AMS100 - High-Resolution Future Climate Projection for Cities
16th Jan 2020@Boston, US

Asian megacity heat stress under future climate scenarios: Impacts of Air-conditioning feedbacks

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University of Reading

Project future climate's urban heat stress

- Future projections of urban heat stress are important to investigate strategies to mitigate urban heat islands and adaptations to urban climate change.
- But, **Human heat stress projections with fine horizontal resolution sufficient to resolve urban climate** (e.g. Kusaka et al. 2012 JMSJ; Doan et al. 2016 UC) **are few**.

- If both temperature and humidity are high, heat stress tends to be high. Such conditions are common in Japan megacities, with high population densities (e.g. Tokyo and Osaka) resulting in high risk of heatstroke during heat waves.

- **Universal Thermal Climate Index (UTCI) allows heatstroke risk with a clear relation to physiological responses (e.g. human body core temperature).**

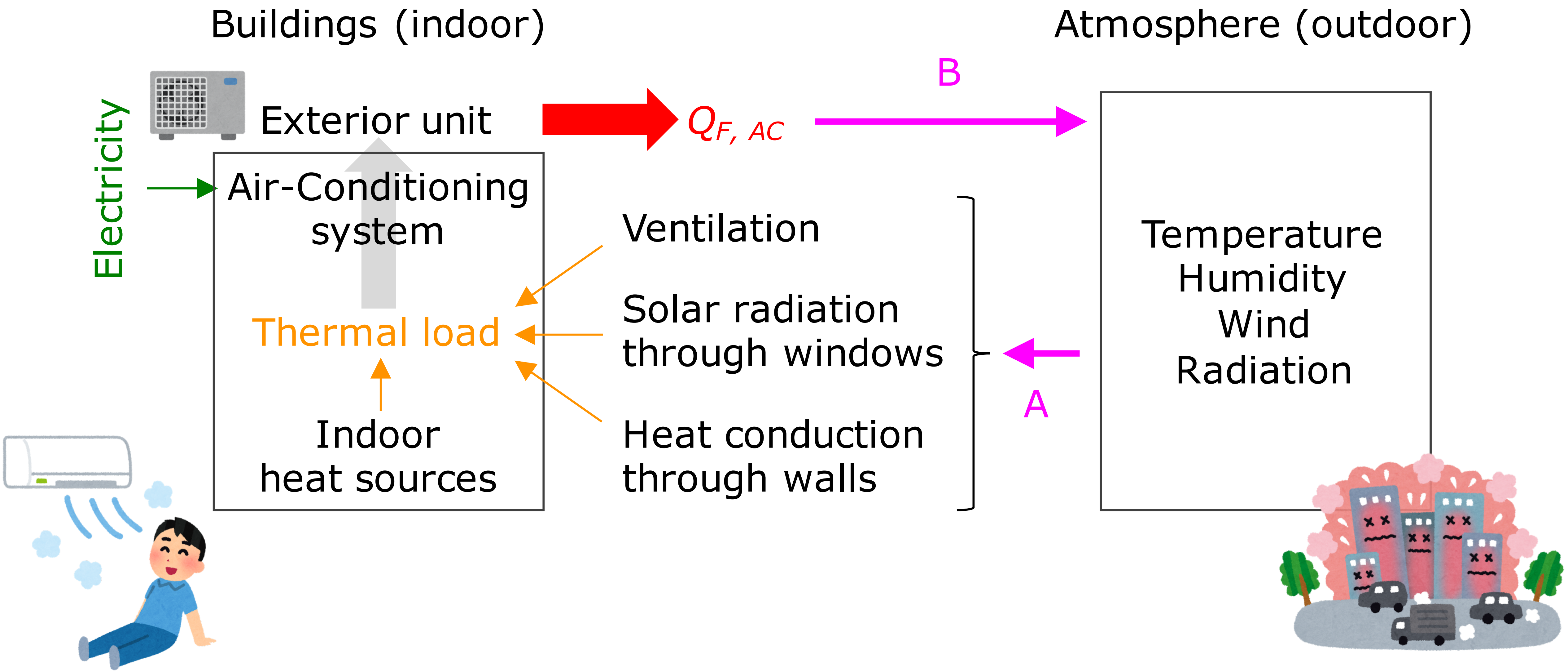
- ***Motivation #1*** : to project future climate's UTCI using dynamical downscaling to 1 km horizontal resolution for Asian megacity Osaka.

How big is the AC-induced feedback on heat stress?

- A human behaviour - **air-conditioning (AC) use** - **induces positive feedback** could worsen urban thermal environment (produce additional temperature increase of 0.6 °C) in Osaka's August early mornings under the +3.0 °C global warming scenario (Takane et al. 2019 npj Climate and Atmospheric Science)

AC-induced positive feedback

~ +0.6°C (Takane et al. 2019)



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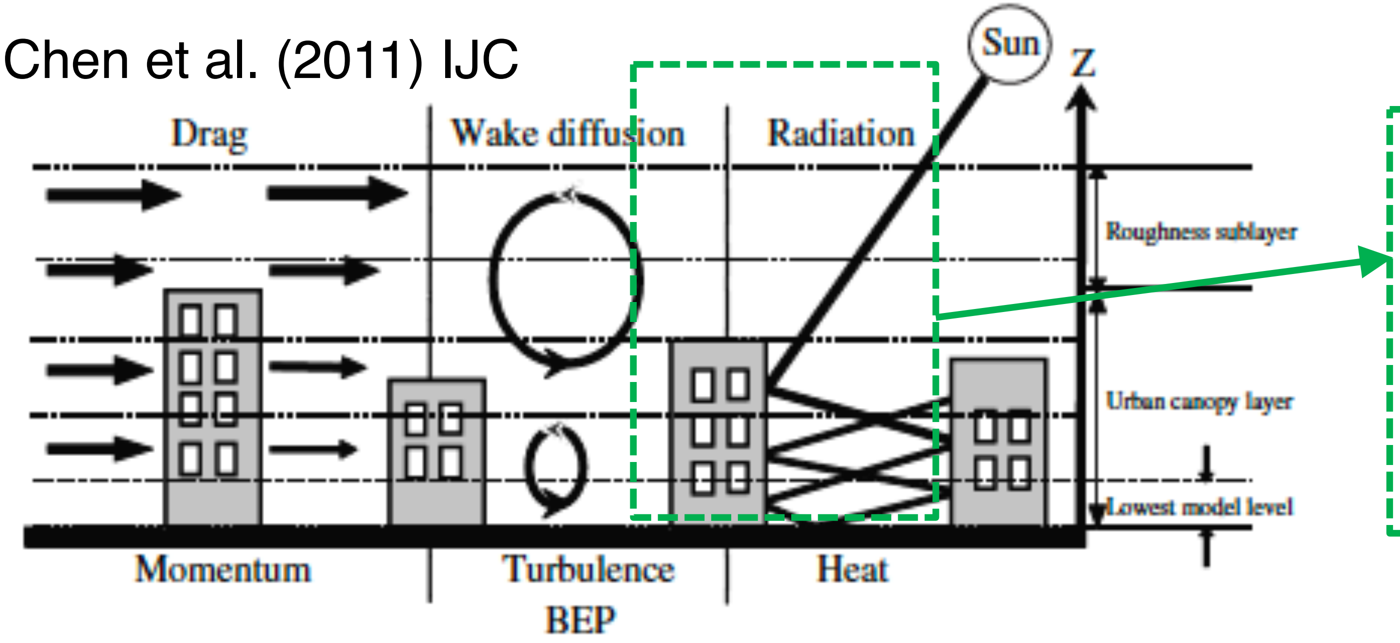
- But **impact on heat stress remains unknow**. Understanding the impact is important.

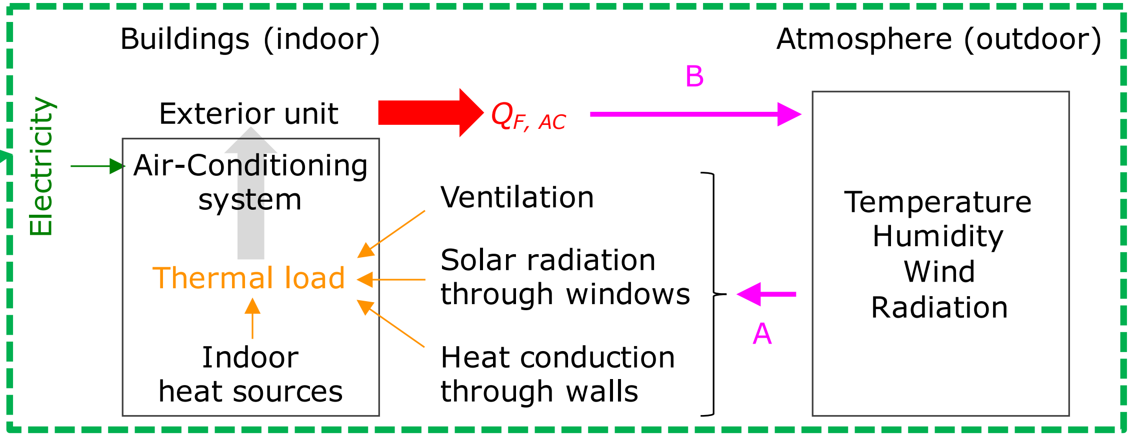
- ***Motivation #2*** : to clear how big the feedback impact on heat stress (UTCI) is.

WRF with modified BEP+BEM parameterisation

Salamanca et al. (2010) TAC
Takane et al. (2017) IJC

Chen et al. (2011) IJC





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

- Residential grids

$$Q_{F,AC,S} = Q_{F,AC}$$

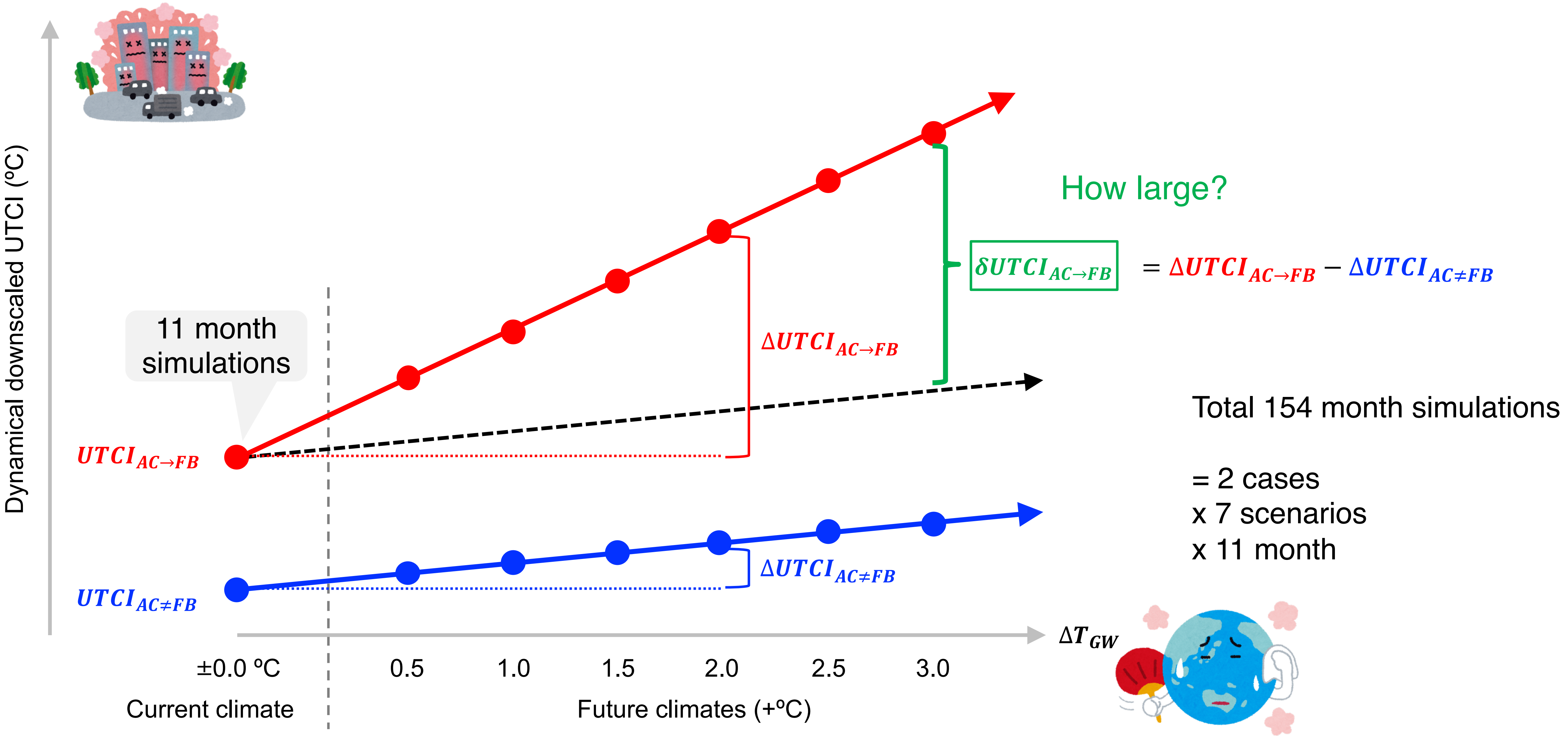
$$Q_{F,AC,L} = 0$$

- Office grids (consider cooling tower)

