 August months) and  $\Delta T_{GW}$  increase and the  $\delta T_{AC \rightarrow FB}$  in Osaka’s surrounding areas are higher than those of the centre of Osaka in both current and future climates (Fig. 2o–t). The diurnal variation of the  $\delta T_{AC \rightarrow FB}$  in residential areas (Fig. 3b) has two main features:

- (1)  $\delta T_{AC \rightarrow FB}$  for current and future climates are relatively small during daytime (notably 09:00–18:00) but larger at night (notably 18:00–06:00), with a peak around 05:00; and
- (2)  $\delta T_{AC \rightarrow FB}$  increases gradually as  $\Delta T_{GW}$  increases (+0.5 °C to +3.0 °C) during the night, indicating that urban warmth will increase overnight.

The relatively small daytime  $\delta T_{AC \rightarrow FB}$ , despite the relatively large daytime  $Q_{F,AC}$ , is because of the relatively high daytime

mixed layer. As  $Q_{F,AC}$  is mixed in a large volume, the impact of  $Q_{F,AC}$  on surface air temperature is reduced. At night,  $Q_{F,AC}$  is smaller, but the mixed layer height is lower. Similar results in previous work<sup>31</sup> support this proposed mechanism.

The relation between  $\Delta T_{GW}$  and downscaled urban warming ( $\Delta T_{AC \rightarrow FB}$  and  $\Delta T_{AC \neq FB}$ ) has two main features for office areas (Fig. 3d):

- (1)  $\delta T_{AC \rightarrow FB}$  tends to increase linearly with  $\Delta T_{GW}$ . This increase is from a feedback:  $\Delta T_{GW}$  modifies  $\Delta Q_{F,AC}$ , contributing to additional urban warming (Fig. 1a, Path 1  $\rightarrow$  Path 2)

$$\Delta T_{GW} \rightarrow \Delta Q_{F,AC} \rightarrow \delta T_{AC \rightarrow FB}$$

- (2)  $\Delta T_{AC \rightarrow FB}$  has a linear trend, as does  $\Delta T_{AC \neq FB}$ .

This is the first study to estimate the ‘additional’ positive feedback impact on future climate associated with AC. We conclude that  $\Delta T_{AC \rightarrow FB}$  has an approximately linear trend (Fig. 3c–f, red). The resulting AC  $\rightarrow$  FB case slope ( $\Delta T_{AC \rightarrow FB}/\Delta T_{GW}$ ) is  $1.18 \text{ °C °C}^{-1}$  for the office areas. This is larger than for the AC  $\neq$  FB case ( $1.13 \text{ °C °C}^{-1}$ ). These results suggest that it is relatively easy to estimate (parameterise) the impact of the feedback.

The two features in the monthly mean (Fig. 3d) are more evident at 05:00 (Fig. 3c) with  $\Delta T_{AC \rightarrow FB}/\Delta T_{GW} = 1.29 \text{ °C °C}^{-1}$ , which is larger than for case AC  $\neq$  FB ( $1.17 \text{ °C °C}^{-1}$ ). At 14:00 feature (1),  $\Delta T_{AC \rightarrow FB}$  and  $\Delta T_{AC \neq FB}$  are essentially the same, and  $\delta T_{AC \rightarrow FB}$  does not increase with  $\Delta T_{GW}$ .

The daily average of normalised  $\delta T_{AC \rightarrow FB}$  (see ‘Methods’) is roughly constant (3–5%) and not dependent on  $\Delta T_{GW}$  for the office area (Supplementary Fig. 1a). The average of normalised  $\delta T_{AC \rightarrow FB}$  at 05:00 increases from 3% (+0.5 °C) to 10% (+3.0 °C) as  $\Delta T_{GW}$  increases (Supplementary Fig. 1a, Supplementary Table 1).

Results for the residential area are similar to the office area, but feature (1) is more evident, especially at 05:00 (Fig. 3e, f). The  $\Delta T_{AC \rightarrow FB} / \Delta T_{GW}$  ( $1.38 \text{ } ^\circ\text{C}^{-1}$ ) is larger than the  $AC \neq FB$  case ( $1.16 \text{ } ^\circ\text{C}^{-1}$ ). As AC is used 24 h per day in residential areas, this cumulatively contributes more to warming than in office areas. The daily average of normalised  $\delta T_{AC \rightarrow FB}$  increases slightly from +0.5 to +3.0 °C, reaching 8% (at +3.0 °C). Thus about 0.25 °C additional urban warming is caused by the feedback when  $\Delta T_{GW}$  is +3.0 °C in the residential area. The normalised  $\delta T_{AC \rightarrow FB}$  at 05:00 increases from 8% (at +0.5 °C) to 20% (at +3.0 °C). This means that about 0.6 °C additional urban warming is caused by the feedback when  $\Delta T_{GW}$  is +3.0 °C (Fig. 3e).

