

# Evaluation of CO<sub>2</sub> reduction effects of buildings with green roofs by using a coupled urban-canopy and building-energy model

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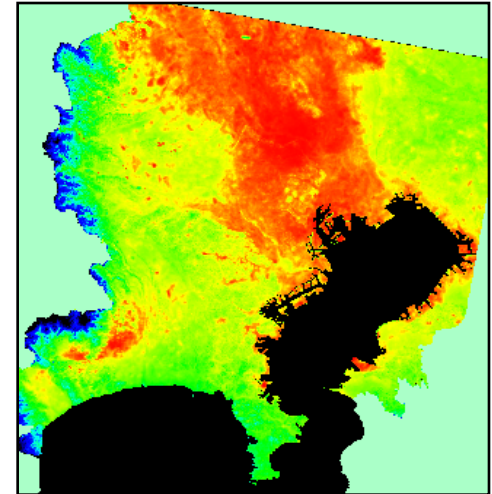
2. Okayama University of Science

# Background and objective

## Urban Heat Island

The urban heat island in the summer is an important issue related to energy demands, the livability in residential areas, and the peak electric power load due to use of air-conditioning.

→ It is important to improve the urban thermal environment.



## Global Warming

Energy saving is a topic of the utmost importance to prevent global warming.

→ Countermeasures to ever-increasing energy demand for air-conditioning are necessary.



**Improving the thermal environment in urban areas is an important issue linked to both the global and urban environment.**

# Background and objective

**Rooftop greening** is one measure that can be used to improve the urban thermal environment.

Vegetation is known to be effective for reducing temperatures via **evapotranspiration processes**.

There is only limited room for large ground-greening projects in urban areas.



This has led to the increased popularity of rooftop greening projects.



Many studies have examined the effectiveness of rooftop greening for **mitigating heat island conditions** and **reducing energy consumption for cooling**, and rooftop greening is thought to be an effective measure for countering the urban heat island.

# Background and objective

## Previous Research

### The evaluations based on actual measurements

If watering is performed to maintain rooftop greening, other environmental loads arise because of factors such as powering pumps.

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### The evaluations based on u

Surface wetness was parameterized (e.g., surface wetness efficiency, vegetation community conductance).

It is necessary to accumulate detailed data on the surface heat balance, surface temperature, and the supplied amount of water.

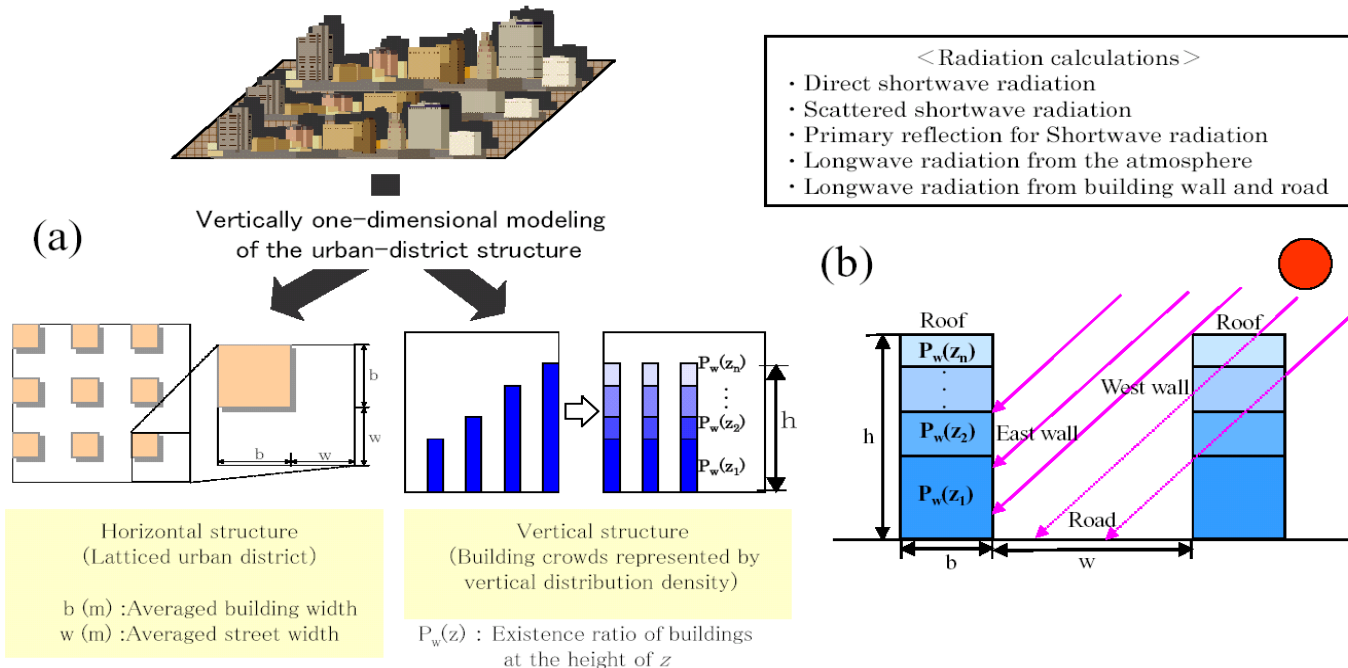
→ Calculations were performed without considering the amount of water used.

The objective of this research is to evaluate the effectiveness of rooftop greening in urban districts for the purpose of heat island mitigation and  $\text{CO}_2$  emission reductions by taking into account the amount of water and needed for watering.

# Coupled urban-canopy and building-energy model

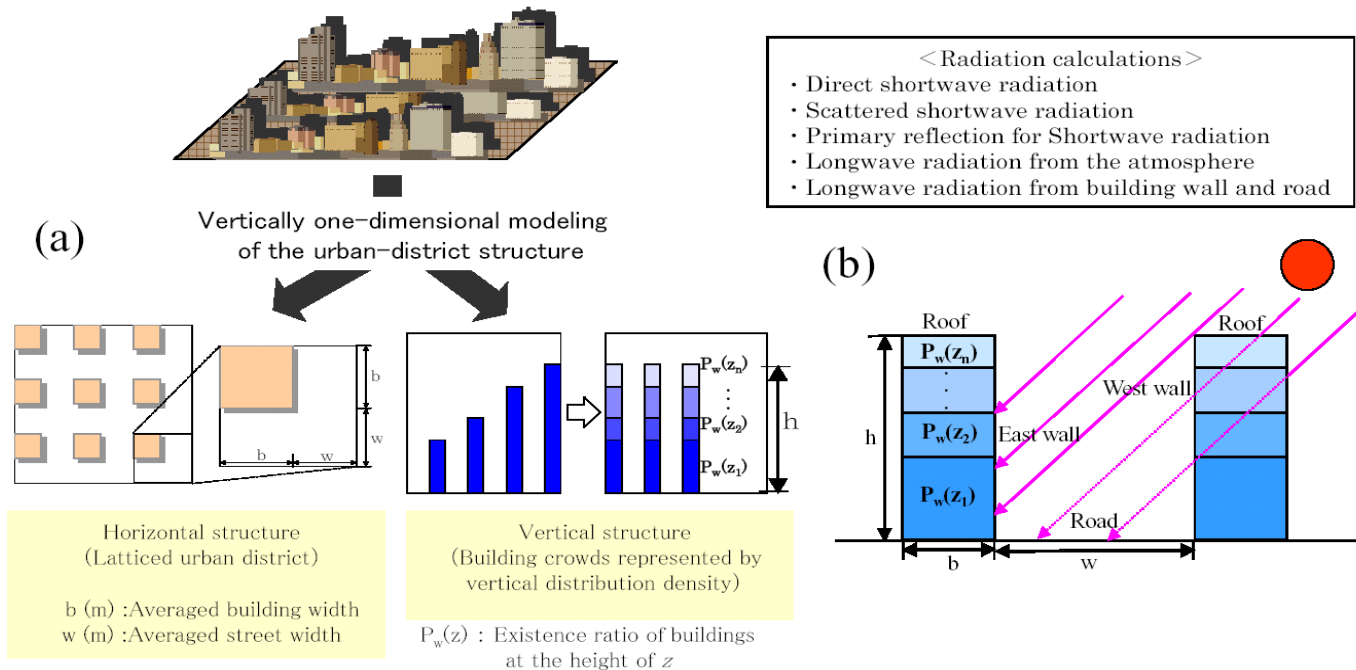
The coupled urban-canopy and building-energy model is used for predicting the heat loads of buildings and the changes in air temperature and energy consumption caused by air conditioning in urban districts.