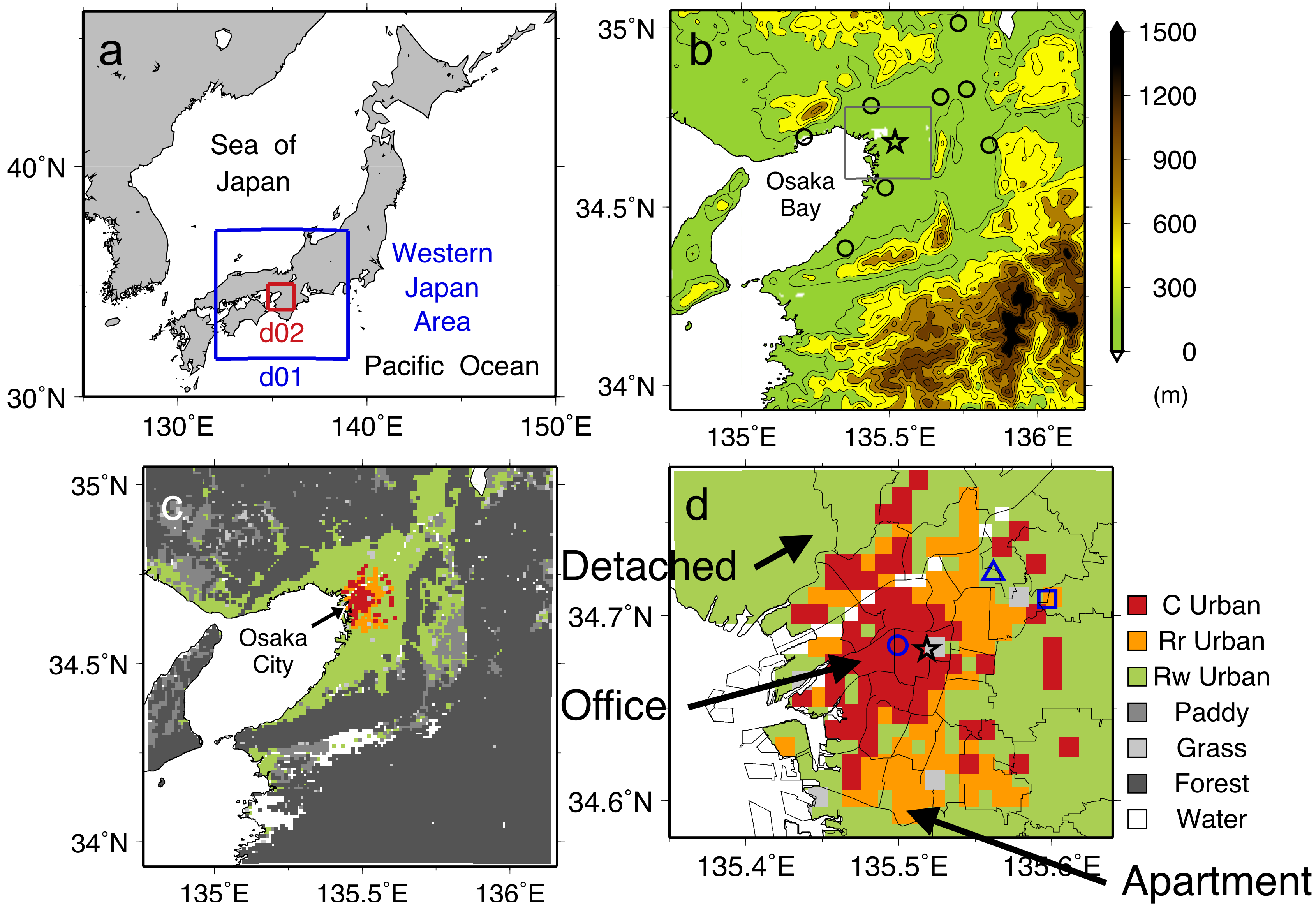
$$Q_{F,AC,S} = 0.722 Q_{F,AC}$$

$$Q_{F,AC,L} = 0.278 Q_{F,AC}$$

How to estimate the feedback impact



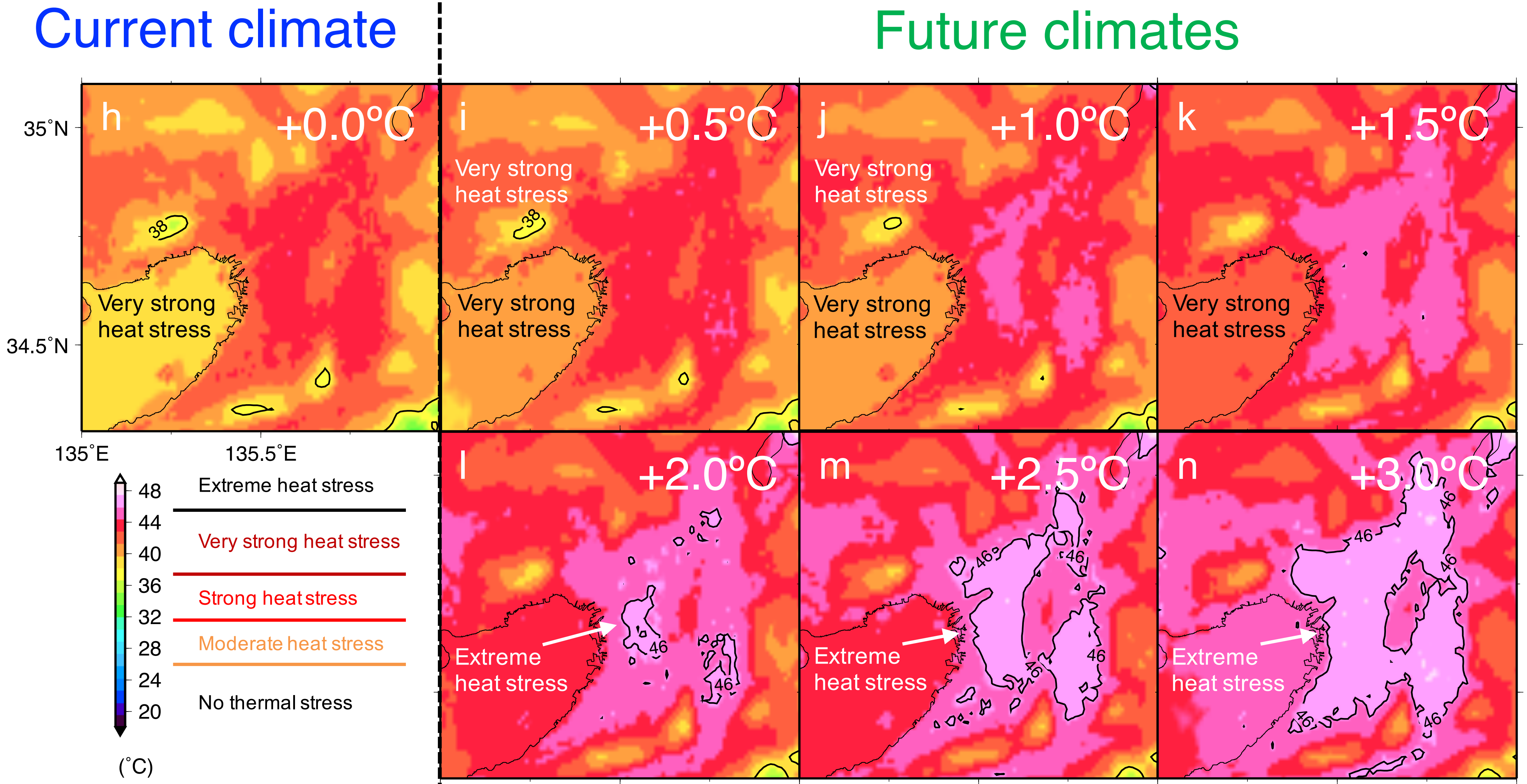
Osaka City (with 20 million population)



- (Olympic game 2020)
- World exposition in 2025


大阪府
中央区
© 2018 ZENRIN
Google Earth
2003
緯度 34.675385° 経度 135.503508° 標高 16 m 高度 1.15 km

The UTCI increase with ΔT_{GW}

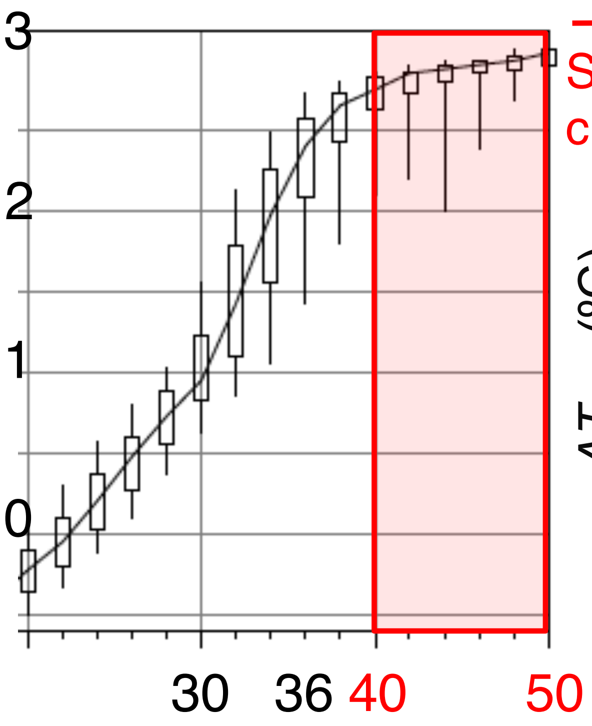


Takane et al. (2020) Environ. Res. Commun.