## DISCUSSION

Importance of the feedback in adapting to future urban climate change

The choice of emission scenario causes uncertainty in projections. For example, the 2070s August mean urban temperatures in Osaka in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios with the A2 scenario projected 0.3 °C higher than A1b.<sup>46</sup> Doan and Kusaka's<sup>11</sup> urban warming projections (current to 2050s) for greater Ho Chi Minh City based on IPCC representative concentration pathway 4.5 (RCP4.5) and RCP8.5 scenarios found different scenarios to cause urban warming differences of 0.5 °C. The feedback uncertainty ( $\sim 0.25 \text{ } ^\circ\text{C}$  for residential areas when  $\Delta T_{GW} = +3.0 \text{ } ^\circ\text{C}$ ) is comparable to these emission scenario differences of 0.3 and 0.5 °C, respectively (Table 1a). Further uncertainty arises from the RCM choice. Kusaka et al.'s<sup>10</sup> August 2050s urban temperature projections in central Tokyo, using WRF and NHRCM (non-hydrostatic model of the Japan Meteorological Agency<sup>47</sup>), had a 10-year mean temperature increase uncertainty between RCMs of  $\sim 0.2 \text{ } ^\circ\text{C}$  (i.e. like the feedback reported here, see Table 1a).

Our work shows  $\delta T_{AC \rightarrow FB}$  could reach 0.25 °C in residential areas. This is comparable to the 0.3–0.5 °C century<sup>-1</sup> estimated global warming in Japan.<sup>48</sup> This feedback impact of 0.25 °C in residential areas is comparable to urban planning scenarios (Adachi et al.,<sup>49</sup> Kusaka et al.<sup>10</sup>) for 'dispersed' ( $\sim 0.34$  and  $0.1 \text{ } ^\circ\text{C}$ , respectively) and 'compact' ( $\sim 0.1$  and  $0.4 \text{ } ^\circ\text{C}$ , respectively) cities and future urbanisation on temperature of  $0.5 \text{ } ^\circ\text{C}^{11}$  (Table 1a).

The feedback impact is small in the daytime but large nocturnally, increasing with  $\Delta T_{GW}$  (Fig. 3). The normalised  $\delta T_{AC \rightarrow FB}$  at 05:00 increases with  $\Delta T_{GW}$ : 10% in the office areas and 20% in the residential areas, when  $\Delta T_{GW}$  is +3.0 °C (Supplementary Fig. 1). These results suggest that mitigating the feedback process before the impact becomes large may be an effective strategy to adapt to climate change in cities as the feedback effect could be comparable to those of past global warming, affecting urban planning scenarios. For example (Supplementary Discussion), the feedback uncertainty for a  $\Delta T_{GW}$  of +2.0 °C is  $\sim 10$  years (Fig. 4b, Table 1b), if we can stop the feedback technologically (e.g. improved coefficient of performance (COP), geothermal energy use) we could postpone a +2.0 °C world by about 10 years.

Application:  $\delta T_{AC \rightarrow FB}$  and  $\delta EC_{AC \rightarrow FB}$  estimates for the recent heat waves in Japan

As shown ('Results'),  $\Delta T_{AC \rightarrow FB}$  and  $\delta T_{AC \rightarrow FB}$  have near linear trends with  $\Delta T_{GW}$ . Also  $\delta T_{AC \rightarrow FB}$  and  $\delta EC_{AC \rightarrow FB}$  are close to linear with  $\Delta T_{AC \rightarrow FB}$ . This suggests that to estimate (parameterise)  $\delta T_{AC \rightarrow FB}$  and  $\delta EC_{AC \rightarrow FB}$  for other future urban climates or for specific events (e.g. heat waves) is straightforward. Table 2 shows gradients ( $a$ ) of linear regression ( $y = ax$ ) between  $\Delta T_{AC \rightarrow FB}$  ( $x$ ) and  $\delta T_{AC \rightarrow FB}$  ( $\delta EC_{AC \rightarrow FB}$ ) ( $y$ ). Here we estimate the  $\delta T_{AC \rightarrow FB}$  and  $\delta EC_{AC \rightarrow FB}$  for the recent heat waves of July 2018 and August 2013

in Japan using our proposed linear relations to illustrate an application.

