Supplemental Material

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Attributing the Urban–Rural Contrast of Heat Stress Simulated by a Global Model

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Supplementary Materials for
Attributing the urban-rural contrast of heat stress simulated by a global model

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The supplementary materials include four sections. The first two sections derive the TRM attribution methods for canopy air temperature and canopy air SWBGT and the counterparts for the 2-m air temperature and 2-m SWBGT, respectively. The third section elaborates on the definitions of various temperatures in models. The last section presents the supplementary figures.

1 The TRM attribution method for canopy air temperature and canopy air SWBGT

1.1 The TRM attribution method for canopy air temperature

Based on the energy balance equation for an infinitely thin surface layer that is horizontally homogeneous, linearizing the emitted longwave radiation term and the saturated specific humidity term yields

$$T_s - T_a = \frac{\lambda_0\{R_n^* - G - \frac{\rho L_v}{r_a + r_s}[q^*(T_a) - q_a]\}}{1 + f_{TRM}}, \tag{S1}$$

where T_a denotes the air temperature at the bottom of the atmospheric model and remains the same between urban and rural tiles, $R_n^* = SW_{in}(1-\alpha) + \varepsilon LW_{in} - \varepsilon\sigma T_a^4$, $f_{TRM} = \frac{r_0}{r_a}(1 + \frac{\delta}{\gamma}\frac{r_a}{r_a + r_s})$, $\delta = \frac{de^*}{dT}|_{T_a}$, $\gamma = \frac{c_p P}{0.622 L_v}$, $r_0 = \rho c_p \lambda_0$, $\lambda_0 = \frac{1}{4\varepsilon\sigma T_a^3}$. This is identical to Eq. 6 of the main article. Based on Eq. S1, the urban-rural difference in surface temperature (ΔT_s) can be attributed to changes in the albedo (α), aerodynamic resistance (r_a), surface resistance (r_s), and ground heat flux (G):

$$\Delta T_s = \frac{\partial T_s}{\partial \alpha}\Delta\alpha + \frac{\partial T_s}{\partial r_a}\Delta r_a + \frac{\partial T_s}{\partial r_s}\Delta r_s + \frac{\partial T_s}{\partial G}\Delta G. \tag{S2}$$

In the following, we document the analytical expression of the partial derivative of T_s with respect to each of the four biophysical factors. First, the sensitivity of surface temperature to surface albedo α can be expressed as:

$$\frac{\partial T_s}{\partial \alpha} = \frac{\partial T_s}{\partial R_n^*}\frac{\partial R_n^*}{\partial \alpha} = \frac{\lambda_0}{1 + f_{TRM}}(-S_{in}). \tag{S3}$$

And the sensitivity of surface temperature to aerodynamic resistance r_a is

$$\frac{\partial T_s}{\partial r_a} = \frac{\lambda_0}{1+f_{TRM}} \frac{\rho L_v [q^*(T_a)-q_a]}{(r_a+r_s)^2} - \frac{\lambda_0}{(1+f_{TRM})^2} \{R_n^* - G - \frac{\rho L_v [q^*(T_a)-q_a]}{r_a+r_s}\} \frac{\partial f_{TRM}}{\partial r_a}, \tag{S4}$$

where $\frac{\partial f_{TRM}}{\partial r_a} = -\frac{r_0}{r_a^2}[1+\frac{\delta}{\gamma}(\frac{r_a}{r_a+r_s})^2]$. Similarly, the sensitivity of surface temperature to surface resistance r_s is

$$\frac{\partial T_s}{\partial r_s} = \frac{\lambda_0}{1+f_{TRM}} \frac{\rho L_v [q^*(T_a)-q_a]}{(r_a+r_s)^2} - \frac{\lambda_0}{(1+f_{TRM})^2} \{R_n^* - G - \frac{\rho L_v [q^*(T_a)-q_a]}{r_a+r_s}\} \frac{\partial f_{TRM}}{\partial r_s}, \tag{S5}$$

where $\frac{\partial f_{TRM}}{\partial r_s} = -\frac{\delta}{\gamma}\frac{r_0}{(r_a+r_s)^2}$. Lastly, the sensitivity of surface temperature to ground heat flux G is

$$\frac{\partial T_s}{\partial G} = -\frac{\lambda_0}{1+f_{TRM}}. \tag{S6}$$

1.2 The TRM attribution method for canopy air SWBGT

In this study, we focus on a combined temperature-humidity measure of heat stress, the Simplified Wet Bulb Globe Temperature (SWBGT, denoted as W), which can be expressed as

$$\mathrm{W} = 0.567T + 0.00632Pq + 3.94, \tag{S7}$$

where P is the pressure assumed to be identical between urban and rural land, and the unit is Pa. As a result, the change in SWBGT is due to the change in T_s and q_s, following

$$\Delta \mathrm{W}_s = 0.567\Delta T_s + 0.00632P\Delta q_s, \tag{S8}$$

where ΔT_s has been discussed earlier (Eq. S2).

The expression of surface specific humidity can be obtained from the bulk formulation for latent heat flux (see Eq. 9 of the main article) as follows:

$$q_s = \frac{r_a}{r_a+r_s}[q^*(T_s)-q_a]+q_a. \tag{S9}$$

Analogous to the attribution of changes in surface temperature, changes in surface specific humidity can be expressed as

$$\Delta q_s = \frac{\partial q_s}{\partial \alpha}\Delta\alpha + \frac{\partial q_s}{\partial r_a}\Delta r_a + \frac{\partial q_s}{\partial r_s}\Delta r_s + \frac{\partial q_s}{\partial G}\Delta G. \tag{S10}$$

Substituting Eqs. S2 and S10 into Eq. S8 yields an attribution equation for SWBGT.