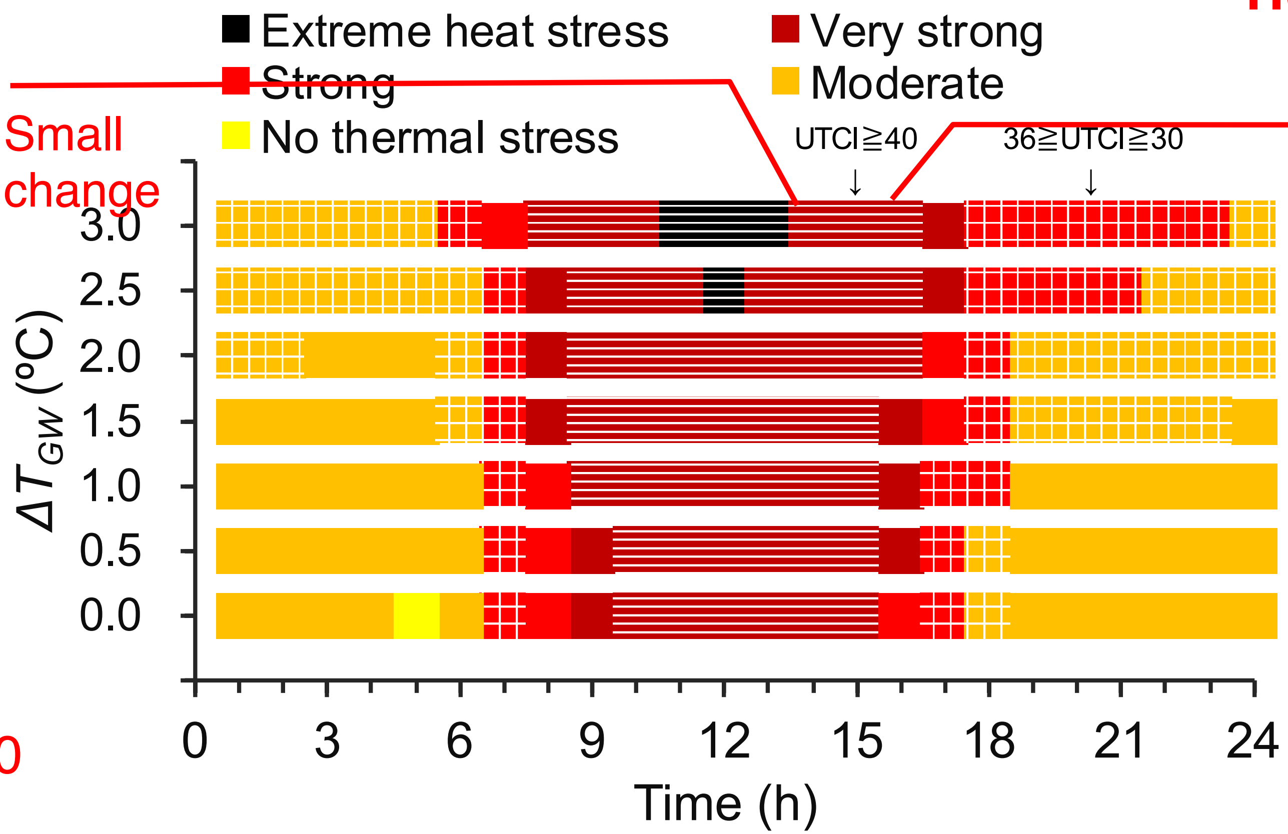
Daytime is dangerous with non-linear increases in body core temp and without thermal sensation change

Motivation #1

Thermal sensation

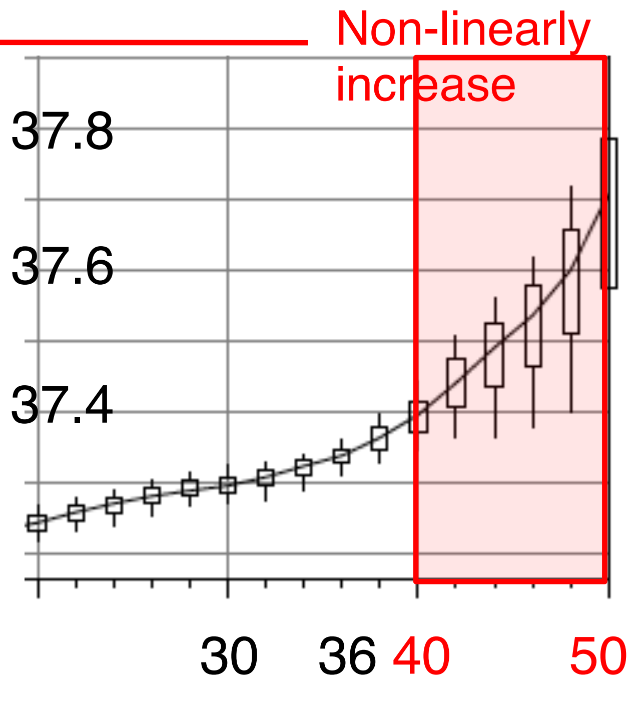


Bröde et al. (2012) IJB



Takane et al. (2020) Environ. Res. Commun.

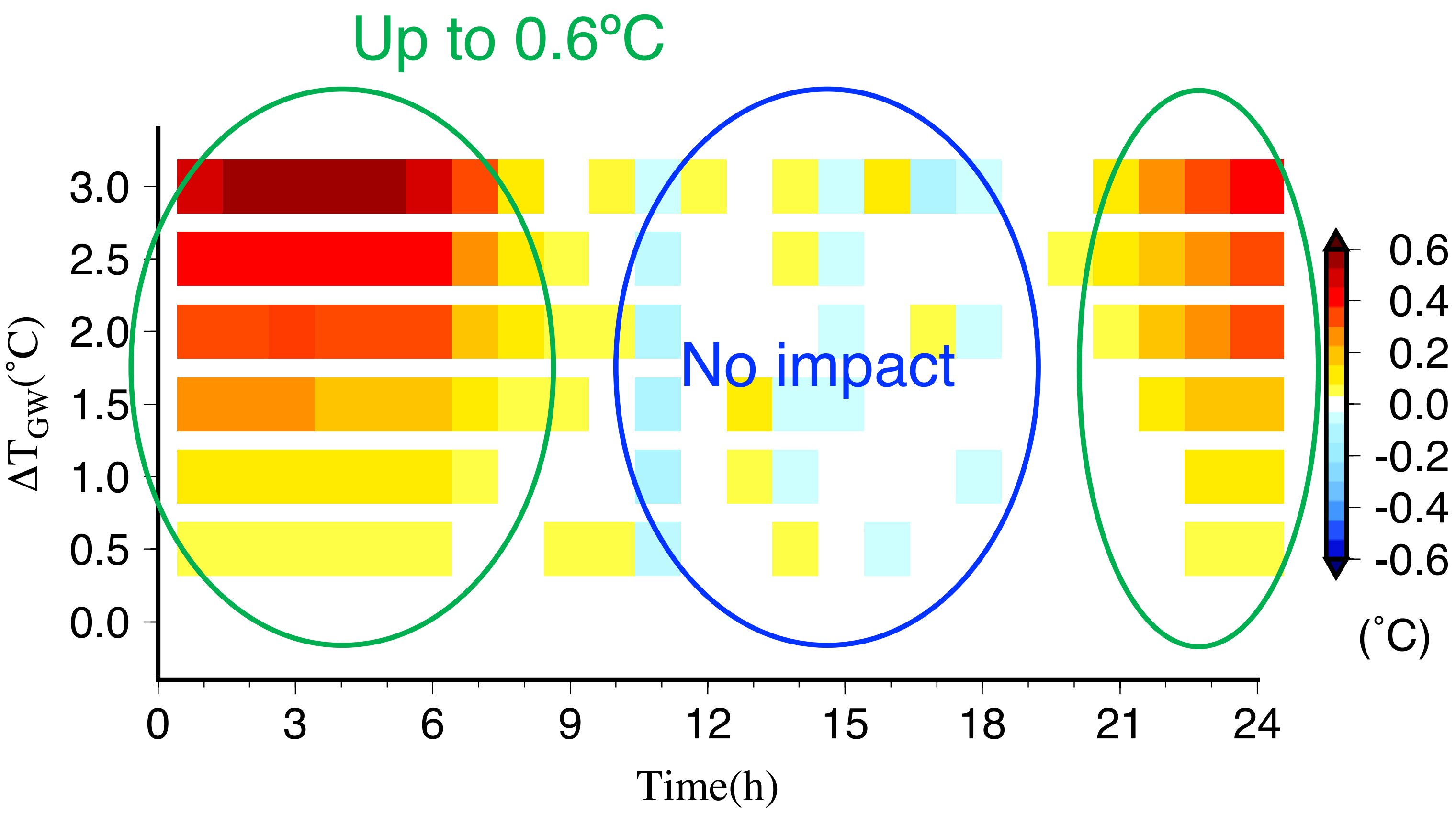
Human body core temp (ºC)



Bröde et al. (2012) IJB

Impact of AC induced feedback on UTCI reaches 0.6ºC

Motivation #2



The AC induced feedback impact is comparable to suggested benefits from urban heat island mitigation techniques in the literature

Takane et al. (2020) Environ. Res. Commun.

Conclusion - novelty

Motivation #1

- **UTCI increases with ΔT_{GW} and AC feedbacks.** An ‘extreme’ heat stress area appears when +2.0 ºC (+2.5 ºC) warming scenario. These are dangerous conditions for people outdoors as they may experience large increases in body core temperature.

Motivation #2

- **Impact of AC induced feedback on UTCI** increase roughly linearly with ΔT_{GW}. At +3.0 ºC warming scenario, this reaches **+0.6 ºC** (**12% of UTCI increase**).
- This size is comparable to suggested benefits from urban heat island mitigation techniques in the literature. Therefore, **the feedbacks are significant and potentially could cancel other mitigation benefits in the future, especially where AC use is large**. Hence, this feedback should not be neglected in future urban climate projections.

Take-home message

Acknowledgments

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- Newton Fund/Met Office WCSSP programme
- The ‘Interdisciplinary Computational Science Program’ in the Center for Computational Sciences, University of Tsukuba

Thank you!

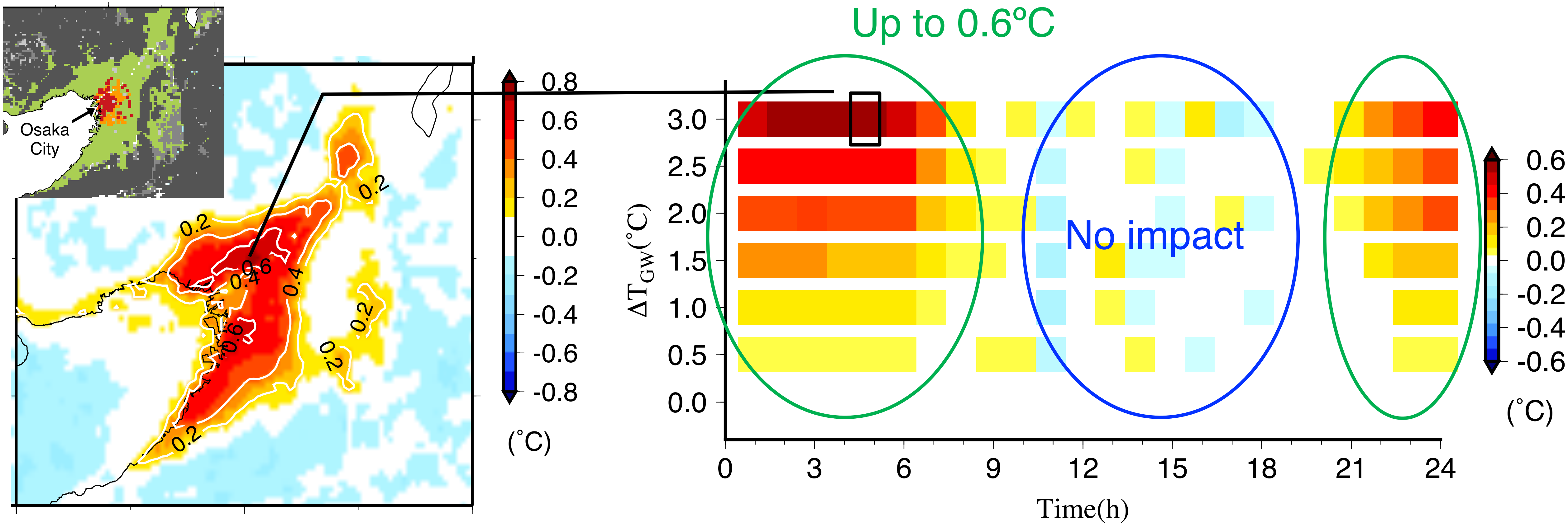
- Verification the model against **high-reso electricity consumption** – Takane et al (2017, Int. J. Climatol.)