The 2013 summer was the warmest on record for Japan (statistics since 1946<sup>50</sup>), with 41.0 °C recorded in western Japan (Shimanto City). In Osaka City, the August monthly mean (30.0 °C) was 0.99 °C higher than the 11-year mean (2000–2010). July 2018 was one of the hottest Julys in Japan since 1946, with Osaka's monthly mean temperature (29.5 °C) 1.63 °C higher than the 11-year mean (2000–2010). Therefore, August 2013 and July 2018 roughly correspond to situations when  $\Delta T_{AC \rightarrow FB} = +1.0 \text{ } ^\circ\text{C}$  and  $+1.5 \text{ } ^\circ\text{C}$ , respectively. Figure 3a, b shows a diurnal variation of the  $\delta T_{AC \rightarrow FB}$  for the two heat waves estimated by linear relations (Table 2a). The  $\delta T_{AC \rightarrow FB}$  for the two heat waves during the night to morning are higher than that for the daytime, especially in the residential areas. The 24-h mean  $\delta T_{AC \rightarrow FB}$  for July 2018 is 0.11 °C in the residential areas, which is higher than the 0.07 °C of August 2013. Similarly, the 24-h mean  $\delta EC_{AC \rightarrow FB}$  for July 2018 is 0.05 W floor-m<sup>-2</sup>, which is higher than 0.03 W floor-m<sup>-2</sup> of August 2013. Estimates of  $\delta T_{AC \rightarrow FB}$  and  $\delta EC_{AC \rightarrow FB}$  could be easily assessed for other heat waves and/or future urban climates in hot cities where significant AC use is common.

## Summary

Here a positive feedback from the interaction between urban warming and AC use is identified and quantified. Analysis of simulations for current and six future climate scenarios (global warming:  $\Delta T_{GW}$ ) is undertaken. For the latter, CMIP5 GCMs simulations with the highest IPCC GHG emissions scenario (RCP8.5) were used. The megacity of Osaka is analysed for August when AC use is at its greatest. From this, it is concluded that:

- (i) Anthropogenic heat emissions from AC use ( $Q_{F,AC}$ ) are predicted to increase linearly with  $\Delta T_{GW}$  from current to future climates. Monthly total  $Q_{F,AC}$  in commercial & office and residential areas are projected to be 1.37 and 1.81 times larger than current climate conditions when  $\Delta T_{GW}$  is +3.0 °C, respectively;
- (ii) This represents a feedback process from current to future climate:

$\Delta T_{GW} \rightarrow \Delta Q_{F,AC}$  ( $Q_{F,AC}$  increase)  $\rightarrow \delta T_{AC \rightarrow FB}$  ('additional' temperature increase from the feedback)

Urban warming calculated when anthropogenic heat fluxes are permitted [case  $AC \rightarrow FB$  ( $\Delta T_{AC \rightarrow FB}$ )] is greater than when they are not included [case  $AC \neq FB$  ( $\Delta T_{AC \neq FB}$ )]. The difference between these two [ $\Delta T_{AC \rightarrow FB} - \Delta T_{AC \neq FB}$ ] provides  $\delta T_{AC \rightarrow FB}$ . This increases almost linearly with  $\Delta T_{GW}$  suggesting urban temperatures will increase faster than global warming due to the increase of the anthropogenic heating (assuming all other characteristics of the city remain constant) in future climates. The normalised  $\delta T_{AC \rightarrow FB}$  at 05:00 (LT) has the larger increase with  $\Delta T_{GW}$ . This reaches 10% of  $\Delta T_{GW}$  in office areas and 20% in residential area. Thus about 0.3 °C (office) and 0.6 °C (residential) additional urban warming is caused by the feedback when  $\Delta T_{GW}$  is +3.0 °C. The  $\delta T_{AC \rightarrow FB}$  is expected to increase  $EC$  through a feedback process:

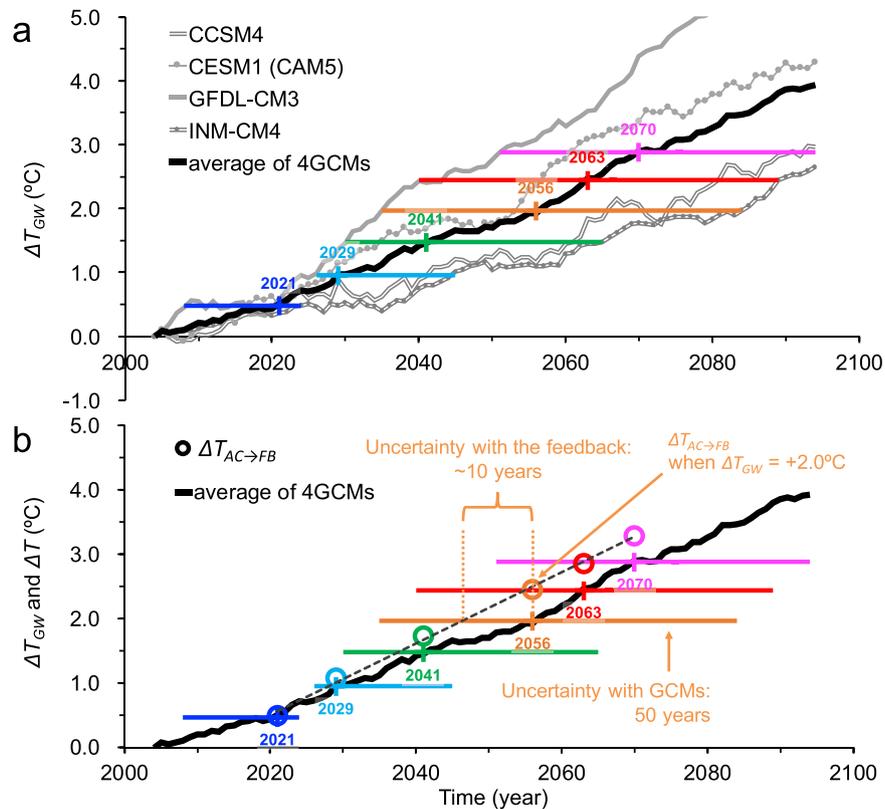
$\Delta T_{GW} \rightarrow \Delta Q_{F, AC} \rightarrow \delta T_{AC \rightarrow FB} \rightarrow \delta EC_{AC \rightarrow FB}$  ('additional'  $EC$  increase from the feedback).