Below we document the sensitivities in Eq. S10. First, the sensitivity of surface specific humidity to surface albedo α can be computed as

$$\frac{\partial q_s}{\partial \alpha} = \frac{\partial q_s}{\partial q^*(T_s)} \frac{\partial q^*(T_s)}{\partial T_s} \frac{\partial T_s}{\partial \alpha} = \frac{r_a}{r_a+r_s} \frac{\partial q^*(T_s)}{\partial T_s} \frac{\partial T_s}{\partial \alpha}. \tag{S11}$$

The derivative of T_s with respect to α has been given earlier (Eq. S3), and the derivative of $q^*(T_s)$ with respect to T_s can be computed from the Clausius-Clapeyron relation (Tetens 1930) and the definition of q, as follows:

$$\frac{\partial q^*(T_s)}{\partial T_s} = \frac{0.622}{P}\frac{2508.3\times 1000}{(T_s+237.3)^2}e^{\frac{17.3T_s}{T_s+237.3}}. \tag{S12}$$

For simplicity, we denote $BB = \frac{\partial q_s}{\partial q^*(T_s)}\frac{\partial q^*(T_s)}{\partial T_s} = \frac{r_a}{r_a+r_s}\frac{\partial q^*(T_s)}{\partial T_s}$ as it shows up later in other sensitivities. The sensitivity of surface specific humidity to aerodynamic resistance r_a is

$$\frac{\partial q_s}{\partial r_a} = BB\frac{\partial T_s}{\partial r_a} + \frac{r_s}{(r_a+r_s)^2}[q^*(T_s)-q_a], \tag{S13}$$

and the sensitivity of surface specific humidity to surface resistance r_s is

$$\frac{\partial q_s}{\partial r_s} = BB\frac{\partial T_s}{\partial r_s} - \frac{r_a}{(r_a+r_s)^2}[q^*(T_s)-q_a]. \tag{S14}$$

Lastly, the sensitivity of surface specific humidity to ground heat flux G is

$$\frac{\partial q_s}{\partial G} = BB\frac{\partial T_s}{\partial G}. \tag{S15}$$

The sensitivities of T_s with respect to aerodynamic resistance r_a, surface resistance r_s, and ground heat flux G in the above equations have been presented earlier.

2 The TRM attribution method for 2-m air temperature and 2-m SWBGT

2.1 The TRM attribution method for 2-m air temperature

Based on the concept of constant-flux layer, the 2-m air temperature T_2 is presented in Eq. 12 of the main article as $T_2 = \frac{r'_a}{r_a}(T_s - T_a) + T_a$, where r'_a is the aerodynamic resistance between 2 meters above the displacement height and the atmosphere. As a result, the attribution of T_2 needs to consider the urban-rural difference in r'_a, in addition to the four biophysical factors previously discussed:

$$\Delta T_2 = \frac{\partial T_2}{\partial \alpha}\Delta\alpha + \frac{\partial T_2}{\partial r_a}\Delta r_a + \frac{\partial T_2}{\partial r_s}\Delta r_s + \frac{\partial T_2}{\partial G}\Delta G + \frac{\partial T_2}{\partial r'_a}\Delta r'_a. \tag{S16}$$

Denoting $f_2 = \frac{r'_a}{r_a}$, we can express the sensitivities of 2-m air temperature to biophysical factors, as follows:

$$\frac{\partial T_2}{\partial \alpha} = f_2\frac{\partial T_s}{\partial \alpha}, \tag{S17}$$

$$\frac{\partial T_2}{\partial r_a} = f_2\frac{\partial T_s}{\partial r_a} - \frac{r'_a}{r_a^2}(T_s - T_a), \tag{S18}$$

$$\frac{\partial T_2}{\partial r_s} = f_2 \frac{\partial T_s}{\partial r_s}, \tag{S19}$$

$$\frac{\partial T_2}{\partial G} = f_2 \frac{\partial T_s}{\partial G}, \tag{S20}$$

$$\frac{\partial T_2}{\partial r'_a} = \frac{T_s - T_a}{r_a}. \tag{S21}$$

Again, the sensitivities of T_s with respect to albedo α, aerodynamic resistance r_a, surface resistance r_s, and ground heat flux G in the above equations have been presented in section 1.1.

2.2 The TRM attribution method for 2-m SWBGT

Similar to the results for canopy air SWBGT, the change of 2-m SWBGT is due to the change of 2-m air temperature and 2-m specific humidity according to

$$\Delta \mathrm{W}_2 = 0.567 \Delta T_2 + 0.00632 P \Delta q_2. \tag{S22}$$

The ΔT_2 has been studied in section 2.1 (Eq. S16). Below we discuss the results for Δq_2.

Similar to the derivation of surface specific humidity (Eq. 9 of the main article), the 2-m specific humidity q_2 can be written as

$$q_2 = \frac{r'_a}{r_a + r_s} [q^*(T_s) - q_a] + q_a, \tag{S23}$$

and the attribution of q_2 can be expressed as:

$$\Delta q_2 = \frac{\partial q_2}{\partial \alpha} \Delta \alpha + \frac{\partial q_2}{\partial r_a} \Delta r_a + \frac{\partial q_2}{\partial r_s} \Delta r_s + \frac{\partial q_2}{\partial G} \Delta G + \frac{\partial q_2}{\partial r'_a} \Delta r'_a. \tag{S24}$$

Combining Eqs. S16, S22, and S24 yields an attribution equation for 2-m SWBGT.

The sensitivities of 2-m specific humidity to various biophysical factors can be expressed as:

$$\frac{\partial q_2}{\partial \alpha} = BB' \frac{\partial T_s}{\partial \alpha}, \tag{S25}$$

$$\frac{\partial q_2}{\partial r_a} = BB' \frac{\partial T_s}{\partial r_a} - \frac{r'_a}{(r_a + r_s)^2} [q^*(T_s) - q_a], \tag{S26}$$

$$\frac{\partial q_2}{\partial r_s} = BB' \frac{\partial T_s}{\partial r_s} - \frac{r'_a}{(r_a + r_s)^2} [q^*(T_s) - q_a], \tag{S27}$$

$$\frac{\partial q_2}{\partial G} = BB' \frac{\partial T_s}{\partial G}, \tag{S28}$$

$$\frac{\partial q_2}{\partial r'_a} = \frac{q^*(T_s) - q_a}{r_a + r_s}, \tag{S29}$$

where $BB' = \frac{\partial q_2}{\partial q^*(T_s)} \frac{\partial q^*(T_s)}{\partial T_s} = \frac{r'_a}{r_a + r_s} \frac{\partial q^*(T_s)}{\partial T_s}$.

3 Temperature definitions

In this section, we clarify temperature definitions in the numerical model in relation to the temperature in the attribution method.

3.1 The canopy air temperature

As mentioned in the main paper, there are multiple surfaces in numerical models, such as the LM4.0 and UCM used in this study. The canopy air temperature (T_{ca}) connects different surface temperatures. One can think of the canopy air as where the sensible and latent heat fluxes from different facets are aggregated and passed to the atmospheric model (see Fig. 1a). The total surface sensible heat flux is usually computed based on the difference between the canopy air temperature and the air temperature at the bottom of the atmospheric model. Therefore, from the atmospheric model's perspective, the canopy air temperature is the temperature at which the total surface sensible heat flux is generated (or at which the different heat sources on the land are aggregated).