## Urban-canopy model



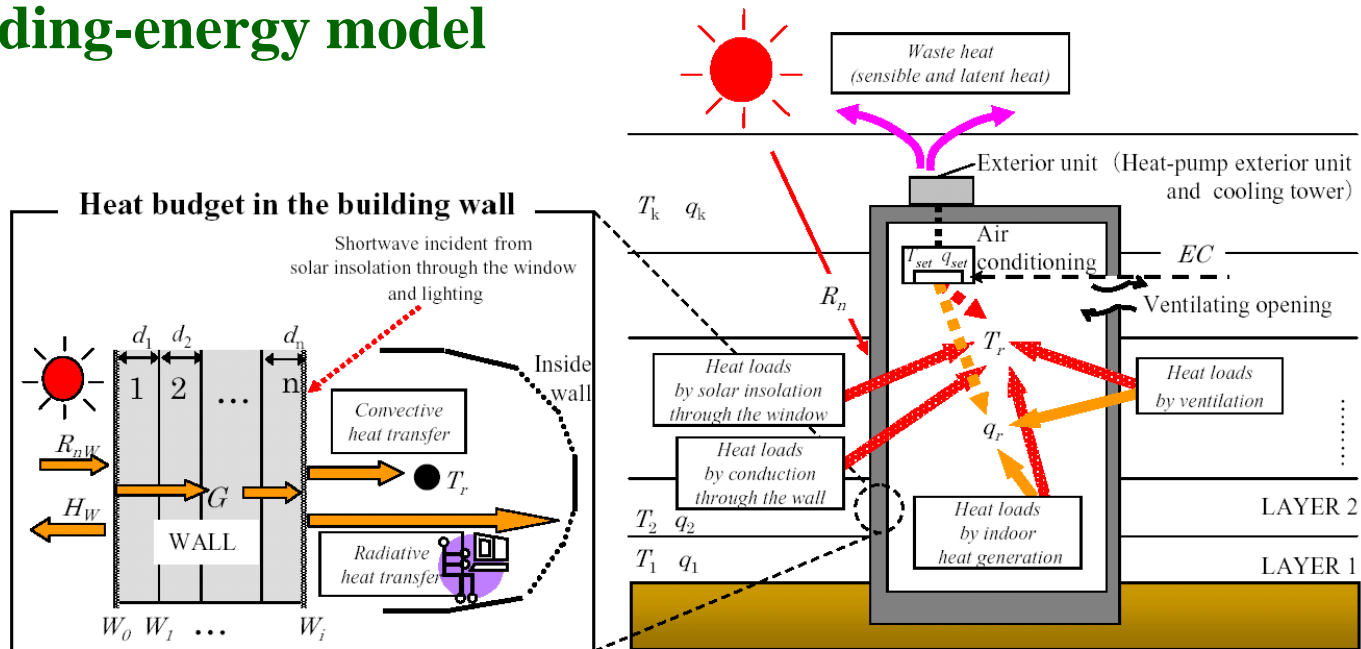
The urban-canopy model corresponds to a local atmospheric model that parameterizes city blocks with an average building width, building interval, and vertical distribution of buildings in order to express horizontally homogeneous city blocks as multiple one-dimensional vertical layers.

## Urban-canopy model



The building-energy model is used for calculating air-conditioning loads, and by incorporating the urban-canopy model, it is capable of calculating city-block-scale air-conditioning loads that include interaction with the outside atmosphere.

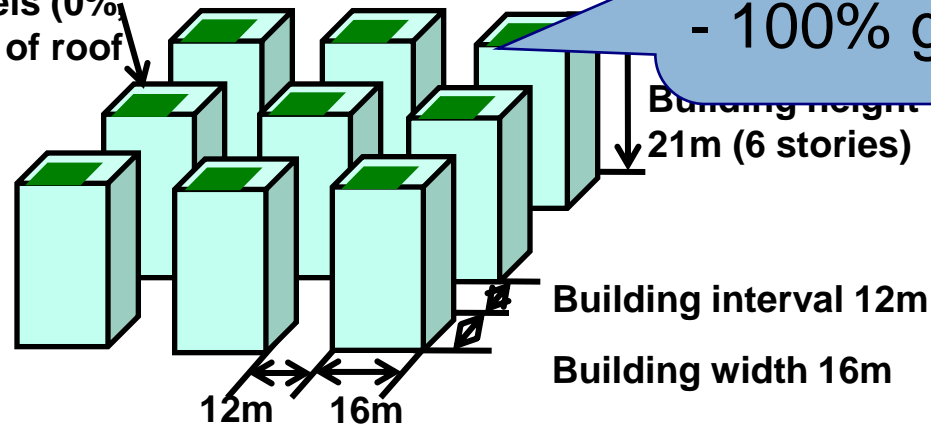
## Building-energy model



# Calculation condition

- Target city block type: Office building district
- Weather condition: A period of consecutive fair weather summer days
- Calculation dates: August 8-10, 2002

Rooftop greening area: Three levels (0%, 50% and 100%) of roof area



- No-greening case
- 50% greening case
- 100% greening case

We set the rooftop greening assumptions to three levels of 0%, 50%, and 100% (i.e., a no-greening case, a 50% greening case, and a 100% greening case, respectively). Other parts of rooftops are set to be concrete surface.



# Framework

Input condition setting of

Calculate CO<sub>2</sub> emissions for watering when the entire amount of water needed for evapotranspiration was supplied with tap water.

The amount of water needed for evapotranspiration from the latent heat flux

CO<sub>2</sub> emission by using powering pumps and tap water

Predict surface heat balance, heat load of buildings, energy consumption due to air-conditioning, and temperature variation etc.

Calculate the CO<sub>2</sub> reduction effect from the differences in CO<sub>2</sub> emissions between the cases (each greening case versus the no-greening case).

Energy consumption for air-conditioning

CO<sub>2</sub> reduction due to air-conditioning load reduction

**Net CO<sub>2</sub> reduction by rooftop greening**

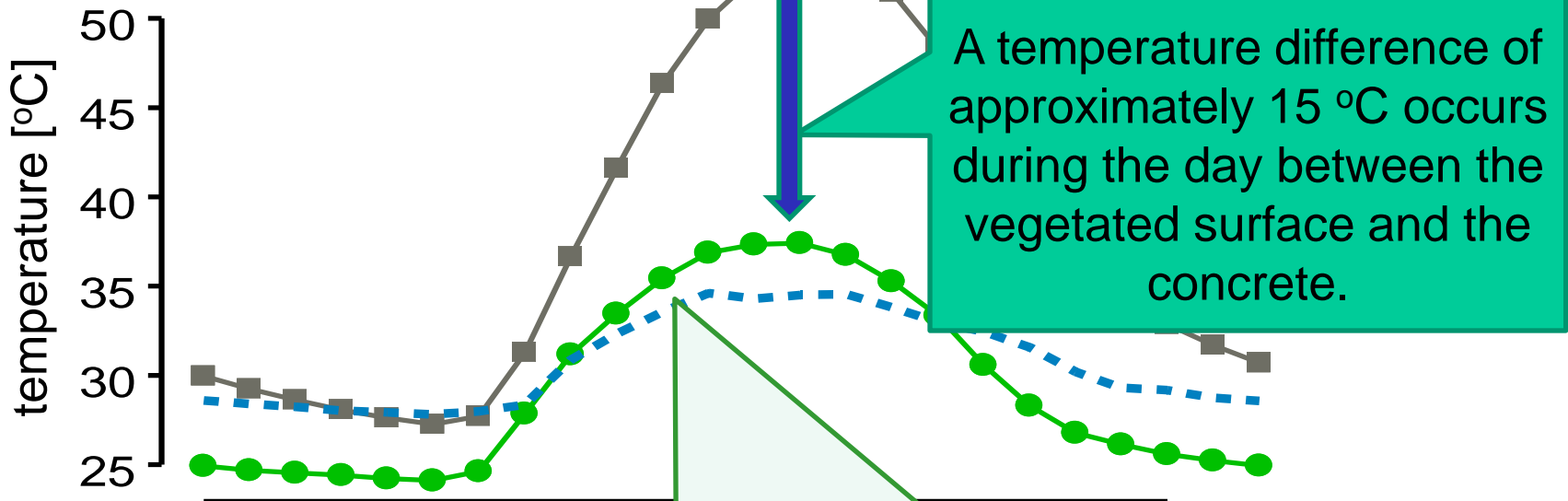
CO<sub>2</sub> Emission  
Radiation  
Surface  
Atmosphere  
Building