The  $EC$  increase calculated by case  $AC \rightarrow FB$  ( $\delta EC_{AC \rightarrow FB}$ ) is greater than that calculated by case  $AC \neq FB$  ( $\delta EC_{AC \neq FB}$ ). The difference between these ( $\delta EC_{AC \rightarrow FB} - \delta EC_{AC \neq FB}$ ):  $\delta EC_{AC \rightarrow FB}$  increased linearly with  $\Delta T_{GW}$ ;

**Table 1.** Uncertainties in summer urban climate simulation projections: **a** Temperatures and **b** time (years) for the indicated warming to occur with the GCMs and the feedback

a						
Uncertainty	Feedback ( $\delta T_{AC \rightarrow FB}$ ) when $\Delta T_{GW} =$ $+3.0^\circ\text{C}$	IPCC GHG emission scenarios		RCMs (WRF and NHRCM)		
		SRES A1b and A2	RCP4.5 and 8.5			
Temperature ( $^\circ\text{C}$ )	0.25	0.3	0.5	0.2		
Reference	This study	Takane et al. <sup>46</sup>	Doan and Kusaka <sup>11</sup>	Kusaka et al. <sup>10</sup>		
Urban planning scenarios						
	Dispersed	Compact	Dispersed	Compact	Urbanisation Expand	
Temperature ( $^\circ\text{C}$ )	$\sim 0.34$	$\sim 0.1$	0.1	0.4	0.5	
Reference	Adachi et al. <sup>49</sup>		Kusaka et al. <sup>10</sup>		Doan and Kusaka <sup>11</sup>	
b						
	$+0.5^\circ\text{C}$	$+1.0^\circ\text{C}$	$+1.5^\circ\text{C}$	$+2.0^\circ\text{C}$	$+2.5^\circ\text{C}$	$+3.0^\circ\text{C}$
GCMs (years)	17	20	36	50	50	$>44^*$
Feedback (years)	0	0	4	10	9	8

\*Calculated from three GCMs (see Supplementary Discussion)



**Fig. 4** Changes in August mean surface air temperature for Japan. **a** Projected increase compared to 2000s (decadal running averages) for four global climate models (CCSM4, CESM1 (CAM5), GFDL-CM3 and INM-CM4; for references, see 'Methods') and the average  $\Delta T_{GW}$  (black line) for four GCMs assuming the RCP8.5 scenario (see text for more details). **b** Time series of  $\Delta T_{GW}$  (thick black line) and  $\Delta T_{AC \rightarrow FB}$  (circles) with maximum uncertainties (colour lines) of four GCMs and linear approximation of  $\Delta T_{AC \rightarrow FB}$  (dashed black line). Values are averaged for three urban categories: commercial and office buildings, fireproof apartments, and wooden detached dwellings

**Table 2.** Gradients of linear regression (sensitivities) between **a**  $\Delta T_{AC \rightarrow FB}$  and  $\delta T_{AC \rightarrow FB}$  ( $^{\circ}\text{C } ^{\circ}\text{C}^{-1}$ ) by time of day and location and between **b**  $\Delta T_{AC \rightarrow FB}$  and  $\delta EC_{AC \rightarrow FB}$  ( $\text{W floor}\cdot\text{m}^{-2} \cdot ^{\circ}\text{C}^{-1}$ )