However, the canopy air temperature is not defined at a particular height. Suppose we had to give some height information to the canopy air temperature. In that case, it perhaps is informative to think of the canopy air temperature on the extrapolated surface-layer temperature profile described by the Monin-Obukhov similarity theory. From this perspective, some models define the canopy air temperature at the thermal roughness length above the displacement height while some other models define the canopy air temperature at the momentum roughness length above the displacement height. The best way to find out where the canopy air temperature is defined on the extrapolated surface-layer temperature profile is to examine whether the thermal roughness length is used in the calculation of r_a. If the thermal roughness length was used to compute r_a, then the canopy air temperature is implicitly defined at the thermal roughness length above the displacement height on the extrapolated surface-layer temperature profile.

For both LM4.0 and UCM used in this study, the canopy air temperature is defined at the thermal roughness length above the displacement height on the extrapolated surface-layer temperature profile. Note that for a bulk surface, the surface temperature is also defined at the thermal roughness length above the displacement height on the extrapolated surface-layer temperature profile (Garratt 1994). Hence one might argue that it is appropriate to use the canopy air temperature to approximate the bulk surface temperature in our study.

Similar to the LM4.0 and UCM in our study, the single-layer UCM in the Weather Research and Forecasting (WRF) model (Kusaka et al. 2001) defines the canopy air temperature at the thermal roughness length above the displacement height on the extrapolated surface-layer temperature profile. In contrast, some models such as CLM (Lawrence et al. 2019; Oleson et al. 2013) define the canopy air temperature at the momentum roughness length above the displacement height on the extrapolated surface-layer temperature profile for vegetated and urban areas. The difference between momentum and thermal roughness length is explained elsewhere (Garratt 1994). In short, the momentum and thermal roughness lengths are the heights (above the displacement height) at which the extrapolated surface-layer wind and temperature profiles reach the surface values of wind and temperature, respectively. For rough surfaces like vegetated or urban canopies, the momentum roughness length is usually larger than the thermal roughness length due to the role of pressure in affecting momentum transport but not heat transport. Nonetheless, it is outside the scope of this study to address the question of whether, in theory, the canopy air temperature should be defined at the momentum roughness length above the displacement height or the thermal roughness length above the displacement height (Kustas et al. 1989; Sun 1999; Kusaka et al. 2001; Friedl 2002), especially for urban areas (Lemonsu, Grimmond, and Masson 2004).

Another question is the relation between the radiative surface temperature and the canopy air temperature. The radiative surface temperature can be inferred from the outgoing longwave radiation with the Stefan-Boltzmann law (see Fig. S1). As can be seen, the canopy air temperature agrees reasonably well with the radiative surface temperature in our simulation.

The radiative surface temperature is not used for attribution because r_a needs to be inferred from the sensible heat flux, the bulk surface temperature, and T_a using Eq. 4 in the main article. Since the sensible heat flux is defined using the canopy air temperature and T_a in the numerical model, using the canopy air temperature to infer r_a gives more reasonable r_a values. In contrast, we find that using the radiative surface temperature yields too many negative r_a.

3.2 The 2-m air temperature

The term '2-m' air temperature is widely used in the literature and is a standard output for nearly all weather and climate models. However, there is some confusion in understanding the physical meaning of this variable, especially over tall canopies (e.g., in urban areas). One tends to think of the 2-m air temperature in urban areas as the air temperature at 2 meters above the street level. However, interpreting the '2-m' air temperature is not as straightforward.

Most numerical models do not resolve the temperature and humidity profiles in the urban roughness sublayer, which extends from the ground to about 2-5 times the average building height. Namely, numerical models do not solve for 2-m air temperature/SWBGT. Instead, numerical models often assume that the layer between the land model and the bottom of the atmospheric model is a constant-flux layer and that the temperature and humidity profiles in this layer are logarithmic under neutral conditions (or described by Monin-Obukhov similarity theory under thermally stratified conditions), as shown in Fig. 1b.

As stated in the main article, the 2-m air temperature is defined at 2 meters above the displacement height (z_d) on the extrapolated surface-layer temperature profile. Therefore, it only corresponds to 2 meters above the ground when there is no canopy (namely, when the displacement height is close to zero). However, over tall canopies (e.g., urban environments), the physical interpretation of the 2-m air temperature becomes complicated. On the one hand, the value of z_d can be on the order of 10 meters for tall canopies, meaning that the 2-m air temperature is not at 2 meters above the street level and is even above most of the buildings and trees. On the other hand, in the framework of Monin-Obukhov similarity theory, everything is defined above the displacement height because the displacement height is where the 'surface' is felt by the surface-layer turbulence (Jackson 1981). Recall that even the surface temperature is defined at the thermal roughness length above the displacement height. When the canopy air temperature is used as a proxy for the bulk surface temperature, as discussed earlier, it is also defined at the thermal roughness length (or for some models' momentum roughness length) above the displacement height. In this sense, the 2-m air temperature is roughly 2 meters above the 'surface' in the modeling world.

Due to the reasons above, in this paper, we view the canopy air temperature in the numerical model as an aggregated 'surface' temperature and the 2-m air temperature in the numerical model as some sort of 'near-surface' temperature. But we caution that there is no one-to-one correspondence between these temperatures and real-world temperature measurements in urban environments.

4 Figures

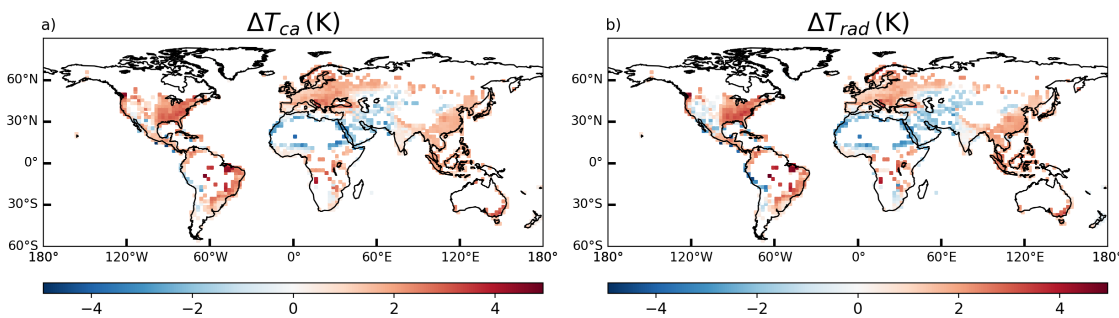

Fig. S1: Spatial distribution of the urban-rural difference in (a) canopy air temperature (ΔT_{ca}) and (b) radiative surface temperature (ΔT_{rad}).