- Impact of AC induced feedback on **temp & electricity demand** – Takane et al. (2019, npj Climate Atmos. Sci.)

- Impact of AC induced feedback on **heat stress** – Takane et al. (2020, Env. Res. Commun.)

@uya_takane

Impact of AC induced feedback on UTCI reaches 0.6ºC

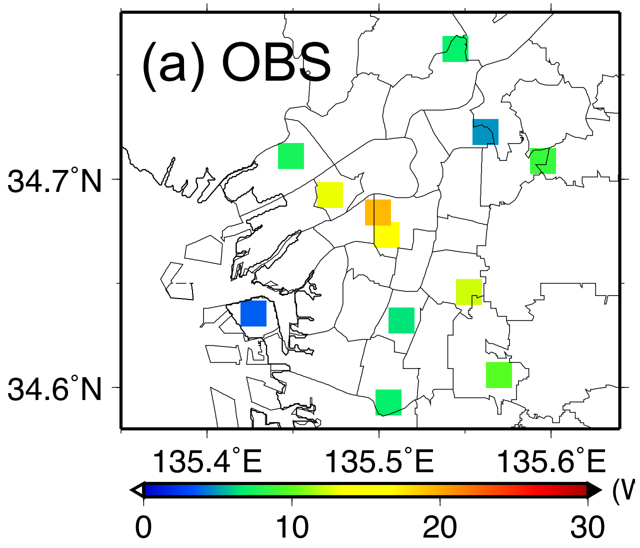


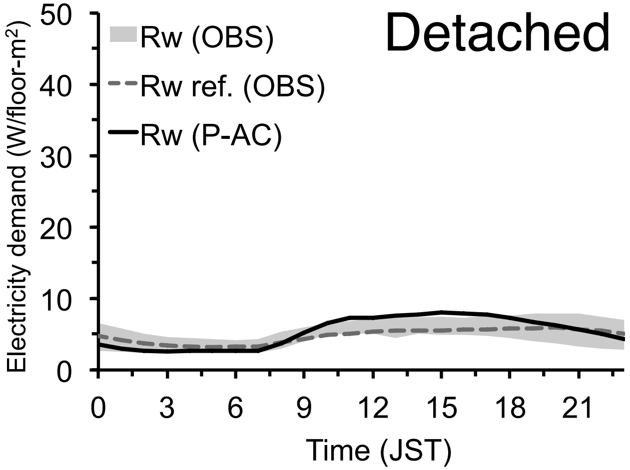
The AC induced feedback impact is comparable to suggested benefits from urban heat island mitigation techniques in the literature

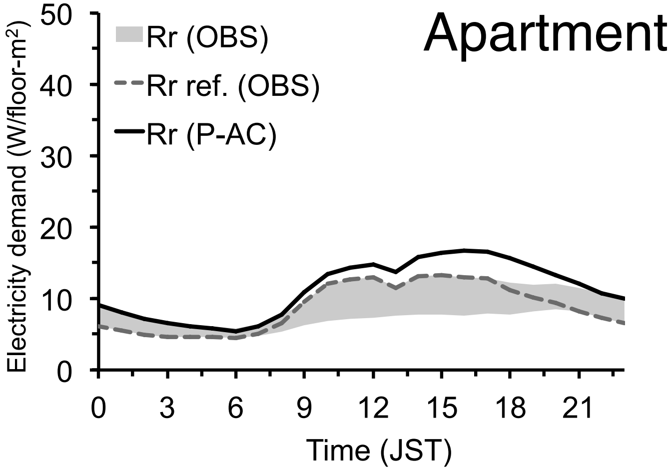
Takane et al. (2020) Environ. Res. Commun.