a									
Time (h)	0	1	2	3	4	5	6	7	
Office	0.0496	0.0532	0.0575	0.0633	0.0714	0.0796	0.0808	0.0681	
Residential	0.1168	0.1302	0.1391	0.1455	0.1458	0.1434	0.1436	0.1027	
Time (h)	8	9	10	11	12	13	14	15	
Office	0.0429	0.0326	0.0231	0.0170	0.0152	0.0133	0.0285	-0.0080	
Residential	0.0554	0.0234	0.0243	-0.0066	-0.0147	0.0378	0.0197	-0.0006	
Time (h)	16	17	18	19	20	21	22	23	Mean
Office	0.0253	0.0205	0.0033	0.0202	0.0157	0.0181	0.0213	0.0358	0.0367
Residential	0.0101	-0.0158	-0.0036	0.0113	0.0297	0.0443	0.0701	0.0923	0.0673
b									
Time (h)	0	1	2	3	4	5	6	7	
Office	0	0	0	0	0	0	0	0	
Residential	0.0364	0.0834	0.1010	0.1160	0.1193	0.1223	0.1137	0.1003	
Time (h)	8	9	10	11	12	13	14	15	
Office	0	-0.0182	0.0469	0.0326	0.0194	0.0759	0.0353	0.0231	
Residential	0.0631	0.0383	0.0134	0.0052	0.0008	0.0017	0.0028	-0.0032	
Time (h)	16	17	18	19	20	21	22	23	Mean*
Office	0.0297	0.0192	0.0187	0.0166	0	0	0	0	0.0289
Residential	0.0026	-0.0006	-0.0021	-0.0010	0.0040	0.0005	-0.0084	0.0101	0.0383

\*Mean when AC in use

- (iii) Uncertainty introduced by the feedback ( $\delta T_{AC \rightarrow FB}$ ) is comparable to that introduced from selection of emission scenario, RCM and/or urban planning scenario. Thus this feedback should not be neglected in future urban climate projection, especially in hot cities where significant AC use is common; and
- (iv) Using linear relations proposed in this study (between  $\Delta T_{AC \rightarrow FB}$  and  $\delta T_{AC \rightarrow FB}$ ), the  $\delta T_{AC \rightarrow FB}$  during recent Japanese heat waves (July 2018 and August 2013) are estimated to be 0.11 and 0.07  $^{\circ}\text{C}$ , respectively. Such an approach can be used to estimate  $\delta T_{AC \rightarrow FB}$  for other heat waves and/or future urban climates in hot cities where significant AC use is common.

## METHODS

To distinguish the difference between current and future climate  $\Delta$  (e.g.  $\Delta T$ ) is used, and between cases with the same  $\Delta T_{GW}$ ,  $\delta$  is used (e.g.  $\delta T$  is a temperature difference between  $AC \rightarrow FB$  and  $AC \neq FB$  (explained later) at current climate or a future climate).

First, the impacts of the feedback ( $\delta T_{AC \rightarrow FB}$ ) on future urban climate from global temperature scenarios (hereafter  $\Delta T_{GW}$ ) are evaluated. Second, we explore how  $\delta T_{AC \rightarrow FB}$  changes in relation to  $\Delta T_{GW}$ . The urban air temperature and  $EC$  calculated by WRF/BEP+BEM were verified using detailed observational data for a year.<sup>51</sup>

## Description of the numerical model

Previously, WRF/BEP+BEM simulated urban air temperature and  $EC$  for April 2013 to March 2014 in Osaka were verified.<sup>51</sup> The modified model reproduced current diurnal and horizontal variations of 2 m urban air temperature and  $EC$  at a 1-h temporal resolution for 12 electric power substations within Osaka City (about 1 km<sup>2</sup> area).

At each time step,  $Q_{F,AC}$  is calculated for each grid as:<sup>19,51</sup>

$$Q_{F,AC} = (H_{out} + E_{out}) + EC = \frac{COP + 1}{COP} (H_{out} + E_{out}) \quad (2)$$

where  $H_{out}$  and  $E_{out}$  are the sensible and latent heat supplied from the AC system for cooling (see section 2.5 of Salamanca et al.<sup>35</sup>), respectively, and COP is the coefficient of performance. The  $H_{out}$  and  $E_{out}$  are calculated from the total sensible,  $H_{inv}$ , and latent,  $E_{inv}$ , heat loads per floor.<sup>35</sup> The  $H_{inv}$  considers four physical processes: (1) solar radiation through the window and the heat exchange between the windows and the indoor air, (2) heat conduction through the walls and heat exchange between the wall, ceiling and pavement and the indoor air, (3) sensible heat exchange through ventilation, and (4) the internal sensible heat generation from equipment and occupants (Fig. 1a). Outdoor weather directly affects the  $H_{in}$  through processes (1–3), and the affected  $H_{in}$  contributes to an increase in  $Q_{F,AC}$  and  $EC$  through the  $H_{out}$  (Fig. 1a Path 1). Here  $Q_{F,AC}$  is split into sensible heat  $Q_{F,AC,S}$  and latent heat,  $Q_{F,AC,L}$ , as commercial and office building areas are considered.<sup>52</sup>

$$Q_{F,AC,S} = 0.722Q_{F,AC} \quad (3)$$

$$Q_{F,AC,L} = 0.278Q_{F,AC} \quad (4)$$

The WRF/BEP+BEM model system assumptions include:<sup>51</sup> (1) individual AC units exist (using a simple parameterisation); (2) a constant COP (implications discussed in Supplementary information) occurs; (3) no  $Q_F$  from traffic occurs; and (4) only typical weekdays occur. Therefore, the results of this study are for these conditions (i.e. weekdays).