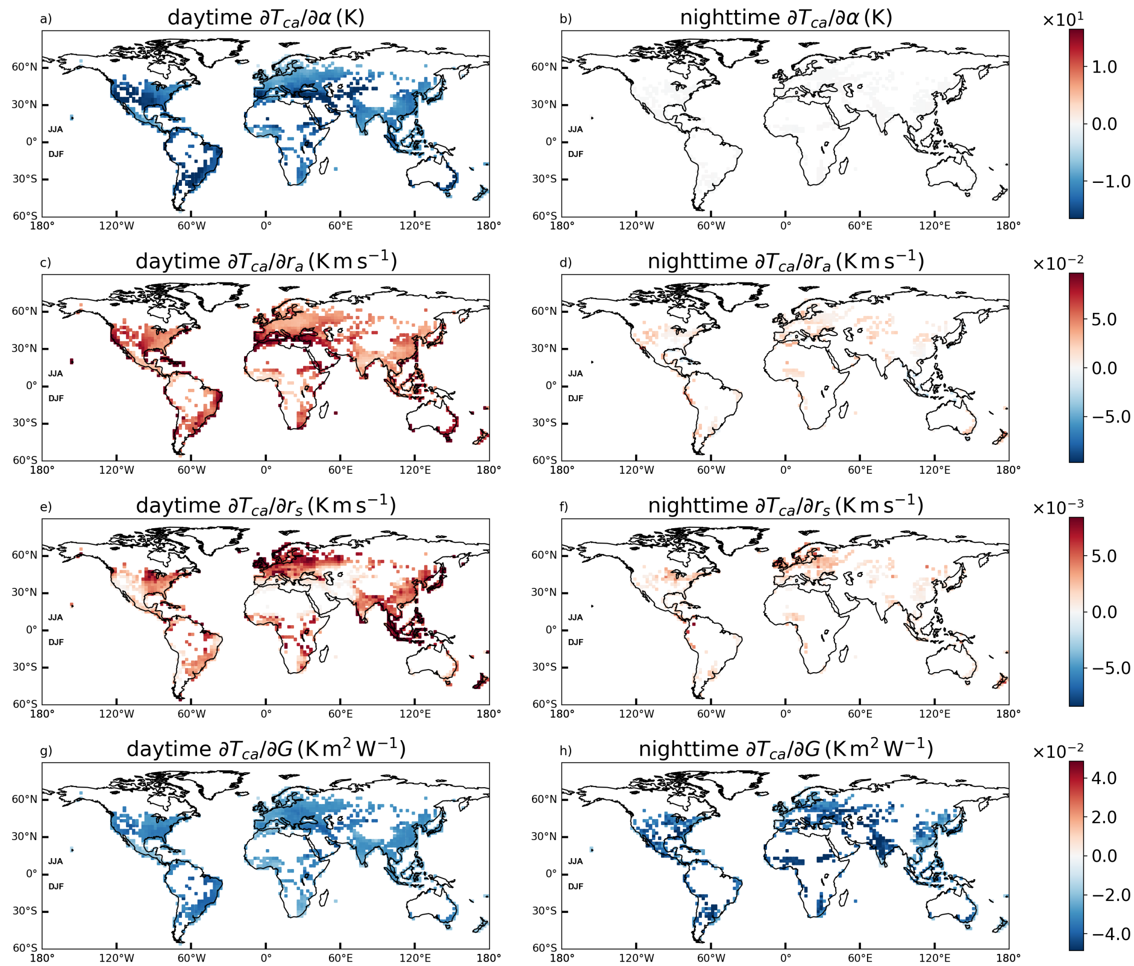

Fig. S2: The sensitivities of canopy air temperature to (a,b) albedo ($\partial T_{ca}/\partial\alpha$), (c,d) aerodynamic resistance ($\partial T_{ca}/\partial r_a$), (e,f) surface resistance ($\partial T_{ca}/\partial r_s$), and (g,h) ground heat storage ($\partial T_{ca}/\partial G$) during daytime (left column) and nighttime (right column).

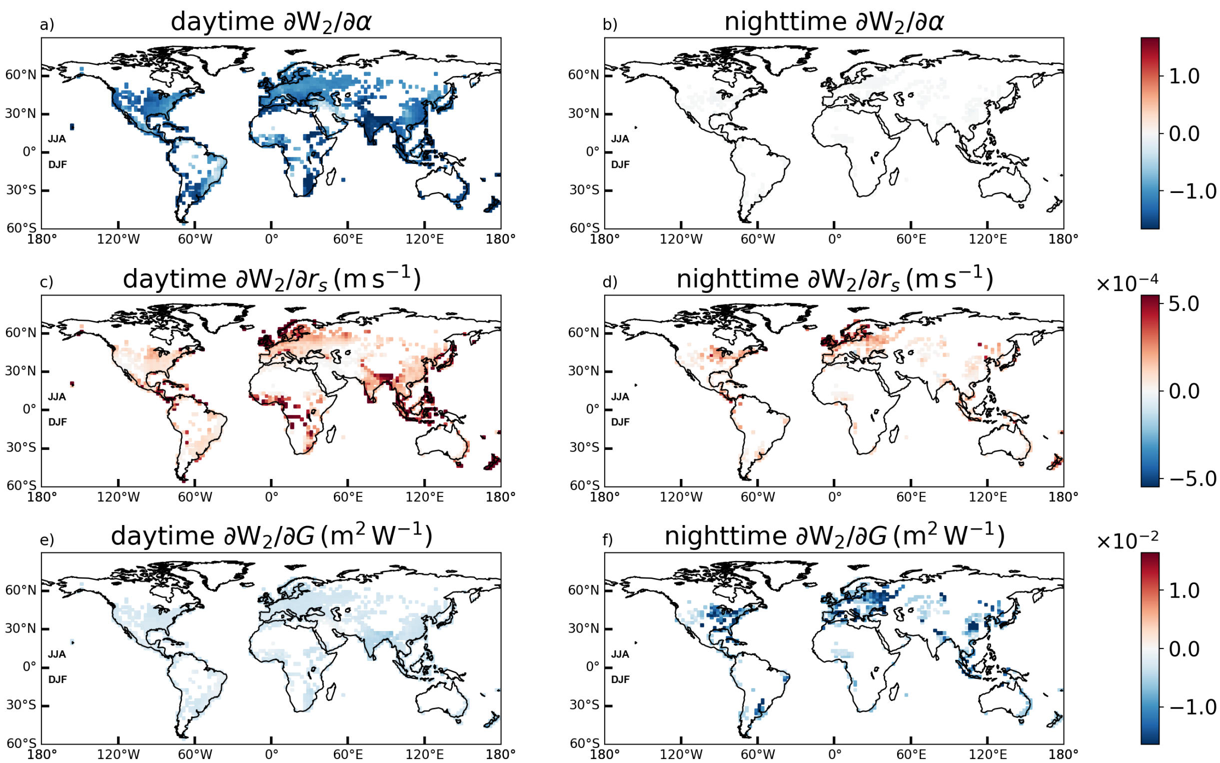

Fig. S3: The sensitivities of 2-m SWBGT to (a, b) albedo ($\partial \mathrm{W}_2/\partial\alpha$), (c, d) surface resistance ($\partial \mathrm{W}_2/\partial r_s$), and (e, f) ground heat storage ($\partial \mathrm{W}_2/\partial G$) during daytime (left column) and nighttime (right column).