# Surface temperature of concrete and vegetation

The rooftop surface temperatures were calculated for the no-greening case and 100% greening case.

(For comparison, the average air temperatures for three cases at the rooftop level were also added to the illustration.)



**Concrete Surface:** Surface temperature rise to 50 °C or more during the day

**Vegetation Surface:** Almost same level as the air temperature

● Case with 100% greening (Vegetation)

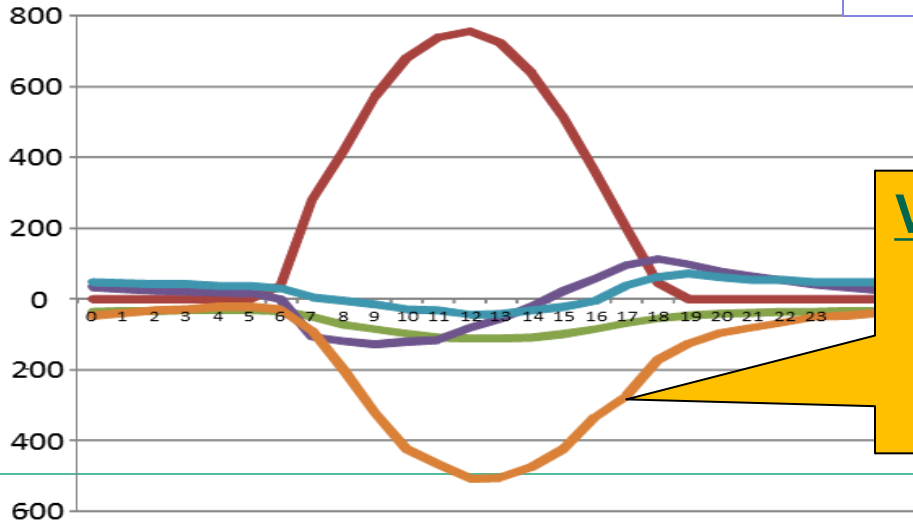
■ (concrete)  
■ temperature of 3 cases

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# Surface heat balance on rooftop surface

## Vegetation Surface

The direction in which heat enters the surface was taken to be positive.



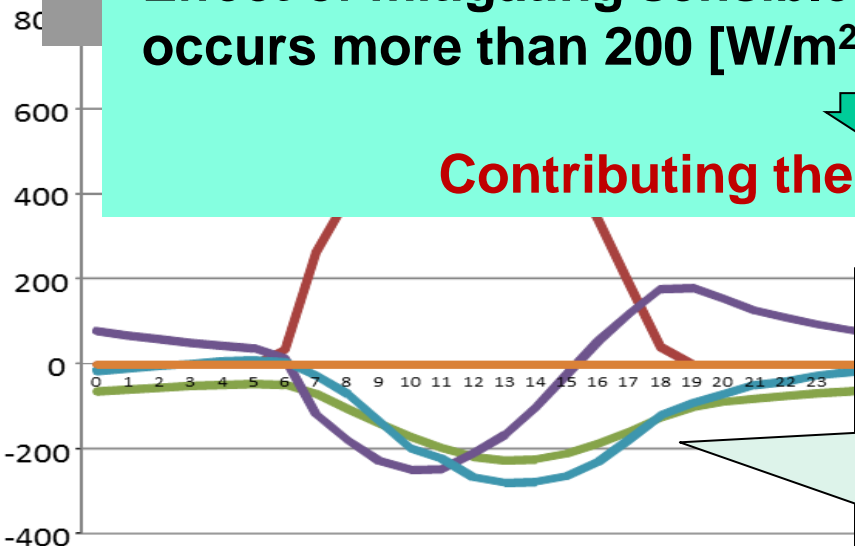
— Short wave radiation

**Vegetation Surface**: About half of the net radiation is released into the atmosphere as latent heat flux.

Effect of mitigating sensible heat flux during a day time occurs more than 200 [W/m<sup>2</sup>] by rooftop greening.



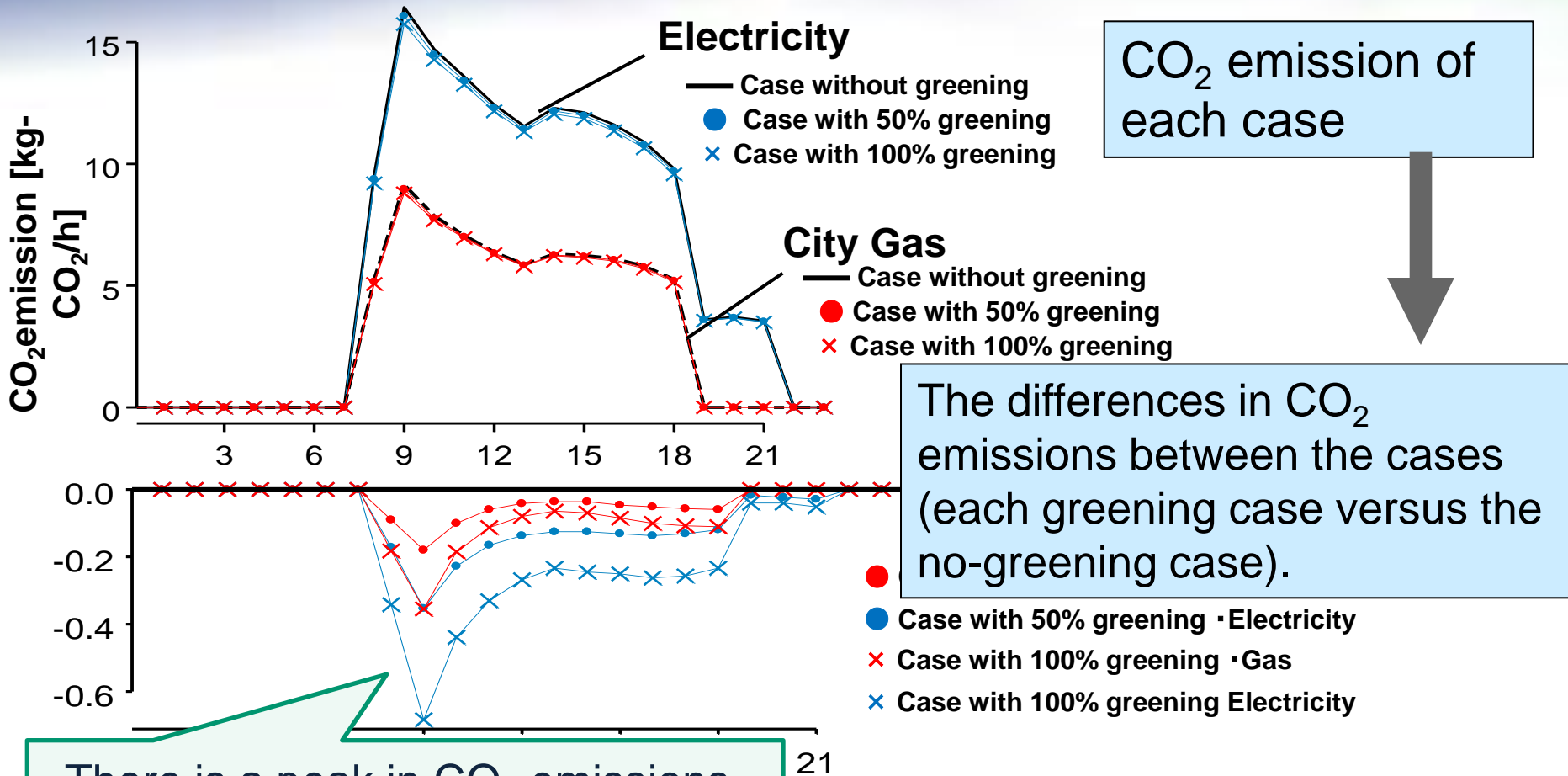
**Contributing the heat island mitigation**