Reproducibility – Electricity consumption

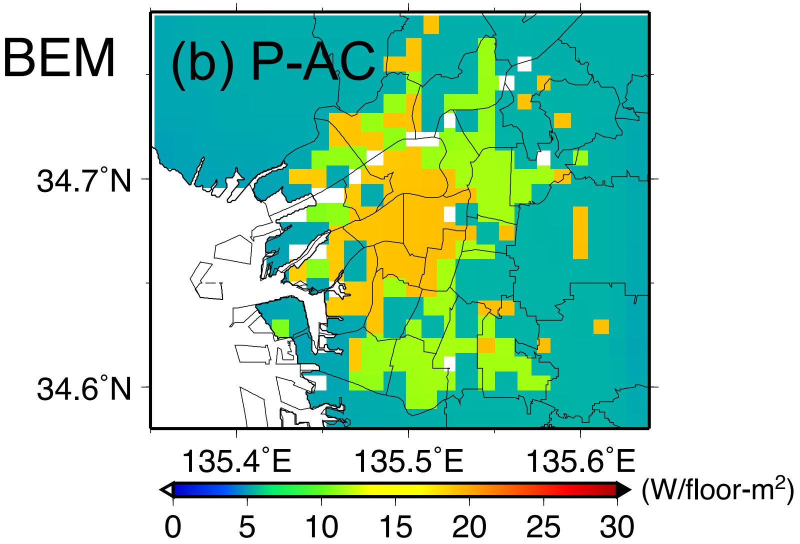
Monthly mean
August 2013

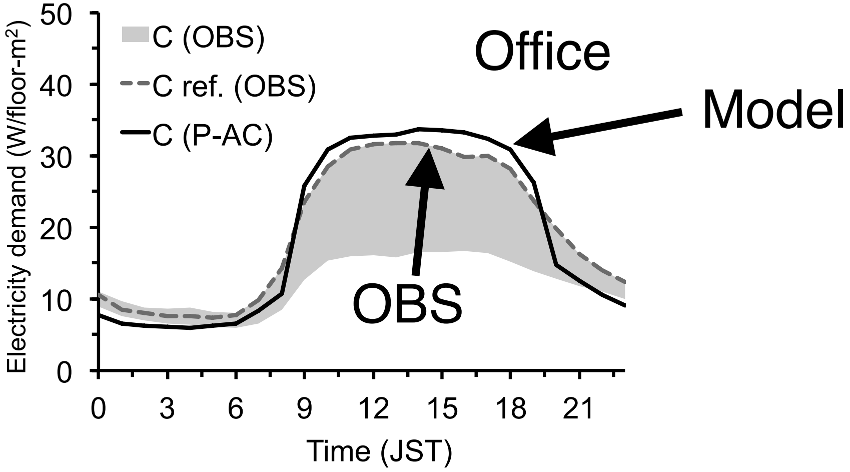






Modified BEP+BEM



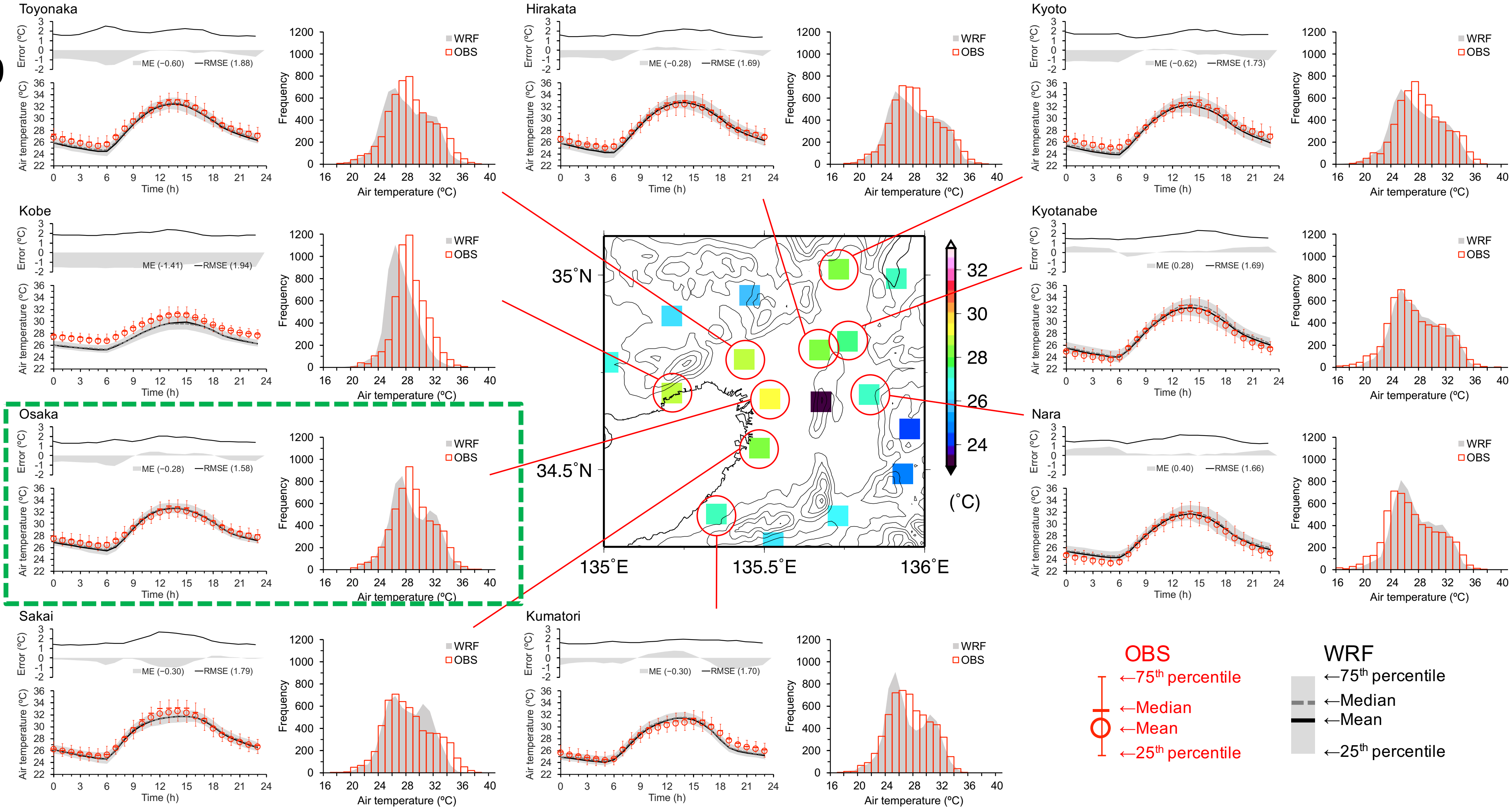


Takane et al. (2017) IJC

Reproducibility – 2-m temperature

August
2000-2010

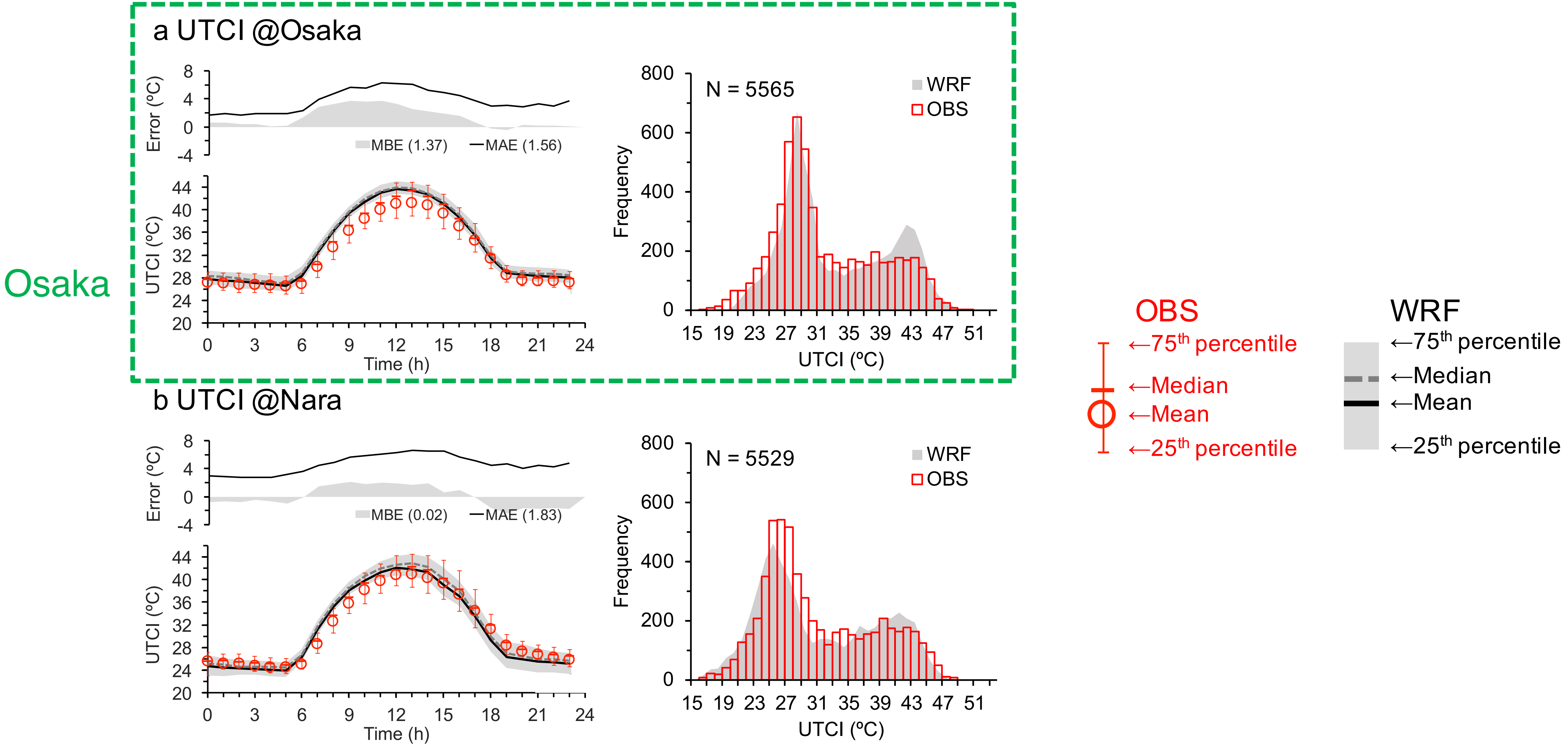
Osaka



Takane et al. (2019) npj Climate and Atmospheric Science

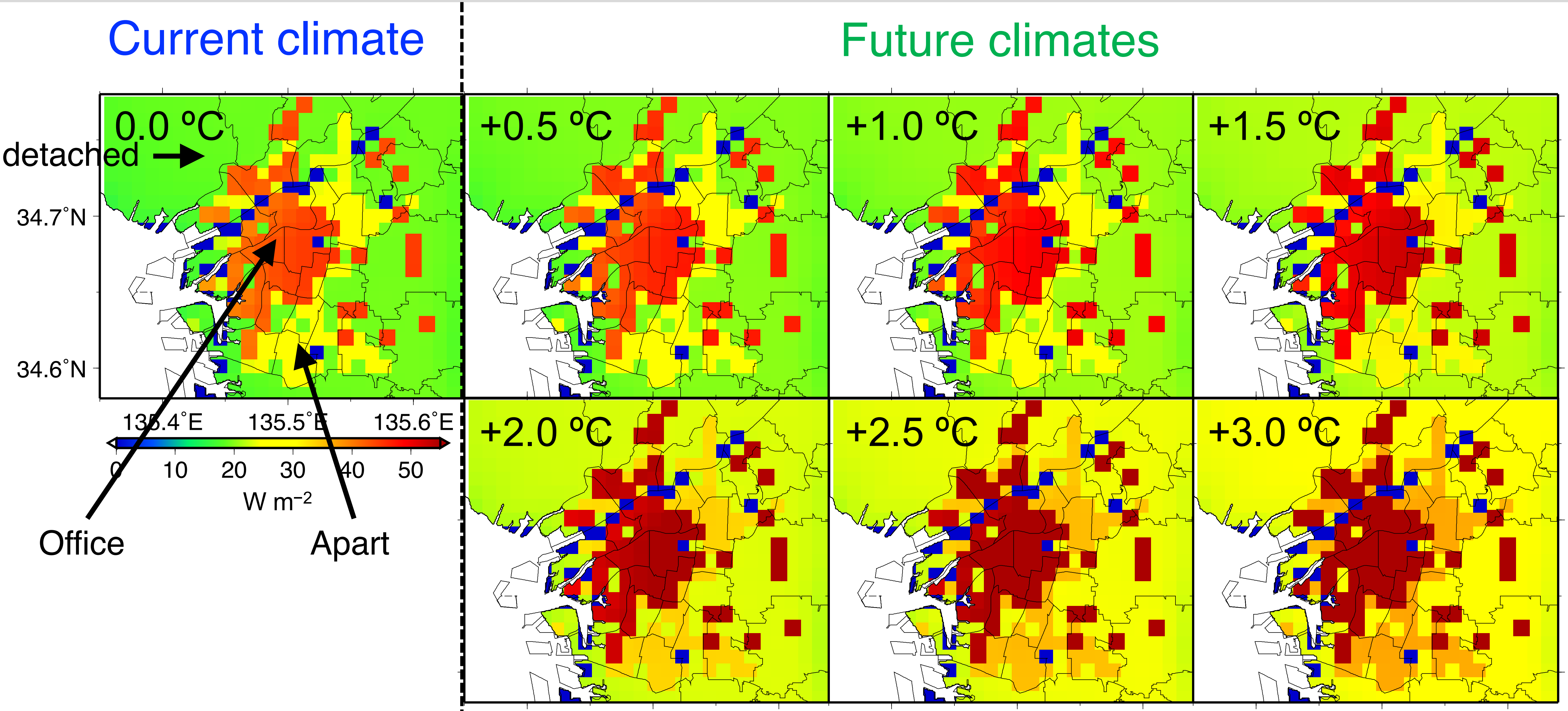
Reproducibility – UTCI

August
2000-2010



Takane et al. (2020) Environ. Res. Commun.

The $Q_{F,AC}$ increase with ΔT_{GW} (14 LT)



Takane et al. (2019) npj Climate and Atmospheric Science

How to estimate the UTCI

2.3 UTCI calculation

The hourly UTCI is calculated for 11 years for each climate scenario using the polynomial parameterisation of the Fiala human physiology model (Fiala *et al*. 2012; Błażejczyk *et al*. 2013) in Bröde *et al*. (2012a). This parameterisation is frequently used because of its computational efficiency (e.g. Bröde *et al*. 2012b; Błażejczyk *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). The mean radiant temperature (T_{mrt}) is estimated from T_g, air temperature, and wind speed (Kinouchi 2001):

$$\varepsilon_h \sigma (T_{mrt} + 273.15)^4 = C_g + R_g \qquad (1)$$

$$R_g = \varepsilon_g \sigma \left(T_g + 273.15\right)^4 \qquad (2)$$

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 ε_g and ε_h 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):

$$C_g = h_{cg}\left(T_g - T_a\right) \qquad (3)$$

$$\frac{h_{cg} D}{\lambda} = 2 + 0.55 Re^{0.5} \left(\frac{c_p \mu}{\lambda}\right)^{\frac{1}{3}}$$

$$(10 < Re < 1.8 \times 10^3) \qquad (4)$$

$$\frac{h_{cg} D}{\lambda} = 2 + 0.34 Re^{0.566} \left(\frac{c_p \mu}{\lambda}\right)^{\frac{1}{3}}$$

$$(1.8 \times 10^3 < Re < 1.5 \times 10^5) \qquad (5)$$

where *Re* is the Reynolds number (UD/v), U is the wind speed, D the diameter of the globe (=0.15 m), v is the kinematic viscosity of air (m^2 s^{-1}), γ is the viscosity coefficient of air (Pa s), λ is the thermal conductivity of air (W m^{-1} K^{-1}), and c_p is the specific heat under a constant pressure (J K^{-1} kg^{-1}).

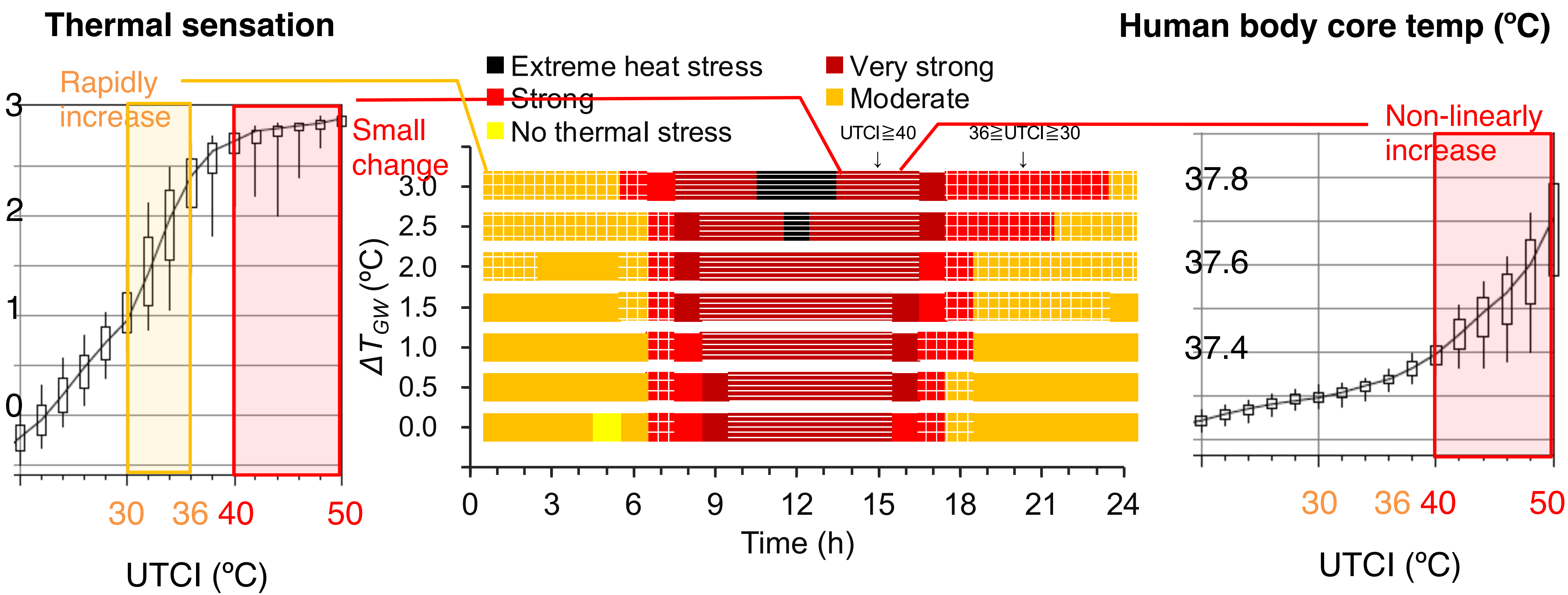
T_g is estimated using the improvement to Okada and Kusaka (2013) in Okada *et al*. (2013):

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

where S_0 is the incoming shortwave radiation (W m^{-2}). An evaluation for one site surrounded by office buildings in Osaka using hourly observations for June to August 2006–2012 reported a root mean square error of 2.15ºC. This equation is applicable for urban environments under all weather conditions, including clear skies and overcast and rainy days (Okada and Kusaka 2013). More detail is given in Section S1 of the Supplementary material.

Takane et al. (2020) Environ. Res. Commun.