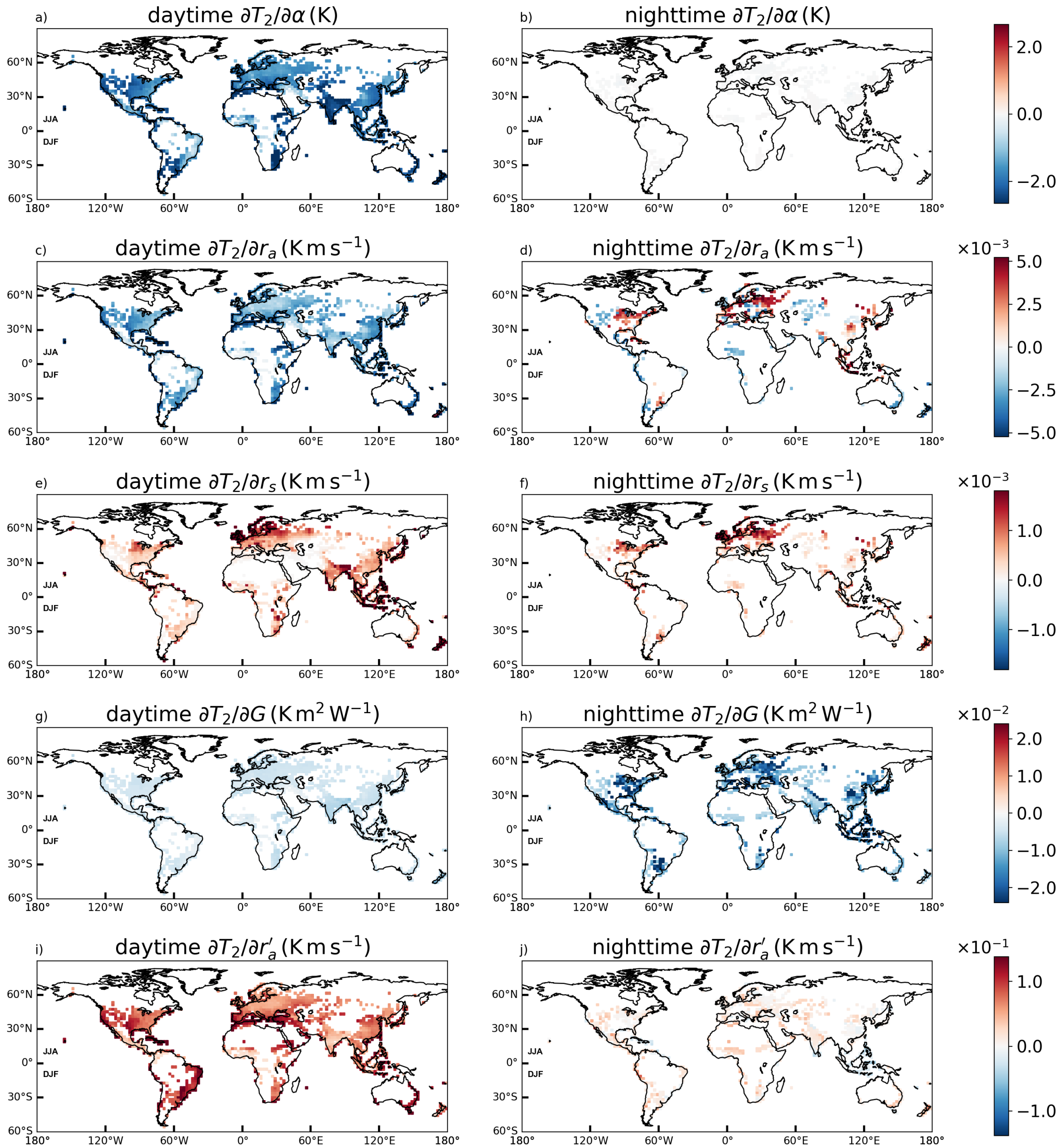

Fig. S4: The sensitivities of 2-m air temperature to (a,b) albedo ($\partial T_2/\partial\alpha$), (c,d) aerodynamic resistance ($\partial T_2/\partial r_a$), (e,f) surface resistance ($\partial T_2/\partial r_s$), (g,h) ground heat storage ($\partial T_2/\partial G$), and (i,j) 2-m aerodynamic resistance ($\partial T_2/\partial r'_a$) during daytime (left column) and nighttime (right column).