Although  $Q_F$  from traffic ( $Q_{F,traffic}$ ) is important<sup>53,54</sup> in some cities, in Osaka<sup>42,52</sup>  $Q_{F,AC}$  is at least two times larger. As traffic is already common in Asian megacities, while AC demand is dramatically increasing<sup>38</sup> (e.g. in Vietnam penetration rates of AC, motorcar and motorbike are 10.8%, 77.4%, and 81.8%, respectively<sup>55</sup>),  $Q_{F,AC}$  has the potential to be a big problem in the future (cf.  $Q_{F,traffic}$ ) but will benefit from COP increases. Future studies will consider  $Q_{F,AC}$  and  $Q_{F,traffic}$  using models such as WRF/CM+BEM.<sup>42</sup> However, the conclusions of this report are not impacted by  $Q_{F,traffic}$  as it is assumed to be constant and uses the single-layer UCM (SLUCM) with a static  $Q_F$ <sup>5,6</sup> profile (traffic and AC) giving parallel results to urban warming without  $Q_F$  emissions (see next section 'Model settings').

### Model settings

Here the Advanced Research WRF model (ver. 3.5.1)<sup>4</sup> was used with the same model parameters (Supplementary Table 3) and physics as previously described.<sup>51</sup> The specific schemes used are: updated Rapid Radiation Transfer Model (RRTMG) short- and long-wave radiation schemes,<sup>56</sup> WRF single-moment three-class (WSM3) cloud microphysics scheme,<sup>57,58</sup> Mellor–Yamada–Janjic atmospheric boundary-layer scheme,<sup>59–61</sup> Noah land surface model,<sup>62</sup> and BEP+BEM model.<sup>34–36</sup> As previously indicated, these models can accurately reproduce the diurnal variation and horizontal distribution of summertime surface air temperature and EC due to AC use.<sup>51</sup>

The model domain (Supplementary Fig. 2a) covers western Japan with 126 x and y grids in both d01 and d02 domains (horizontal resolution 5 and 1 km, respectively, and two-way nesting). As the reanalysis captures the summer synoptic-scale features (high-pressure system) around Japan,<sup>63</sup> a larger coarse grid is not needed. The model top is 50 hPa, with 35 vertical sigma levels. The vertical resolution close to the ground (WRF atmospheric first layer height) is nearly 50 m. Therefore, 10 building layers below 50 m (5 m resolution) in BEP/BEM is used, as in previous studies,<sup>42,51</sup> due to high model reproducibility for 2 m air temperature and EC in Osaka with the first layer at 50 m. With a mean building height of about 25 m in the office area, 50 m corresponds to the constant flux layer. The innermost domain urban grid classifications are based on the dominant building type, using land use and land cover and topographic data sets from the Geospatial Information Authority of Japan data and Osaka City GIS polygon (building footprint) data, with building use (type), building height and total floor area for each building (Supplementary Fig. 2c, d) grouped into: (i) commercial and business grids (i.e. mainly commercial and office buildings; hereafter C), (ii) residential grids with predominantly fireproof apartments (Rr), and (iii) residential grids with predominately wooden detached dwellings (Rw). The outer and inner domain urban grids outside Osaka City are classified as Rw.

For current climate simulation, initial and boundary conditions are derived from the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data<sup>64</sup> and merged satellite and in situ global daily sea surface temperature (MGDSST) data.<sup>65</sup> For future climate simulations, we also use a modified the NCEP–NCAR and MGDSST as initial and boundary conditions (see details in the next subsection). As previously,<sup>3</sup> time integration is conducted from 00:00 UTC July 27 to September 1 (i.e. August with 5 days spin-up) for 11 years 2000–2010 to allow climatological discussion of the simulation results. Other studies integrate for only 1 month, several weeks or days (current and future climate), which is insufficient for climatological discussion in general. In Osaka, August is the hottest month, with more clear skies (cf. June, July and September, rainy season) and the highest EC recorded. These model settings are termed the control simulation (case AC → FB) (Fig. 1b, red arrow) for all climates, including current and six future climates (see next subsection).