Daytime is dangerous with non-linear increases in body core temp and sweat production and without thermal sensation change



Bröde et al. (2012) IJB

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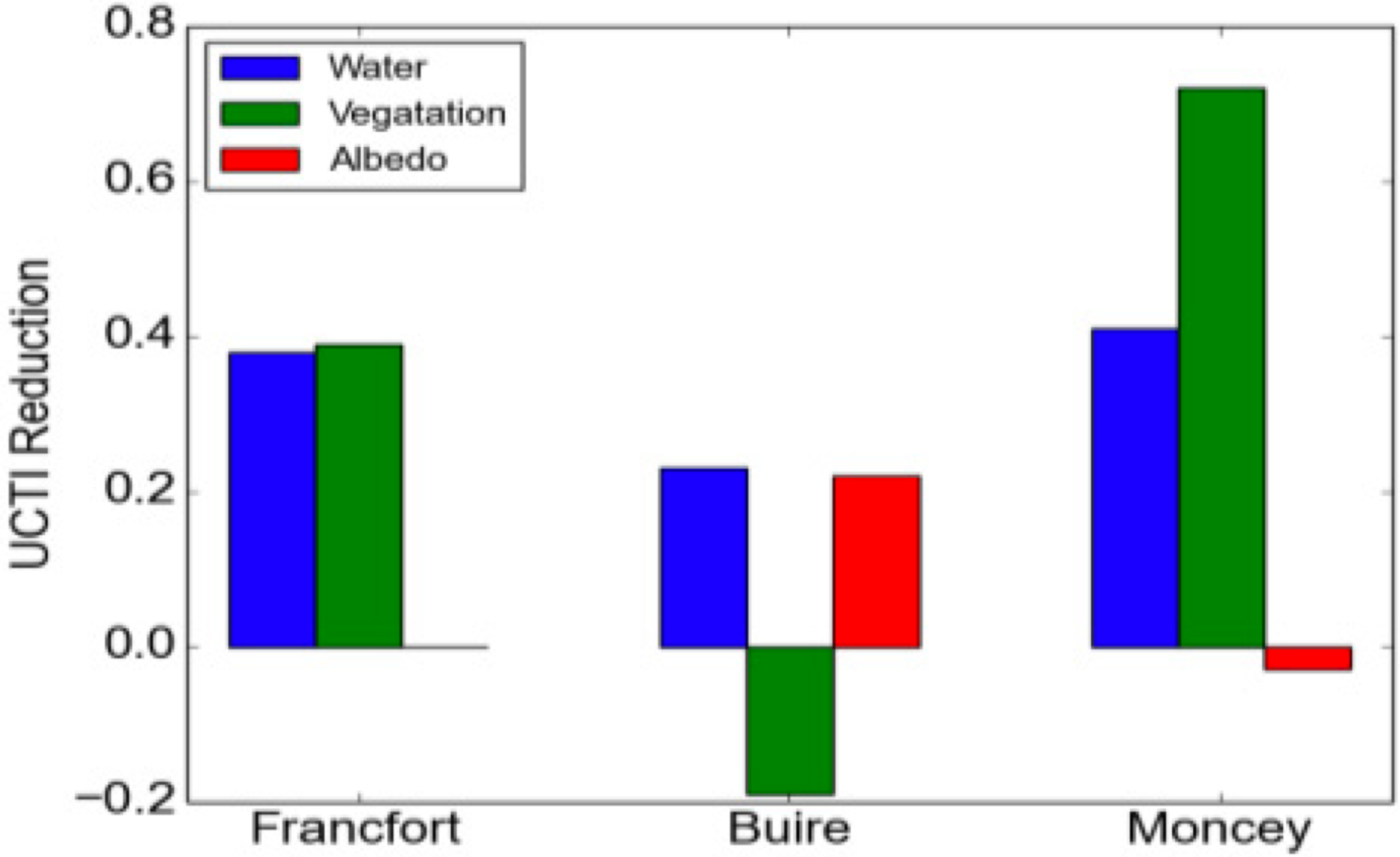
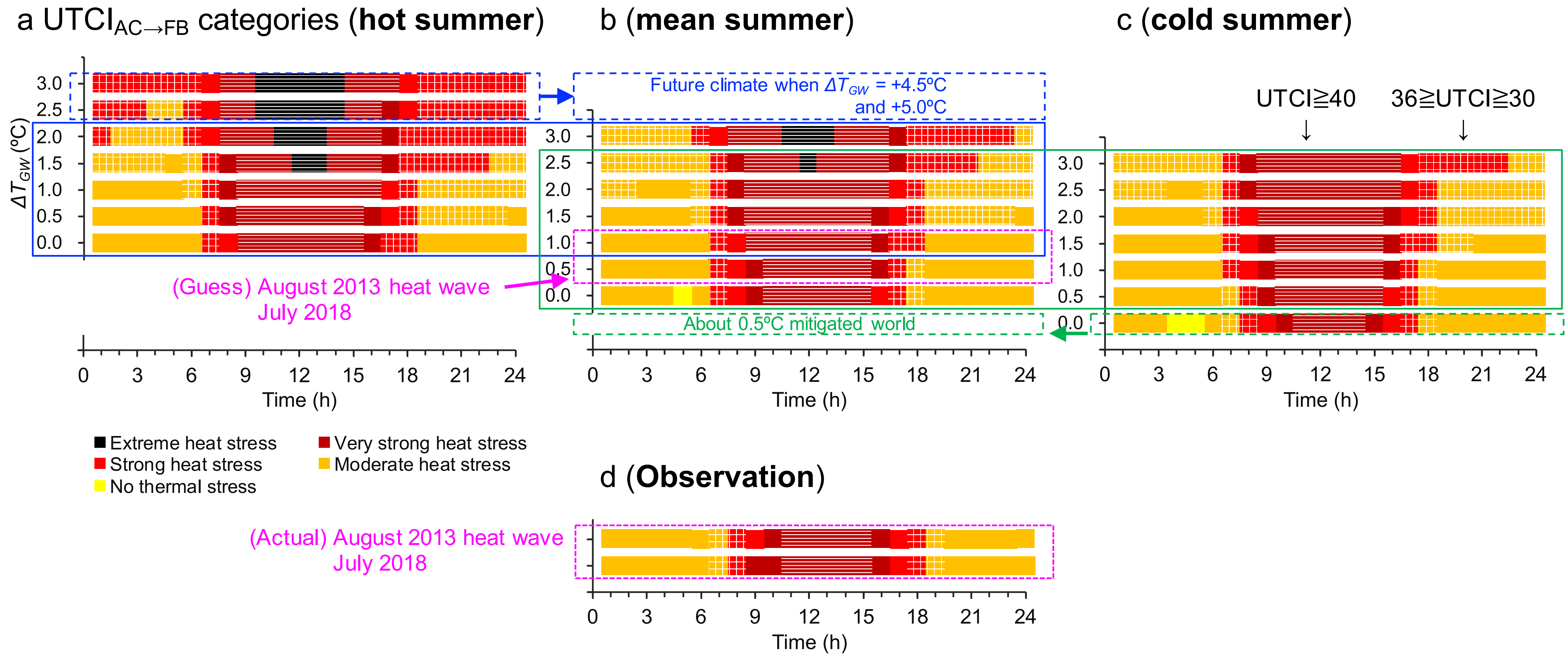
The AC feedback impact is comparable to benefits from urban heat island mitigation techniques

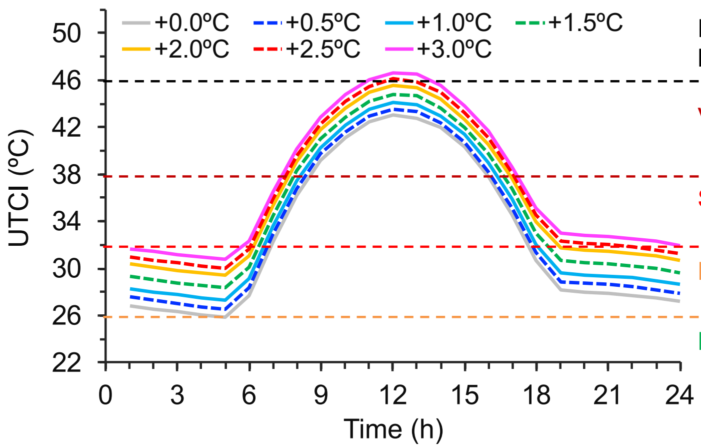


Morille and Musy (2017)



Takane et al. (2020) Environ. Res. Commun.

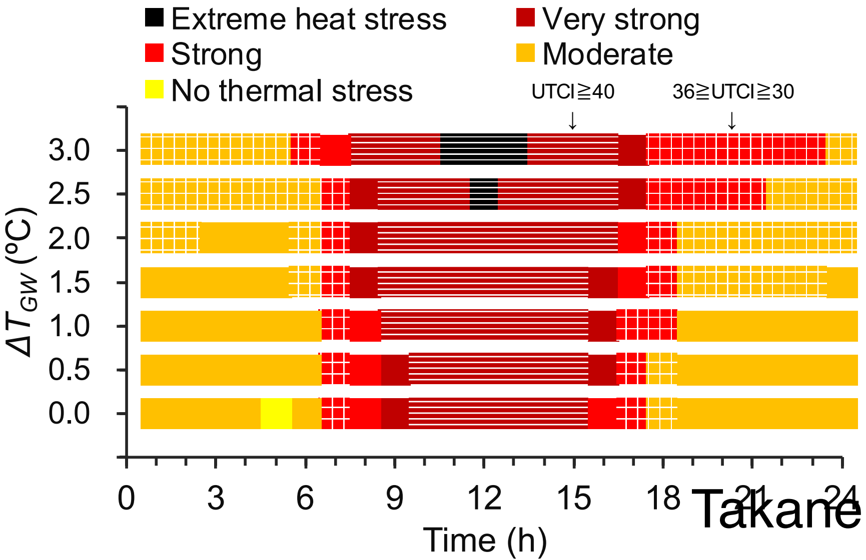
a UTCI$_{AC \rightarrow FB}$



Stress category	Criterion derived from UTCI-Fiala model response (Bröde et al. 2012)
Extreme heat stress	48ºC: Increase in Tre time gradient, steep decrease in total net heat loss 46ºC: Averaged sweat rate >650 g h^{-1}, steep increase
Very strong	40ºC: Core to Tskm gradient <1K (at 30 min) 38ºC: Increase in Tre at 30 min
Strong	36ºC: DTS 120 min > +2 33ºC: Averaged sweat rate > 200 g h^{-1}, increase in Tre at 120 min
Moderate	30ºC: Change of slope (vs. UTCI) in Tskm, Tskfc, Tskhn, sweat rate, Tre 26ºC: Average sweat rate >100 g h^{-1}, DTS 120 min <1, DTS >0.5 (average value)
No thermal stress	