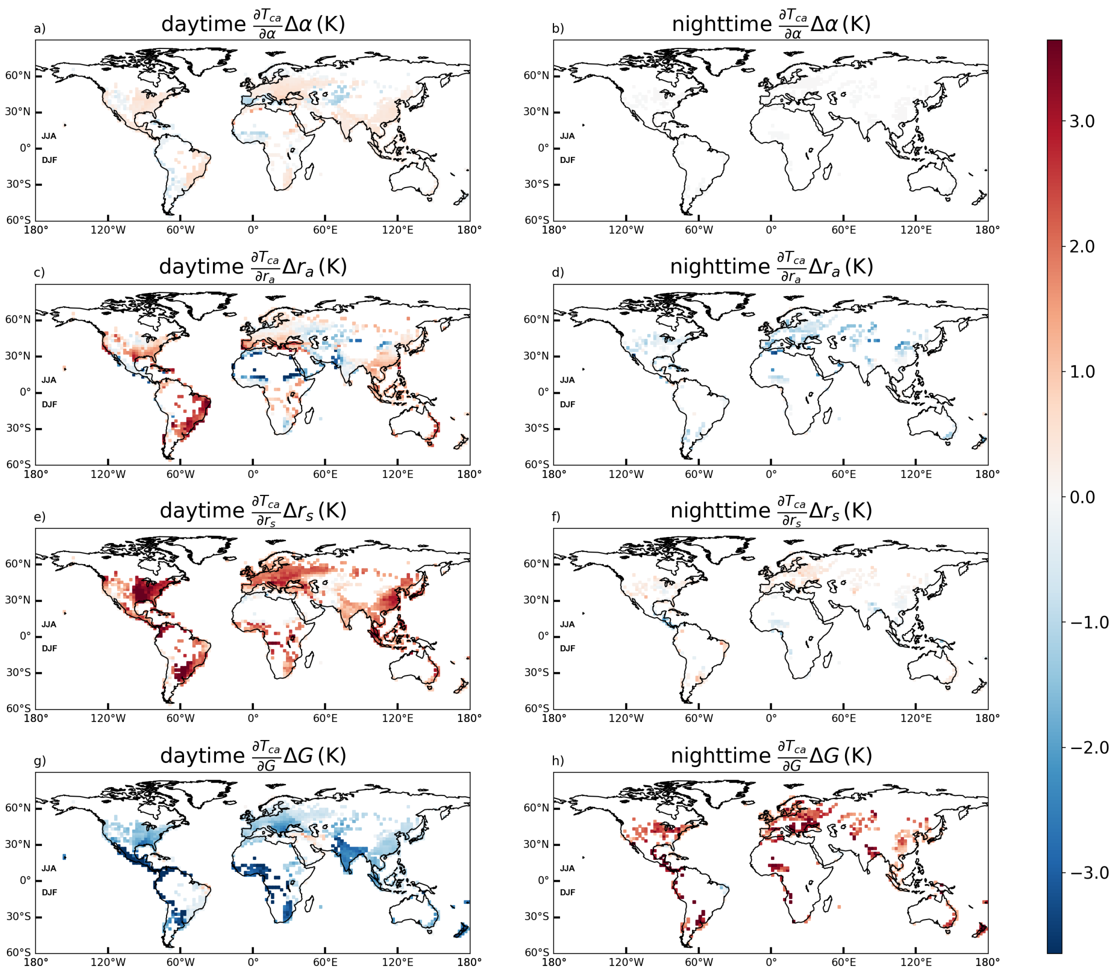

Fig. S5: The contributions to ΔT_{ca} from (a,b) albedo ($\frac{\partial \mathrm{T}_{ca}}{\partial \alpha}\Delta\alpha$), (c,d) aerodynamic resistance ($\frac{\partial \mathrm{T}_{ca}}{\partial r_a}\Delta r_a$), (e,f) surface resistance ($\frac{\partial \mathrm{T}_{ca}}{\partial r_s}\Delta r_s$) and (g,h) heat storage ($\frac{\partial \mathrm{T}_{ca}}{\partial G}\Delta G$) during daytime (left column) and nighttime (right column).

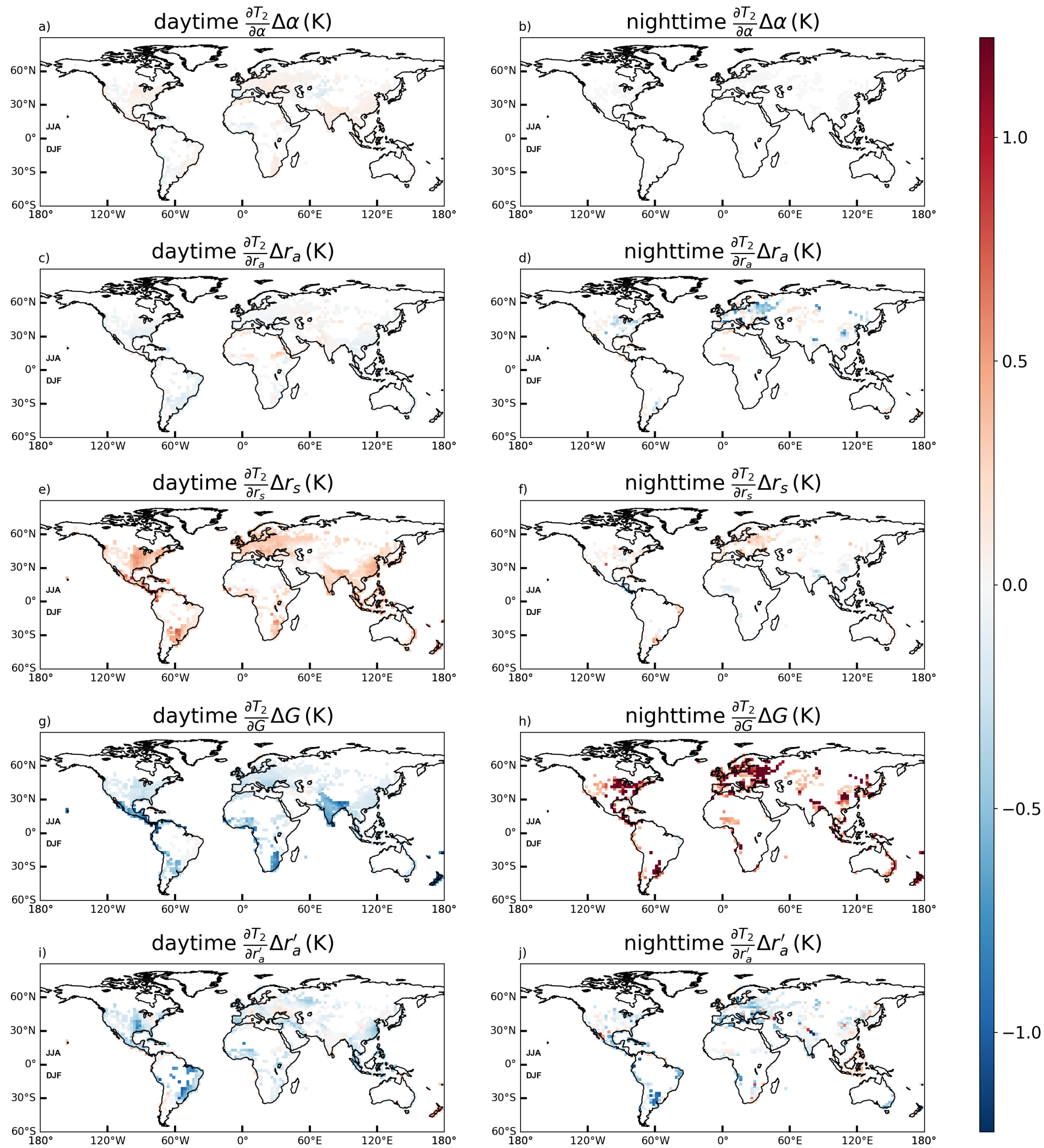

Fig. S6: The contributions to ΔT_2 from (a,b) albedo ($\frac{\partial T_2}{\partial \alpha}\Delta\alpha$), (c,d) aerodynamic resistance ($\frac{\partial T_2}{\partial r_a}\Delta r_a$), (e,f) surface resistance ($\frac{\partial T_2}{\partial r_s}\Delta r_s$), (g,h) heat storage ($\frac{\partial T_2}{\partial G}\Delta G$), and (i,j) 2-m aerodynamic resistance ($\frac{\partial T_2}{\partial r'_a}\Delta r'_a$) during daytime (left column) and nighttime (right column).