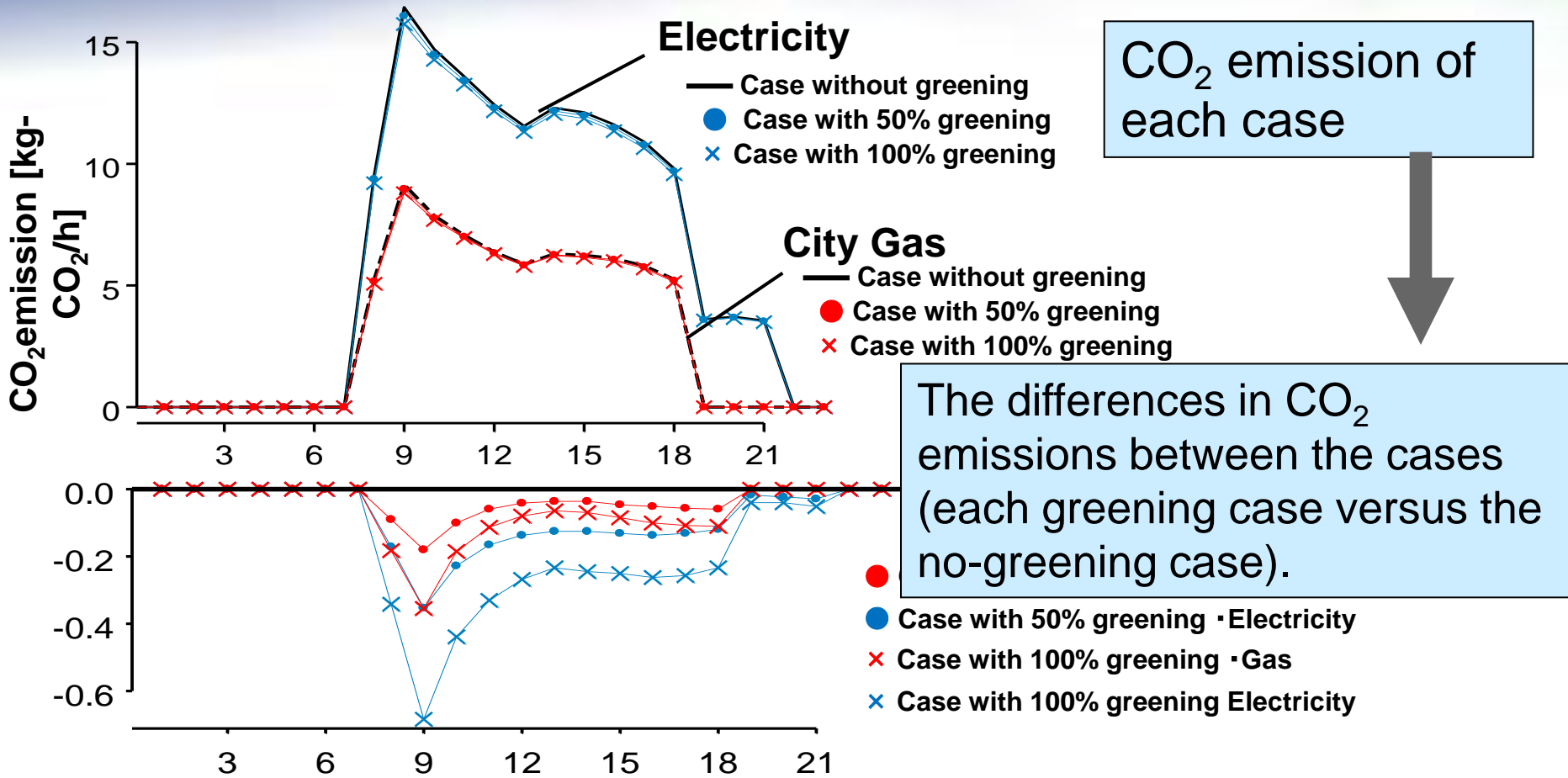
— Heat conduction

**Concrete Surface**: The sensible heat flux and the long wave radiation increase since the latent heat flux does not occur.

# CO<sub>2</sub> reduction by cooling energy saving



# CO<sub>2</sub> reduction by cooling energy saving

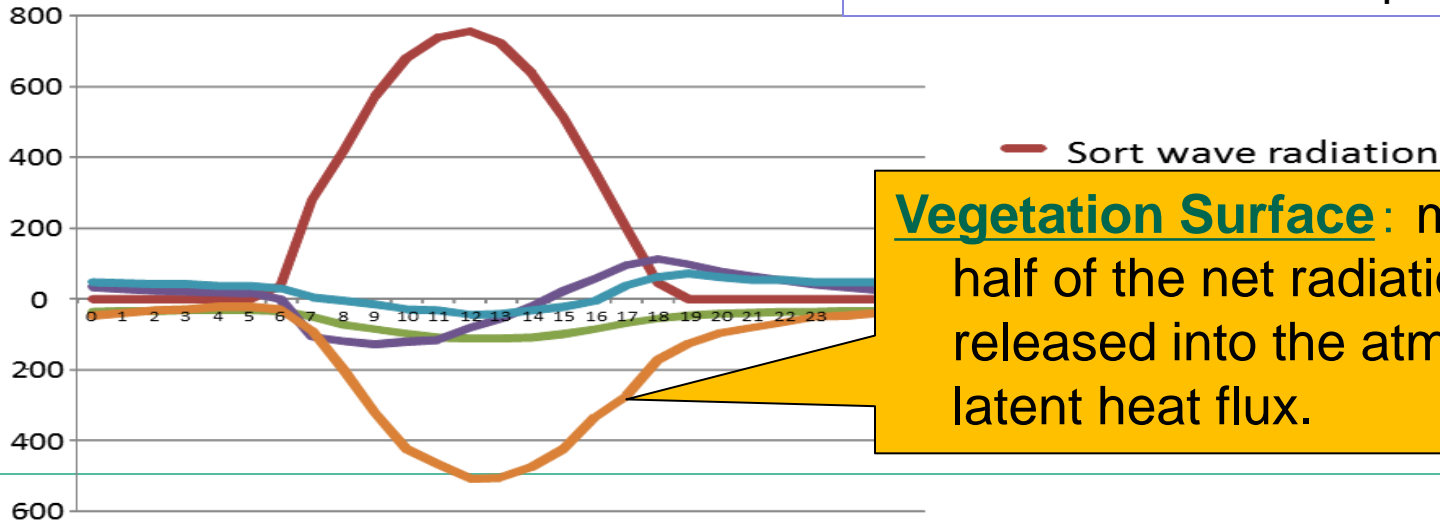


In terms of daily cumulative values, the CO<sub>2</sub> reduction effect was 2.93 kg-CO<sub>2</sub>/day in the 100% greening case and 1.47 kg-CO<sub>2</sub>/day in the 50% greening case.

# Surface heat balance on rooftop surface

## Vegetation Surface

The direction in which heat enters the surface was taken to be positive.