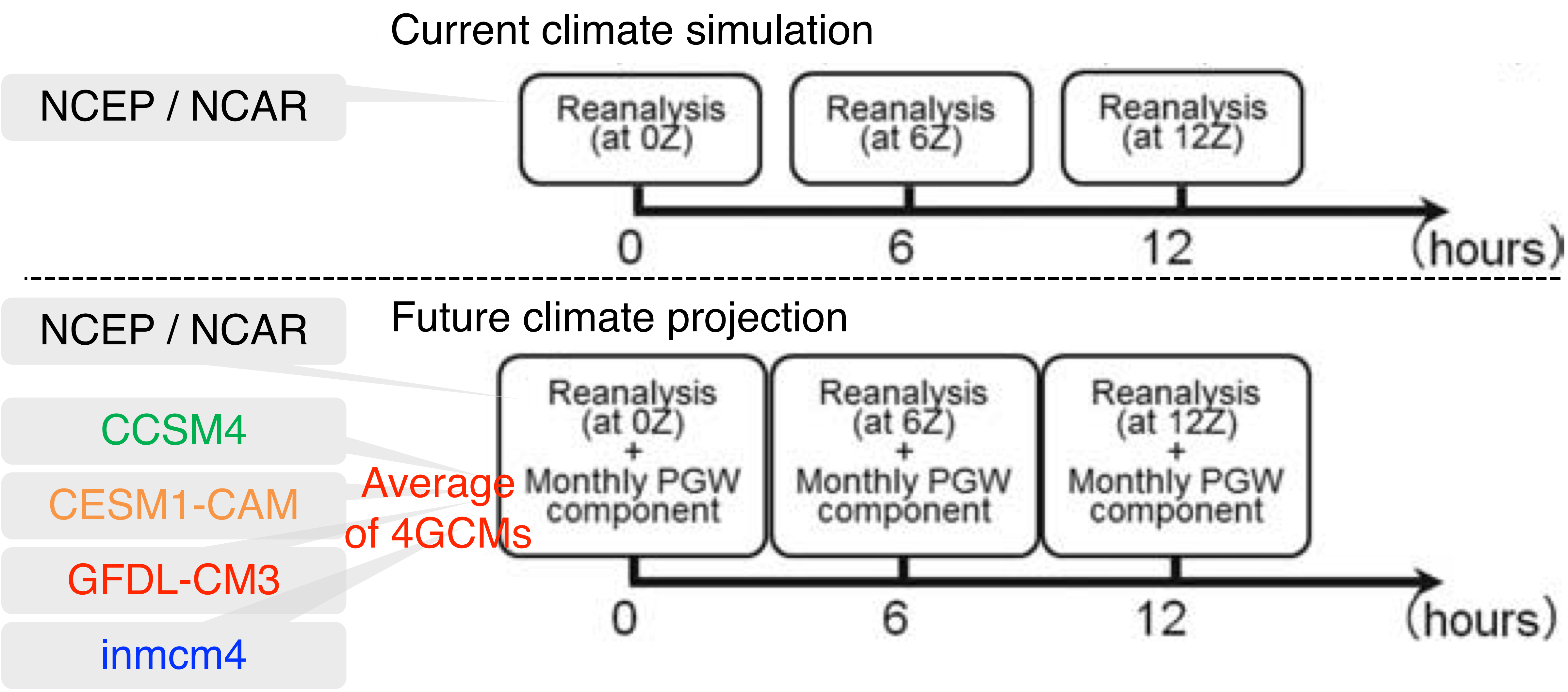
Tre: rectal temperature (human core temperature) (ºC) Tskm: mean skin temperature (ºC)
Tskfc: face skin temperature (ºC) Tskhn: hand skin temperature (ºC)
DTS: dynamic thermal sensation (-3 ... +3)

b UTCI$_{AC \rightarrow FB}$ stress categories

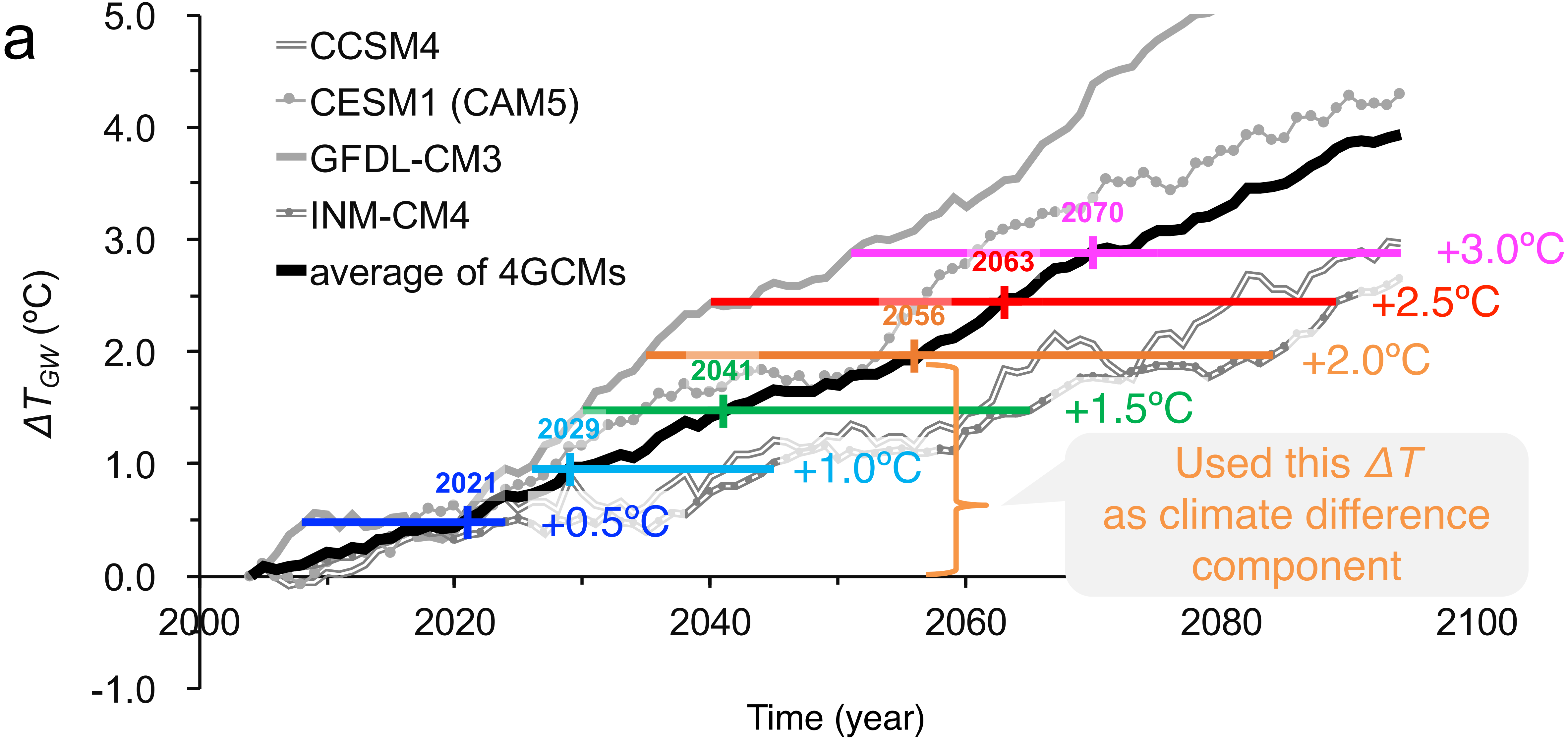


Takane et al. (2020) Environ. Res. Commun.

How to project future climate (Pseudo Global warming method)