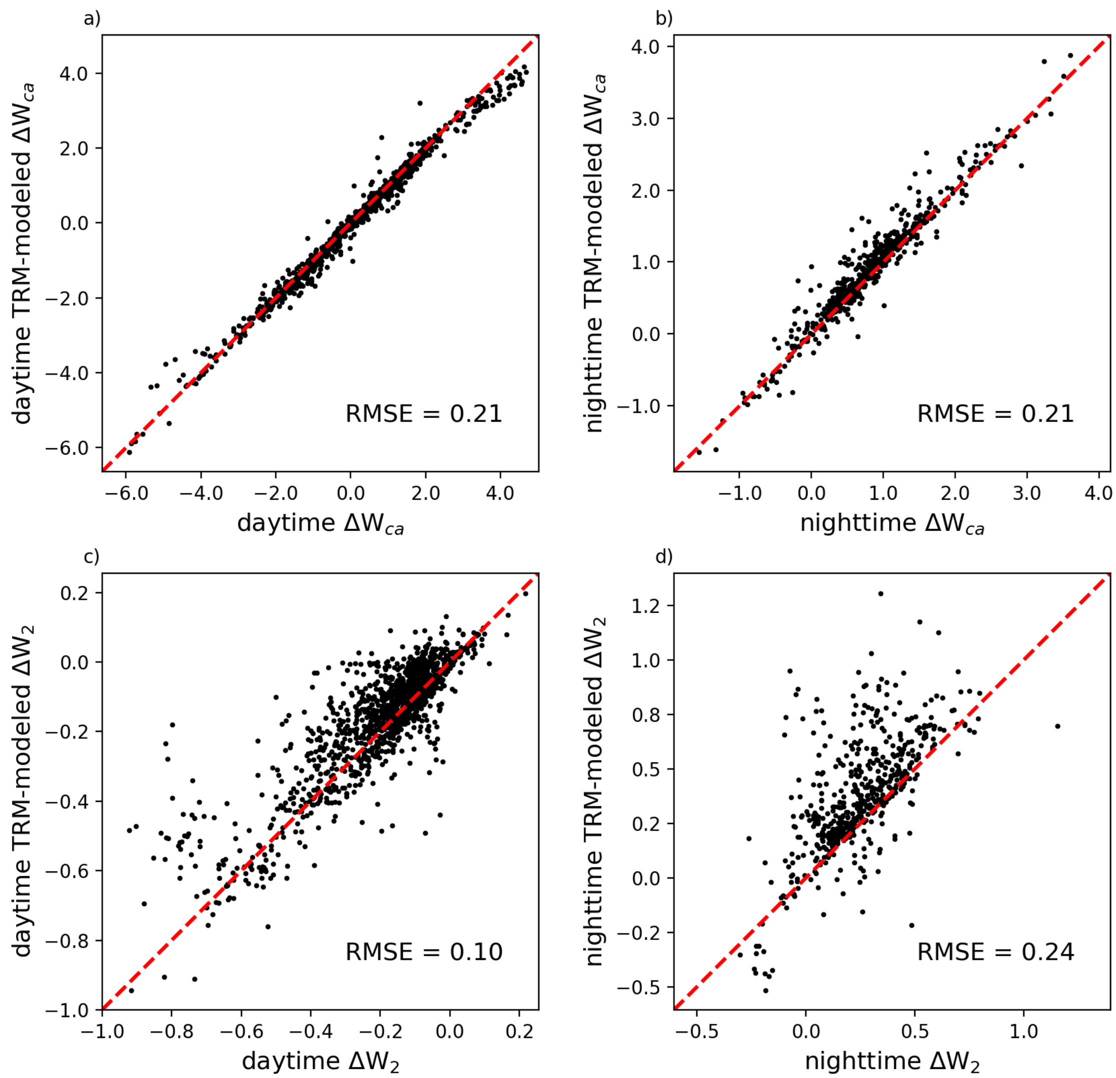

Fig. S7: The comparison of the GFDL-simulated versus the TRM-modeled (a, b) ΔW_{ca} and (c, d) ΔW_2 during daytime (left column) and nighttime (right column). The red dashed lines indicate the 1:1 lines.