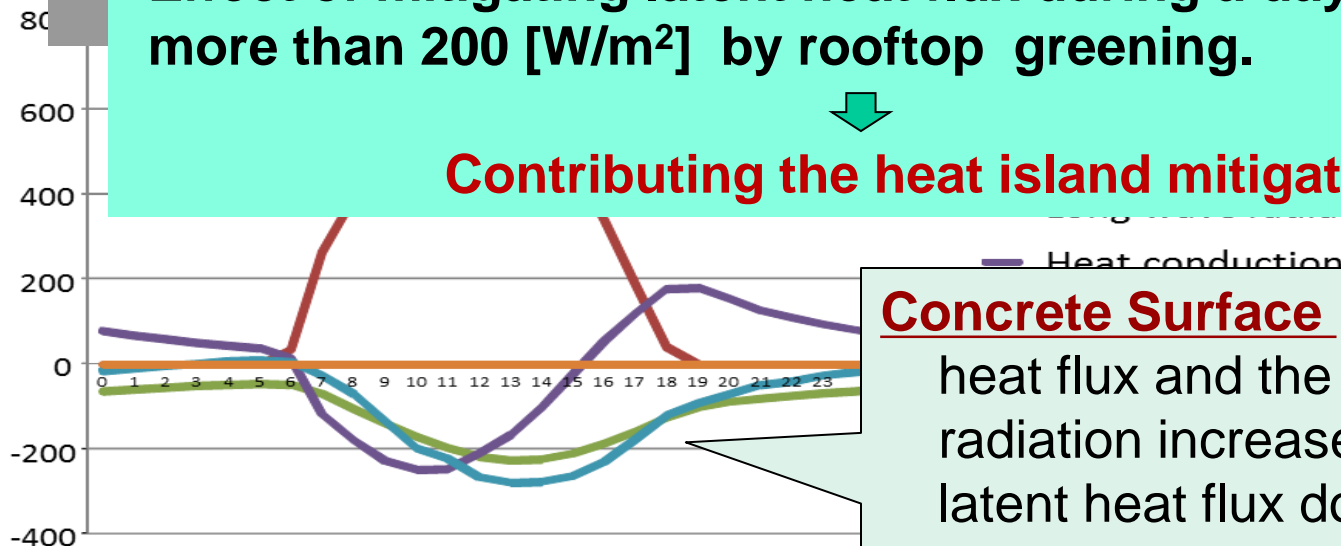


**Vegetation Surface**: more than half of the net radiation is released into the atmosphere as latent heat flux.

Effect of mitigating latent heat flux during a day time occurs more than 200 [W/m<sup>2</sup>] by rooftop greening.



**Contributing the heat island mitigation**

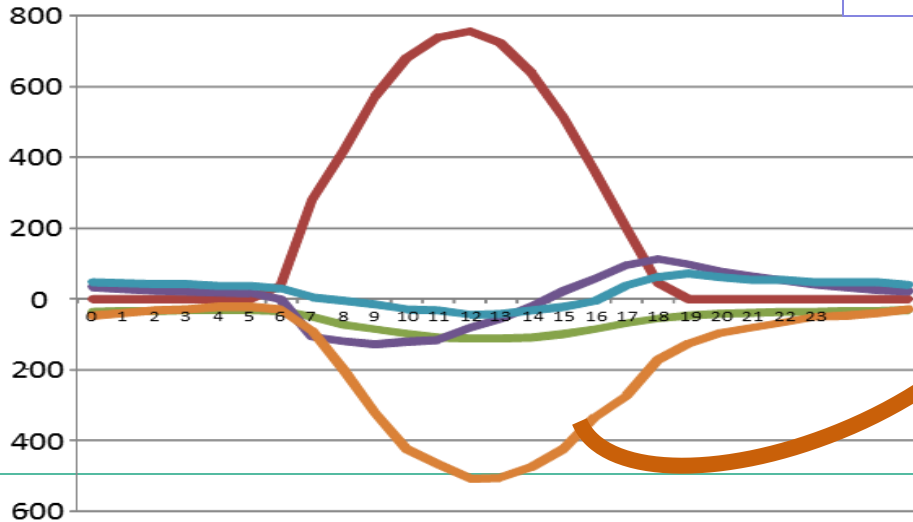


**Concrete Surface**: The sensible heat flux and the long wave radiation increase since the latent heat flux does not occur.

# Surface heat balance on rooftop surface

## Vegetation Surface

The direction in which heat enters the surface was taken to be positive.



The amount of water needed for evapotranspiration from the latent heat flux.

— Latent heat flux

CO<sub>2</sub> emission by using powering pumps and tap water.

## Concrete Surface

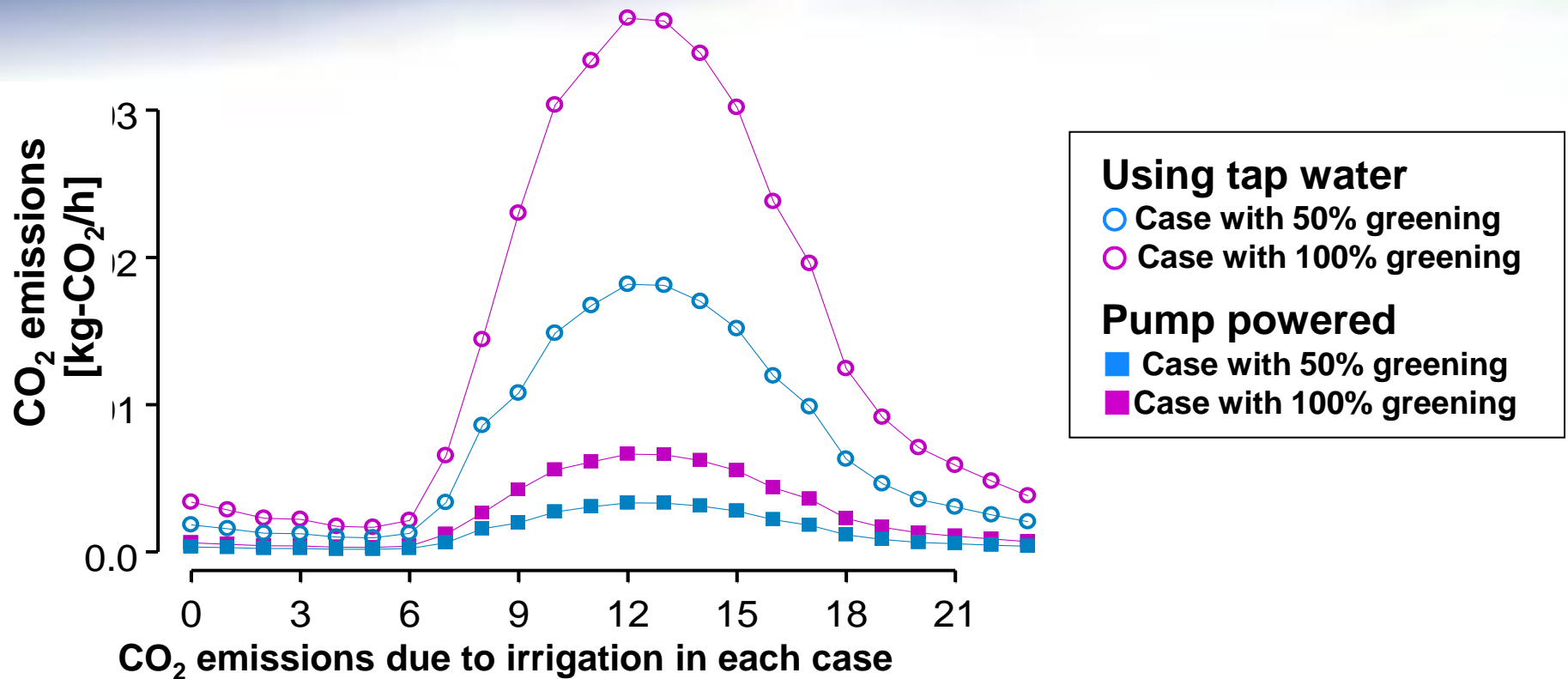


Tap water: Calculation was done with CO<sub>2</sub> emissions of 0.193 [kg-CO<sub>2</sub>/m<sup>3</sup>] for tasks such as water purification, delivery and distribution

Pump power: Pump power was calculated by setting pump efficiency to 0.6, and letting the rooftop height be the lifting height.