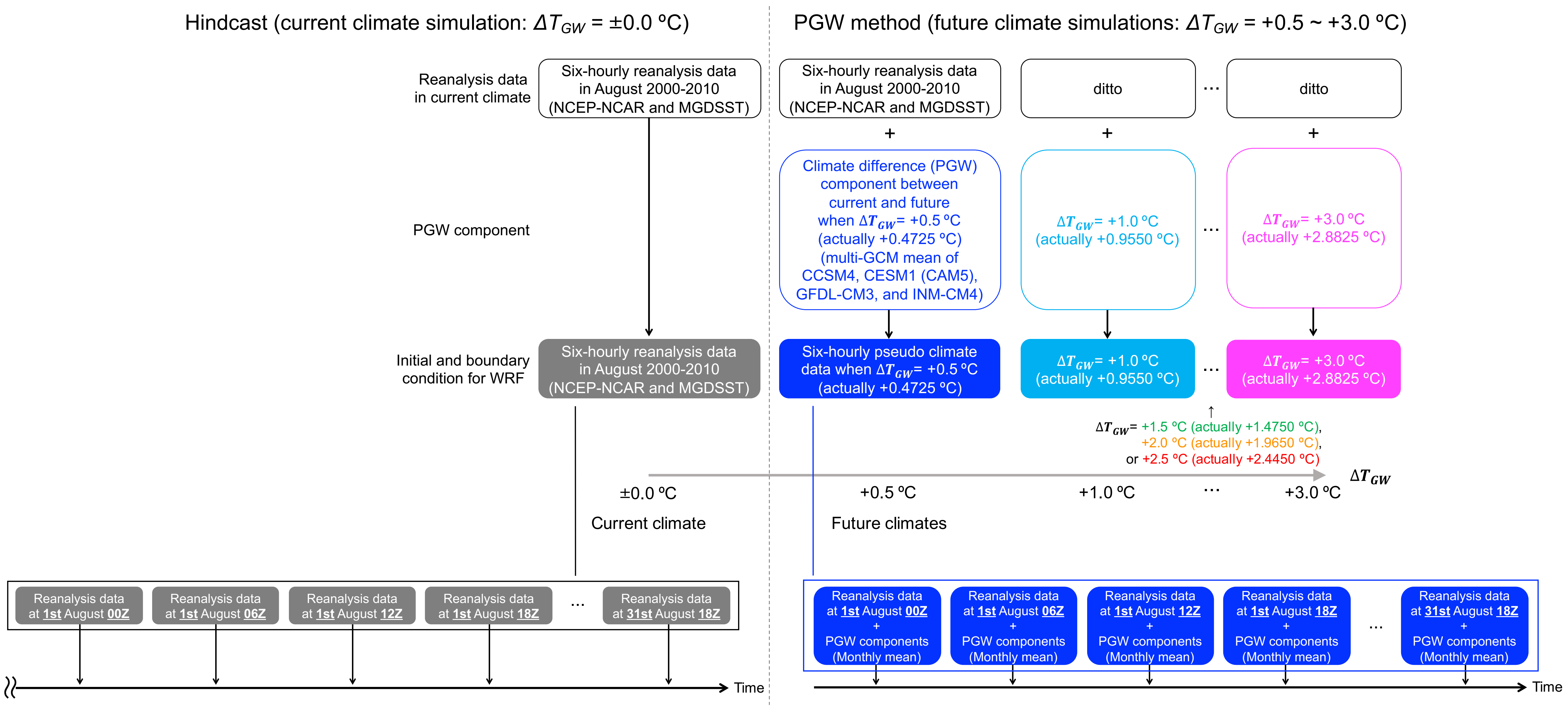


How to project future climate



Used this ΔT as climate difference component

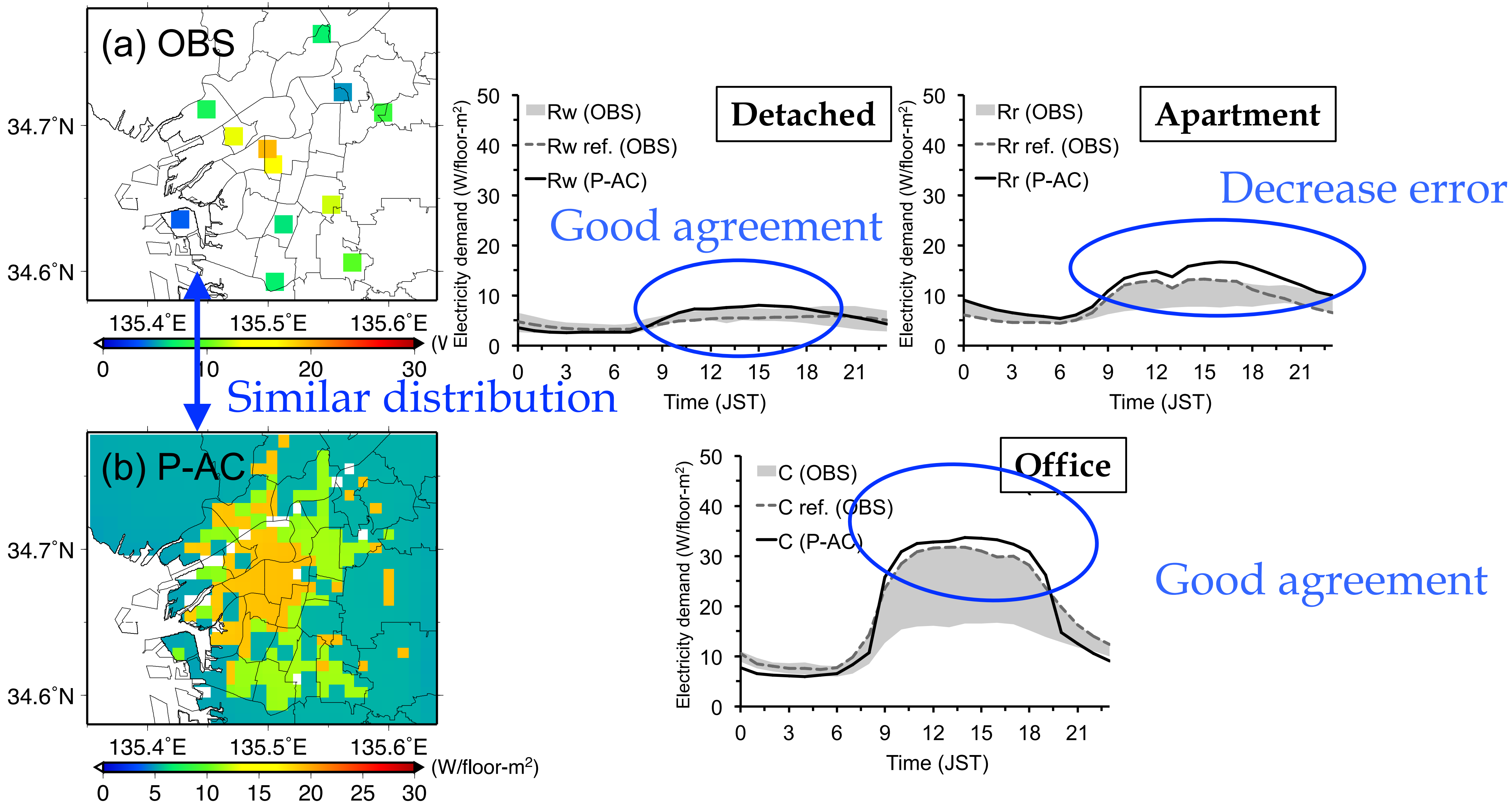
How to project future climate



Urban categories	Facet Thickness (m) Number of layers	Material	Thermal conductivity ($W m^{-1} K^{-1}$)	Volumetric heat capacity ($\times 10^6 J m^{-3} K^{-1}$)	Surface albedo (-)	Surface emissivity (-)
Commercial and office (C)	Roof 0.03 m 10 layers	Lightweight concrete /concrete/rock-wool board (ex 3rd to 4th layers)	0.520	1.4650	0.20	0.97
		Insulation (air gap/styrene foam) (3rd to 4th layers)	0.014	0.09346	-	-
	Wall 0.0225 m 10 layers	Tile/mortar/concrete/sealed air gap/plasterboard (ex 9th layer)	0.710	1.6950	0.20	0.97
		Insulation (air gap/styrene foam) (9th layer)	0.019	0.06675	-	-
		Window (glass)	Area fraction on the walls: 0.33			
	AC system	Electric air-source heat-pumps (rated COP=3.58 (cooling)): 100% - Target room temperature: 27 ℃ (for cooling) - Initial and end local times of AC system: 0800-1900 (LT)				
Fireproof apartment (Rr)	Roof 0.0225 m 10 layers	Concrete/styrene foam/ asphalt (ex 3rd layer)	0.897	1.8150	0.20	0.97
		Insulation (air gap/styrene foam) (3rd layer)	0.030	0.04376	-	-
	Wall 0.0234 m 10 layers	Concrete/plasterboard (ex 9th layer)	1.050	1.9340	0.20	0.97
		Insulation (air gap/styrene foam) (9th layer)	0.042	0.03126	-	-
		Window (glass)	Area fraction on the walls: 0.18			
	AC system	Electric air-source packaged air conditioners (rated COP=5.03): 100% - Target room temperature: 28 ℃ (for cooling) - Initial and end local times of AC system: 0000-2400 (LT)				
Wooden detached dwellings (Rw)	Roof 0.0095 m 10 layers	Slate/plywood/plasterboard (ex 5th to 8th layers)	0.181	0.5281	0.20	0.97
		Insulation (air gap/styrene foam) (5th to 8th layers)	0.032	0.02616	-	-
	Wall 0.011 m 10 layers	Mortar/plywood/plasterboard (ex 5th to 8th layers)	0.323	0.9983	0.20	0.97
		Insulation (air gap/styrene foam) (5th to 8th layers)	0.032	0.02616	-	-
		Window (glass)	Area fraction on the walls: 0.18			
	AC system	Electric air-source packaged air conditioners (rated COP=5.03): 100% - Target room temperature: 28 ℃ (for cooling) - Initial and end local times of AC system: 0000-2400 (LT)				

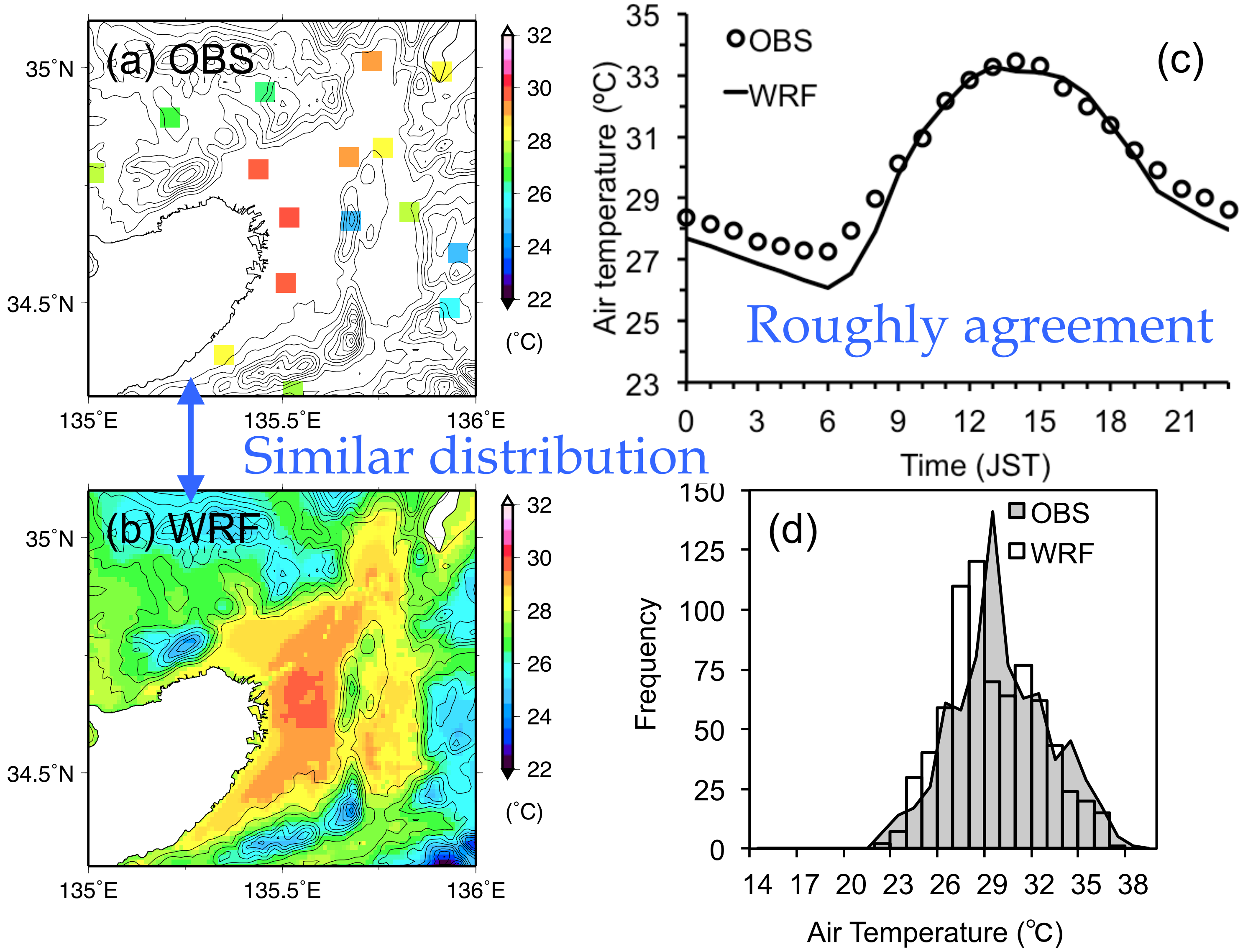
The model successfully reproduced electricity demand

Electricity demand Monthly mean of August 2013



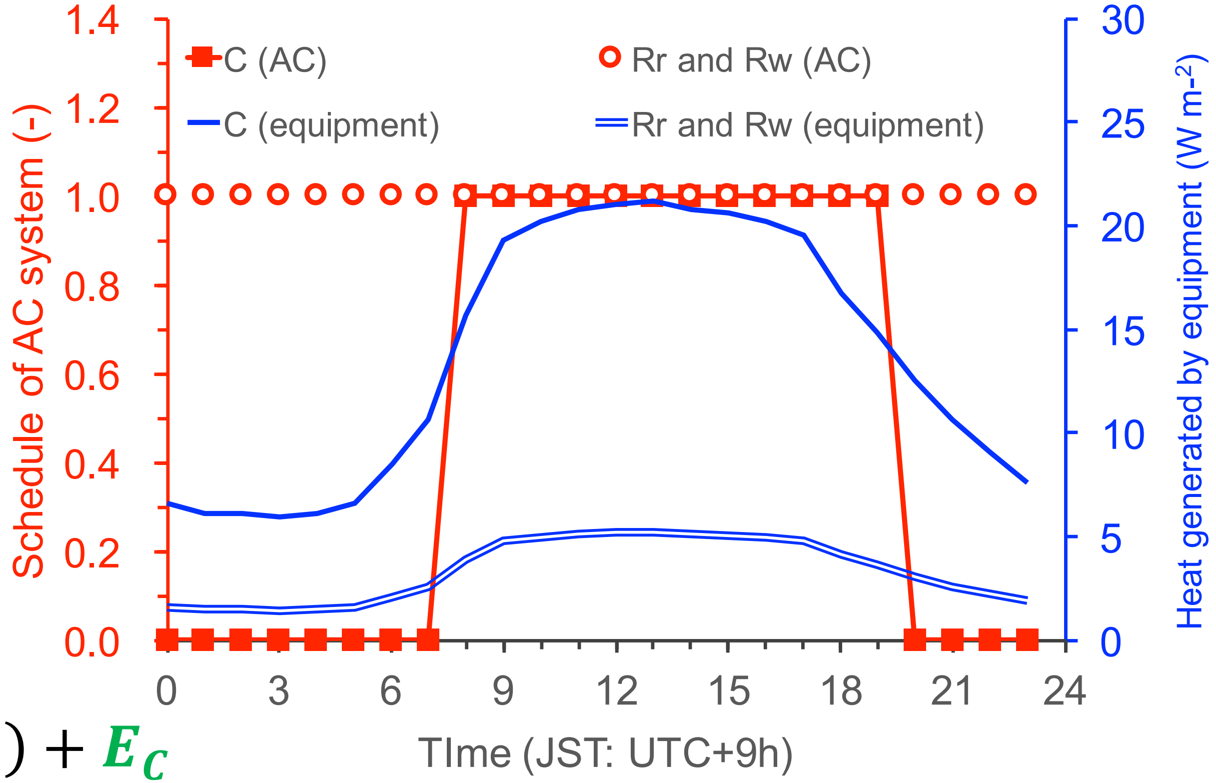
The model successfully reproduced urban temperature

Urban Temp Monthly mean of August 2013



AC settings

	AC	COP	Target room temp
C	Electric air-source heat-pumps	3.58	27 ºC
Rr	Electric air-source packaged air conditioners	5.03	28 ºC
Rw	Electric air-source packaged air conditioners	5.03	28 ºC



Energy demand

Sensible heat load of the build.

$$E_C = \frac{1}{COP}(H_{out} + E_{out})$$

coefficient of performance

Latent heat load of the build.

$$Q_A = (H_{out} + E_{out}) + E_C$$