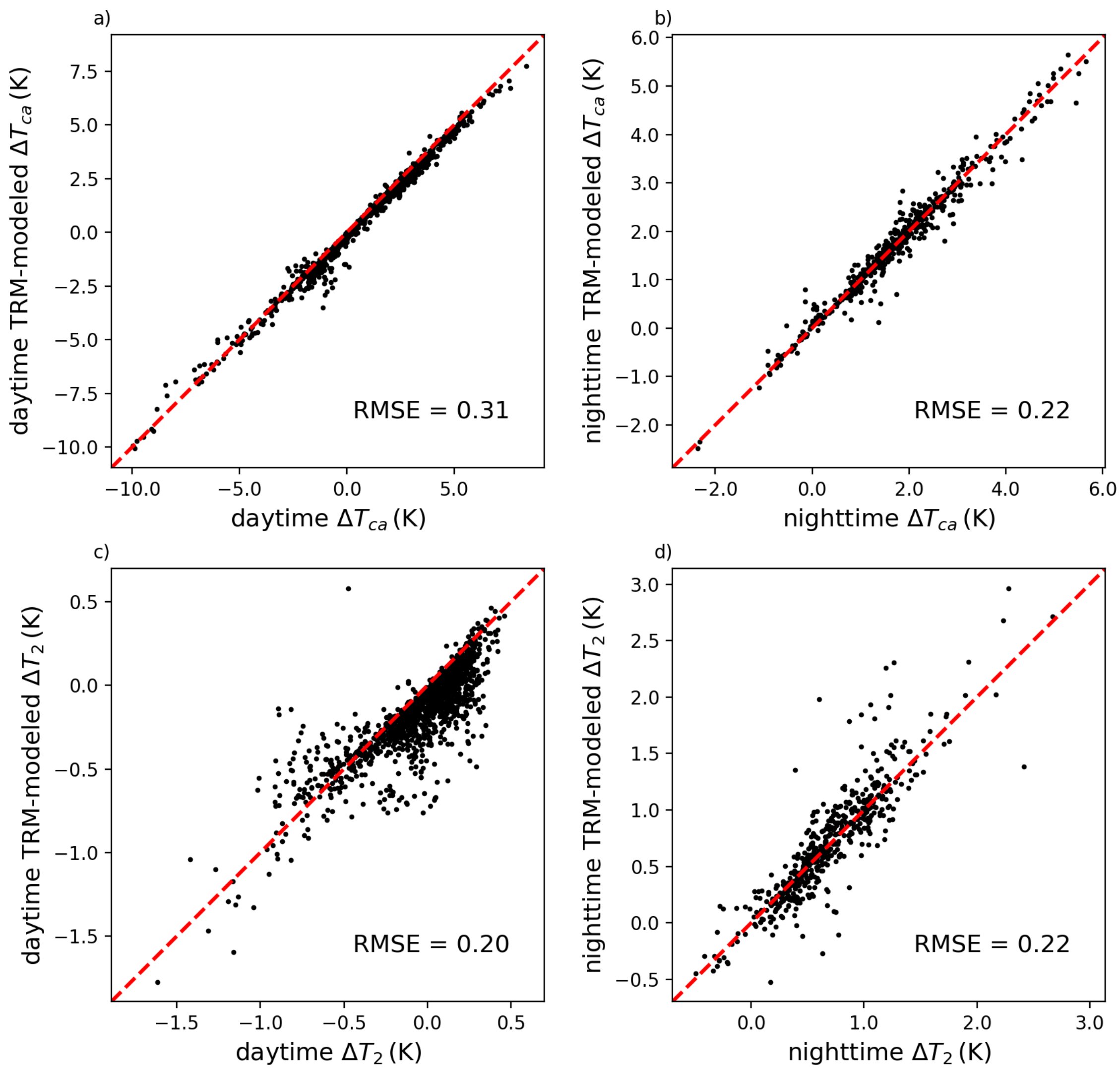

Fig. S8: The comparison of the GFDL-simulated versus the TRM-modeled (a,b) ΔT_{ca} and (c,d) ΔT_2 during daytime (left column) and nighttime (right column). The red dashed lines indicate the 1:1 lines.

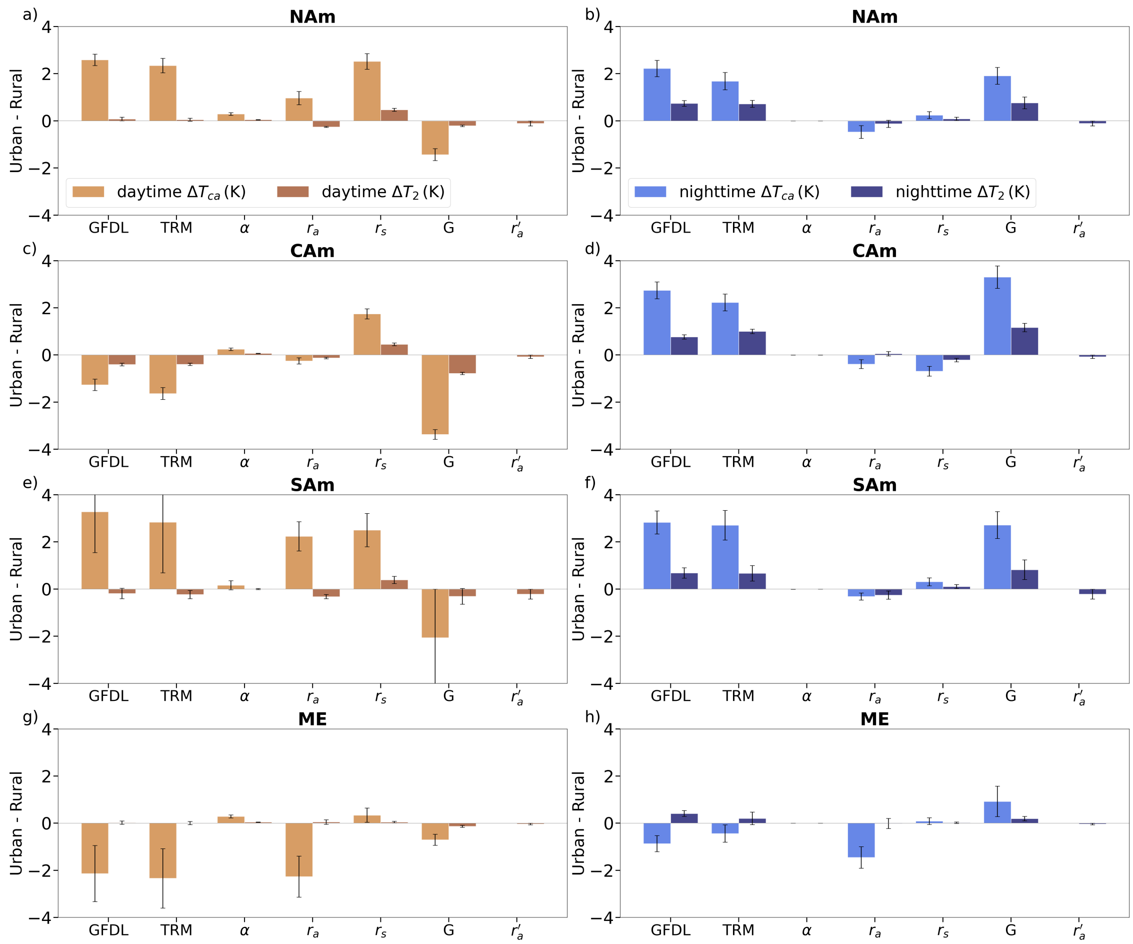

Fig. S9: Regionally-averaged attribution results for urban-rural contrasts of canopy air temperature (ΔT_{ca}) and 2-m air temperature (ΔT_2) over (a, b) North America (NAm), (c,d) Central America (CAm), (e,f) South America (SAm), and (g,h) Middle East (ME) during daytime (left column) and nighttime (right column). ΔT_{ca} and ΔT_2 are represented by yellow and brown bars over the daytime and by blue and dark blue bars over the nighttime. GFDL represents the simulated ΔT_{ca} and ΔT_2 by the numerical model. TRM represents the sum of the four contributions calculated from the TRM method. α, r_a, r_s, G, and r'_a represent the contributions from albedo, aerodynamic resistance between the surface and the atmosphere, surface resistance, heat storage, and aerodynamic resistance between the 2-m level and the atmosphere, respectively. The error bars are the standard error and indicate the spatial variability.

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