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# CO<sub>2</sub> emissions due to watering



## CO<sub>2</sub> emissions due to powering pumps;

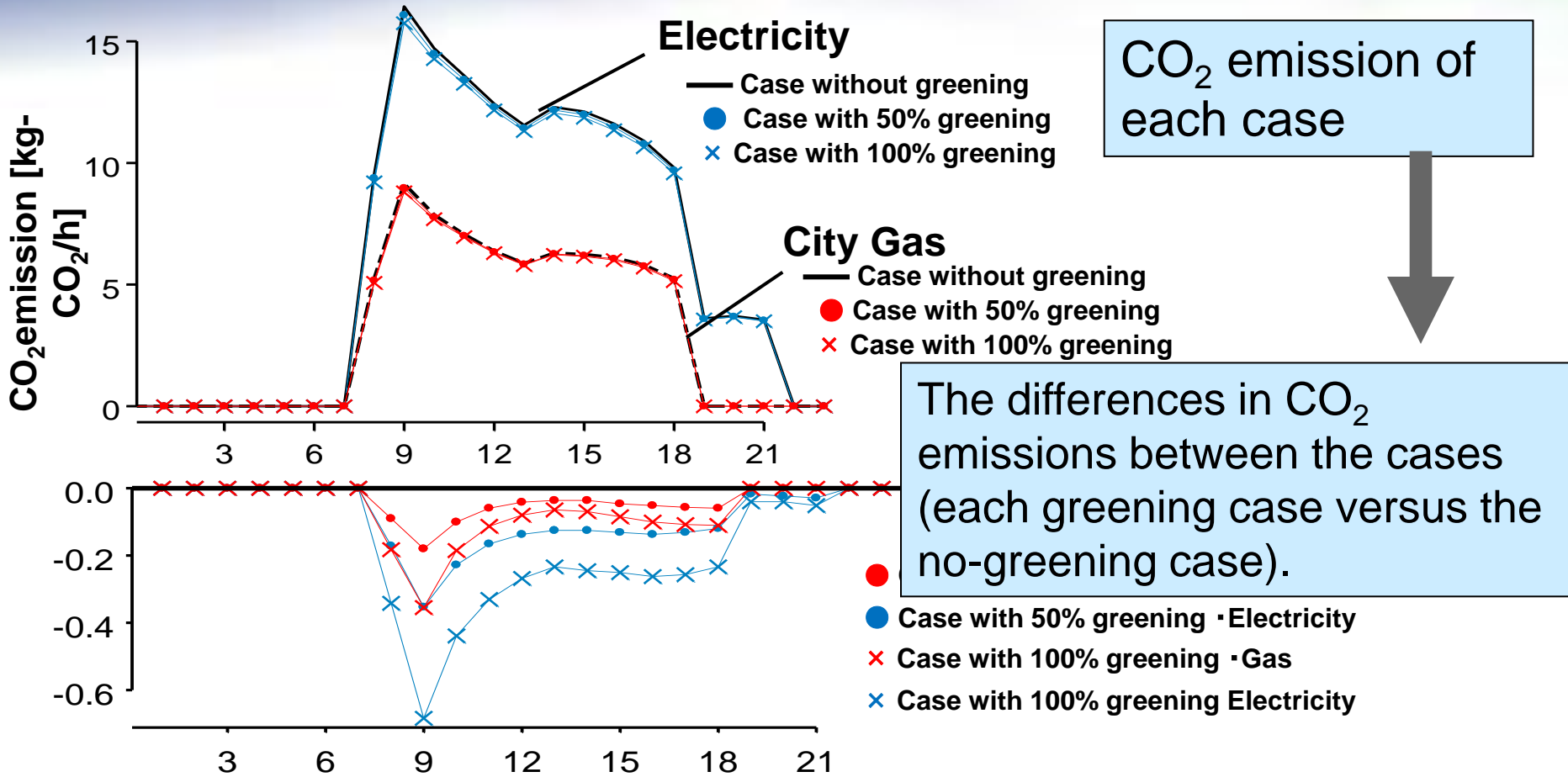
- Case with 100% greening : 0.064[kg-CO<sub>2</sub>/Day]
- Case with 50% greening : 0.032[kg-CO<sub>2</sub>/Day]

## CO<sub>2</sub> emissions due to the use of tap water

- Case with 100% greening : 0.35[kg-CO<sub>2</sub>/Day]
- Case with 50% greening : : 0.18[kg-CO<sub>2</sub>/Day]

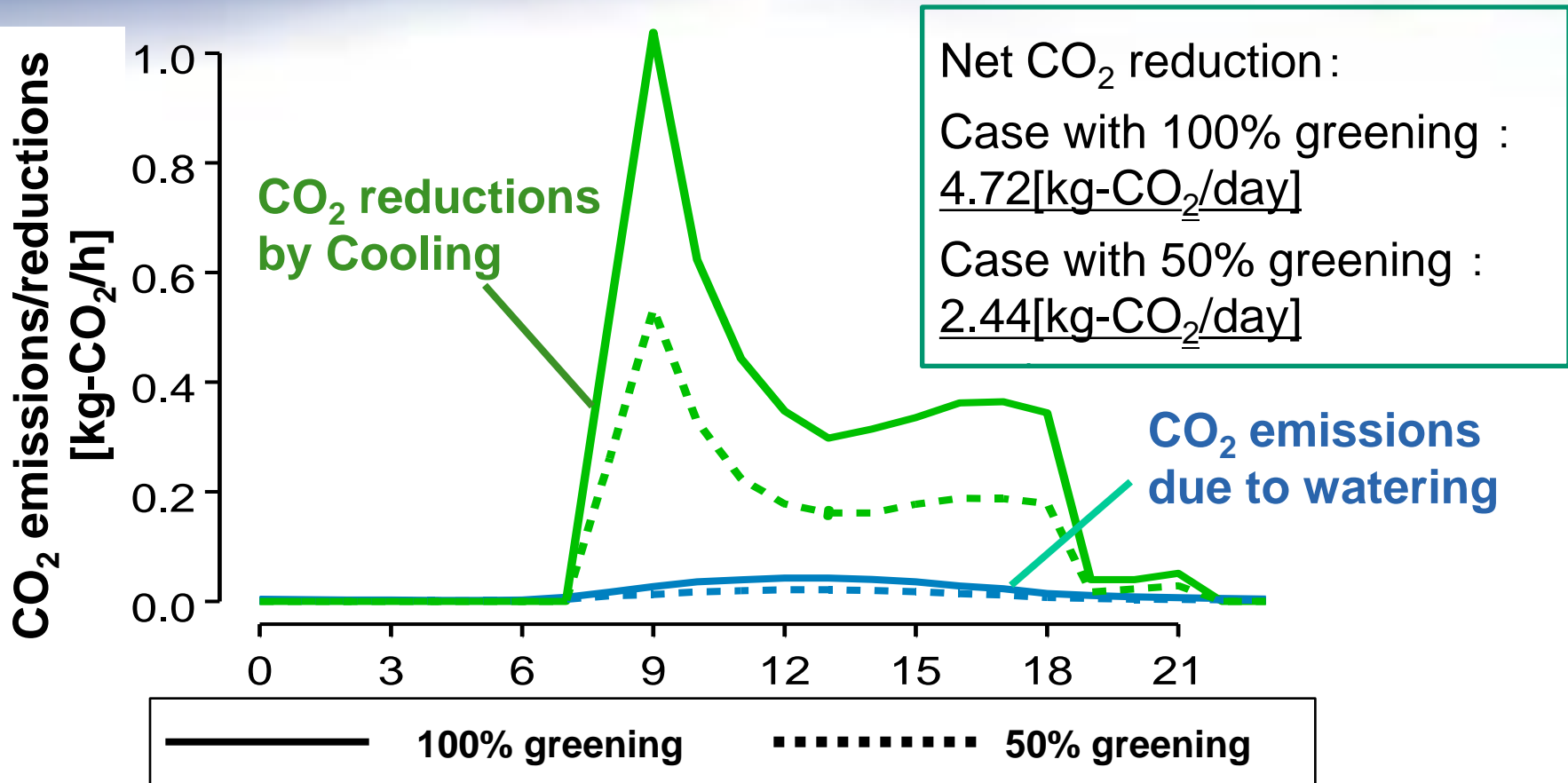


# CO<sub>2</sub> reduction by cooling energy saving



In terms of daily cumulative values, the CO<sub>2</sub> reduction effect was 2.93 kg-CO<sub>2</sub>/day in the 100% greening case and 1.47 kg-CO<sub>2</sub>/day in the 50% greening case.