The no- $Q_F$ , AC simulation (case AC ≠ FB) differs from case AC → FB as  $Q_{F,AC} = 0 \text{ W m}^{-2}$  (Fig. 1b, blue arrow); i.e. the  $[AC \neq FB] - [AC \rightarrow FB]$  difference is caused by  $Q_{F,AC}$  and it causes the feedback ( $\delta T_{AC \rightarrow FB}$ ). Current climate conditions (August 2000–2010) and six future climates are simulated. Here  $\delta T_{AC \rightarrow FB}$  is estimated by  $\Delta T_{AC \rightarrow FB} - \Delta T_{AC \neq FB}$  (Fig. 1b). In the current climate case,  $\delta T_{AC \rightarrow FB}$  is 0 °C as we assume there is no long-term climate change (decades) (i.e. no increase in forcing temperature and  $\Delta T_{AC \rightarrow FB}$  and  $\Delta T_{AC \neq FB}$  are 0 °C). Of course,  $\delta T_{AC \rightarrow FB}$  may not be 0 °C in the real current climate, but it is difficult to estimate  $\delta T_{AC \rightarrow FB}$  from current

climate only, and our objectives are to clarify  $\delta T_{AC \rightarrow FB}$  in relation to future urban climate and how  $\delta T_{AC \rightarrow FB}$  is changed by climate change (see 'Introduction'). Therefore, here ' $\delta T_{AC \rightarrow FB}$  driven by decades of climate change' is the focus and is estimated by a time slice experiment, including current climate simulation and six future projections. In a similar way,  $\delta EC_{AC \rightarrow FB}$  is estimated by  $\Delta EC_{AC \rightarrow FB} - \Delta EC_{AC \neq FB}$ . To determine  $\delta T_{AC \rightarrow FB}$  and  $\delta EC_{AC \rightarrow FB}$ , it is assumed all conditions (e.g. urban structures, human activities and AC system technology) remain constant, except for background climate change. Although AC technology will improve, it is important to know the maximum (potential) impact of the feedback driven by climate change on future urban air temperature. A constant COP scenario is used as the RCP8.5, and Shared Socioeconomic Pathway 3 scenario assumes slow technological change in the energy sector.<sup>66,67</sup>

We assume that  $\delta T_{AC \neq FB}$  is constant with  $\Delta T_{GW}$ ; i.e. black dashed arrow ( $\Delta T_{const,QF}$ ) parallel to the blue arrow ( $\Delta T_{AC \neq FB}$ ) in Fig. 1b. To confirm this, the impact of  $Q_F$  on surface air temperature (i.e. like  $\delta T_{AC \neq FB}$ ), on future climate, was conducted with simulations using SLUCM, which has a static  $Q_F$ <sup>5,6</sup> (includes traffic and AC). Urban warming, when  $Q_F$  in the future was the same as for the current climate ( $\Delta T_{const,QF}$ : Fig. 1b, black dashed arrow), paralleled urban warming with a no- $Q_F$  emitted case, like  $\Delta T_{AC \neq FB}$ , although different urban parameterisation was used. A reason why we used SLUCM (not BEP/BEM) to confirm black dashed arrow ( $\Delta T_{const,QF}$ )'s gradient ( $\Delta T_{const,QF} / \Delta T_{GW}$ ) (and then compared with that of blue arrow ( $\Delta T_{AC \neq FB}$ ) by BEP/BEM) is that it is quite difficult to calculate the black dashed arrow by the BEP/BEM, because  $Q_{F,AC}$  at every time step (6 s) in future climates has to be completely same as that of current climate. To confirm the black arrow's gradient by SLUCM is technically much easier and essentially same as that by the BEP/BEM.

### Climate projections

Six future climates, with background temperature increases (global warming:  $\Delta T_{GW}$ : +0.5, +1.0, +1.5, +2.0, +2.5, and +3.0 °C) relative to the current climate, are simulated. These are based on the ensemble mean results from four GCMs used in the Climate Model Intercomparison Project (CMIP5)<sup>68</sup>: CCSM4,<sup>69</sup> CESM1 (CAM5),<sup>70</sup> GFDL-CM3<sup>71</sup>, and INM-CM4.<sup>72</sup> However, the ensemble mean of only three GCMs (CCSM4, CESM1 and GFDL-CM3) is used when  $\Delta T_{GW} > +3.0$  °C, as INM-CM4 does not reach +3.0 °C at 2100. The simulations considered the highest IPCC GHG emissions scenario (RCP8.5) (Fig. 4). CESM1 (CAM5) and CCSM4 have good model climate performance index scores<sup>73</sup> and summertime synoptic pressure patterns around Japan perform better than other GCMs. GFDL-CM3 and INM-CM4 are selected to cover minimum to maximum uncertainties in GCM projections. By using several GCMs, the uncertainties in the GCM projections (horizontal colour bars, Fig. 4) are incorporated in the RCM. A similar GCMs selection method for future urban climate projection was used by Adachi et al.<sup>9</sup>