# CO<sub>2</sub> reductions due to rooftop greening



CO<sub>2</sub> reduction due to cooling energy is clearly greater than CO<sub>2</sub> emissions due to watering.

The CO<sub>2</sub> reduction effect can be obtained using rooftop greening even when taking into account CO<sub>2</sub> emissions due to watering.

# Conclusion

This research evaluated the effectiveness of rooftop greening for mitigating urban heat island conditions and reducing CO<sub>2</sub> emissions while taking into account the amount of water needed for evapotranspiration.

In this research, a coupled urban-canopy and building-energy model was used to carry out simulations.



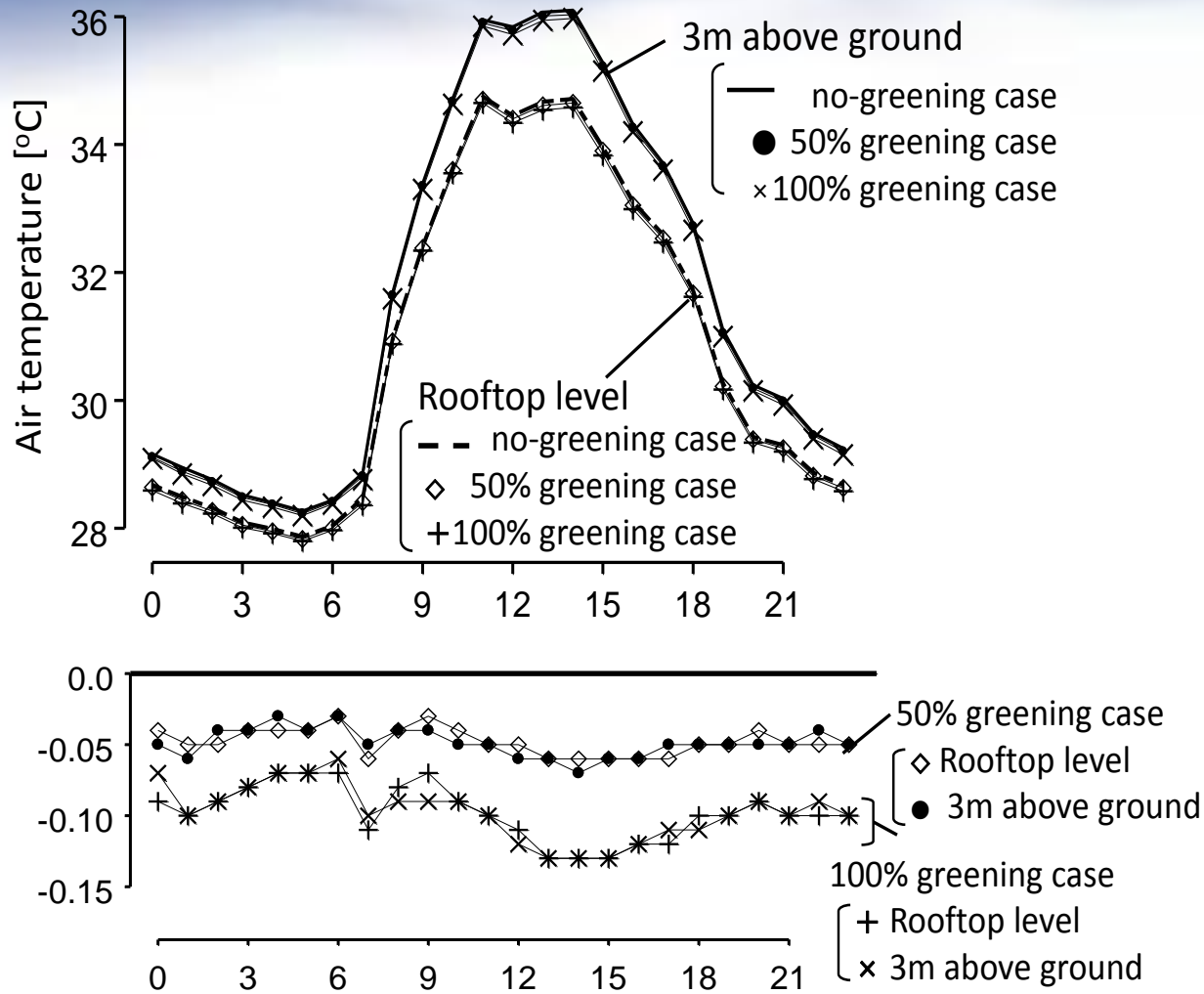
The CO<sub>2</sub> reduction effect of rooftop greening was evaluated. In particular, this evaluation was carried out by taking into account both the CO<sub>2</sub> reductions that resulted from the decreases in surface temperatures and cooling energy and the CO<sub>2</sub> emissions associated with watering. The data showed that the former was clearly greater in terms of direct effects. Thus, a CO<sub>2</sub> reduction effect can be achieved in buildings where rooftop greening is adopted.

One future research direction should be to incorporate a detailed water balance model that takes into account precipitation and the water retention effectiveness of the soil layer.

**Thank you very much for your kind attention.**

Table 1: Summary of calculation conditions for standard case

Temperature setting for cooling (°C)	26.0
Humidity setting for cooling (relative humidity: %)	50.0
Total transmission of solar insolation at window surface (-)	0.3
Amount of outside air introduced per unit floor area (m <sup>3</sup> /m <sup>2</sup> /h)	3.0
Position of air vent (for introducing outside air)	Each floor
Occupied floor area per person present indoors (m <sup>2</sup> /person)	10.0
Air-conditioned area as a percentage of building total floor area (-)	0.75
Heat produced by human bodies per unit floor area (W/m <sup>2</sup> )	Sensible heat: 6.27 Latent heat: 5.34
Building floor height (m/floor)	3.5
Thermal transmittance of outer walls (W/m <sup>2</sup> /K)	0.68
Heat capacity per unit cross-sectional area of outer walls (J/m <sup>2</sup> /K)	3.11×10 <sup>5</sup>
Heat source system, heat source equipment breakdown percentages	Electric heat pump: 66.9% Absorption type (City gas) : 33.1%



***Fig. 2 (top) Temperature in each case scenario, and (bottom) the temperature differences for those cases (i.e., each case with greening - each case without greening).***