For future projection experiments, climate difference components between current and future are estimated by the four individual GCMs. For example, for  $\Delta T_{GW} = +0.5$  °C, it was identified that the August mean surface air temperature difference, averaged spatially around Japan, became nearly +0.5 °C for each GCM. The other climate variables (e.g. geopotential height, horizontal wind and sea surface temperature) are extracted for each GCM for the identified years, and an ensemble mean is calculated for all variables. For  $\Delta T_{GW} = +0.5$  °C, the ensemble mean surface air temperature difference component is +0.4725 °C (Supplementary Fig. 3) (i.e. nearly +0.5 °C). The actual ensemble mean surface air temperature differences for  $\Delta T_{GW} = +0.5, +1.0, +1.5, +2.0, +2.5$  and +3.0 °C are +0.4725, +0.9550, +1.4750, +1.9650, +2.4450 and +2.8825 °C, respectively (Supplementary Fig. 3). For the six  $\Delta T_{GW}$  cases, the climate difference for each variable (i.e. wind components, geopotential height and temperature) are added to the NCEP–NCAR and MGDSST data (Supplementary Fig. 3), therefore changing the atmospheric variables such as long-wave radiation. Note, future climate relative humidity is assumed to be the same as the current climate.<sup>74–78</sup>

The PGW method<sup>7,8</sup> was used to create regional climate projections<sup>3,10,11,21,79–81</sup> and has been previously verified.<sup>80,82,83</sup> For example, Kawase et al.<sup>82</sup> projected East Asia's 1960s climate by the PGW method using 1990s reanalysis data and PGW increment, calculated by the climate difference between the 1990s and 1960s. They compared the 1960s projection results with a hindcast simulation for the same period using reanalysis data. They showed that the 1960s projection could reproduce some decadal changes in the rainfall shown within the hindcast simulation, thus indicating that the PGW method could reproduce actual energy

balance change using reanalysis, as precipitation is calculated in response to the atmospheric energy balance.

Yoshikane et al.<sup>83</sup> compared PGW and direct downscaling from GCM for East Asian future climate projections and found no significant differences in temperature and precipitation (i.e. atmospheric energy balances were similar). Snowfall<sup>79,81,84</sup> research, a process strongly influenced by atmospheric energy balance near the surface, and torrential rain<sup>85</sup> studies, caused by atmospheric buoyancy near the surface, have also successfully used PGW methods. Therefore, the PGW method is reasonable for use in future projection research. An advantage of using the PGW method is a reduction in GCM climate bias as the method uses modified objective analysis/re-analysis data rather than GCM output.<sup>10</sup> A disadvantage is that perturbations in meteorological variables are not considered.<sup>86</sup> As Adachi et al.<sup>87</sup> show, the perturbation component is equally important as the climatology component for summer precipitation, hence the PGW method is inappropriate for this. However, the perturbations do not affect near-surface air temperatures change (current to future climates) in western Japan, including Osaka during summer.<sup>87</sup> Thus the difference in climatology projected by a GCM has a larger influence than the difference in perturbation on the downscaled temperature change and its variability in the climate projections.<sup>87</sup> Hence, as the main contributor to the temperatures change was climate change (PGW) component, their results indicate that PGW method is appropriate for our purpose. As we focus on August, a dry period in Japan, surface air temperature is little impacted by precipitation. The PGW method is used as it enabled the study to focus on internal physical (feedback) processes in the RCM and to remove bias from individual GCMs. It also allows for direct comparison with previous PGW studies that report projected urban temperature uncertainties with selections of RCM, GHG emission scenarios and urban planning scenarios (see Table 1 and main text).

### Normalised feedback impact

Three urban land uses are selected for analysis (Supplementary Fig. 2d): commercial and office buildings, fireproof apartments, and wooden detached dwellings. These types of areas were evaluated for surface air temperature and EC model performance.<sup>48</sup>

To address the question (1), a normalised  $\delta T_{AC \rightarrow FB}$  (feedback impact) per future climate is determined:

$$\text{Normalised } \delta T_{AC \rightarrow FB} = \frac{(\Delta T_{AC \rightarrow FB} - \Delta T_{AC \neq FB})}{\Delta T_{GW}} \quad (5)$$

where  $\Delta T_{AC \rightarrow FB}$  and  $\Delta T_{AC \neq FB}$  are urban warming calculated by the AC  $\rightarrow$  FB and AC  $\neq$  FB, respectively, as explained in Fig. 1.

All times referred to are LT. Japan does not use summertime.

### DATA AVAILABILITY

The downscaling data by the WRF are deposited in local storage at AIST. This is available from the corresponding author upon reasonable request. The source code of the WRF and future projection results by four global climate models (CCSM4, CESM1 (CAM5), GFDL-CM3 and INM-CM4) that support findings of this study are available from websites: <http://www2.mmm.ucar.edu/wrf/users/> and <https://esgf-node.llnl.gov/projects/esgf-llnl/>, respectively. The observational data used in this study are available from the website of the Japan Meteorological Agency: <https://www.jma.go.jp/jma/index.html>.

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## AUTHOR CONTRIBUTIONS

Y.T., Y.K. and M.H. conceived the study and designed the analyses. S.G. provided an important idea. M.H. prepared the forcing data for regional climate simulations, and Y.T. conducted the simulations and analysis using this forcing data. Y.T. wrote the original manuscript and S.G., Y.K. and M.H. provided comments, feedback and revisions to the manuscript.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

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