Rooftop greening area:  
Three levels (0%, 50% and  
100%) of roof area

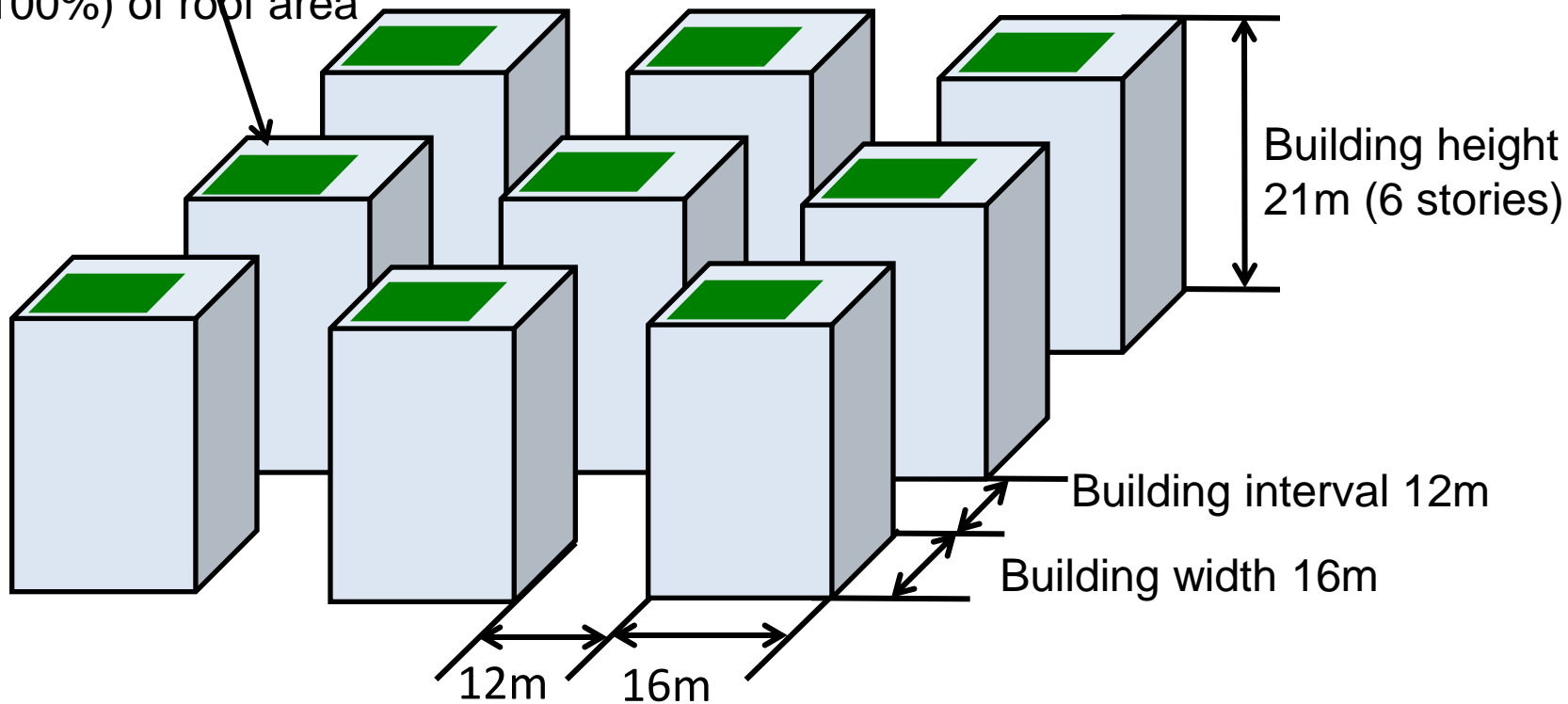


図-1 本研究における建物モデルの設定

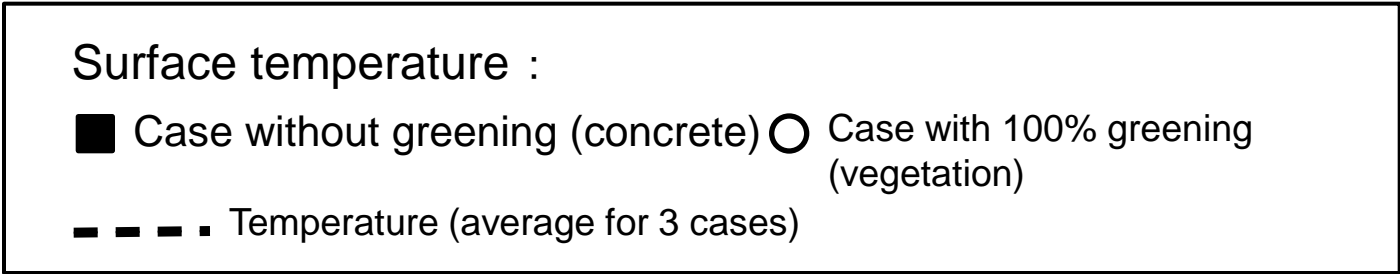
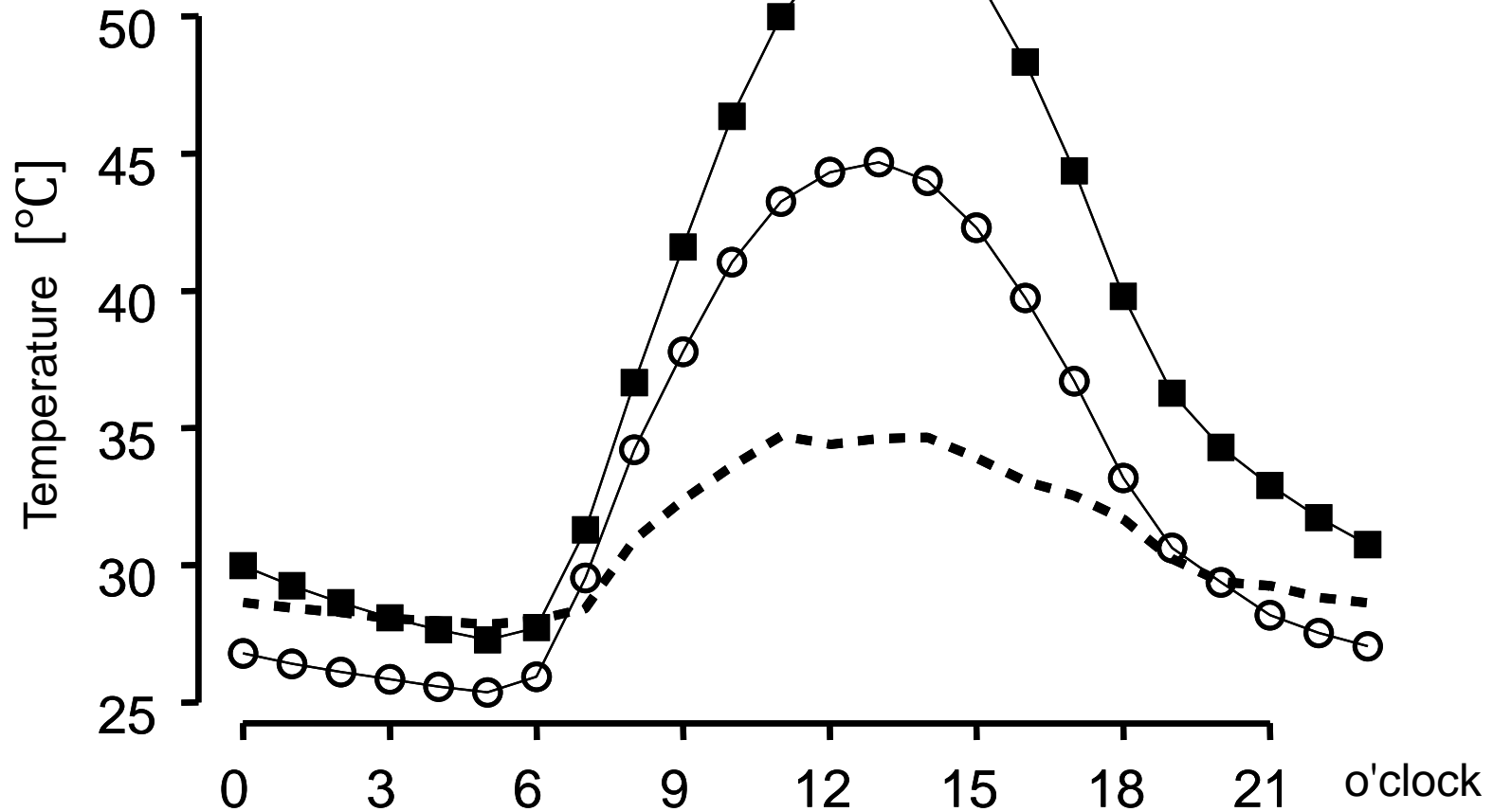
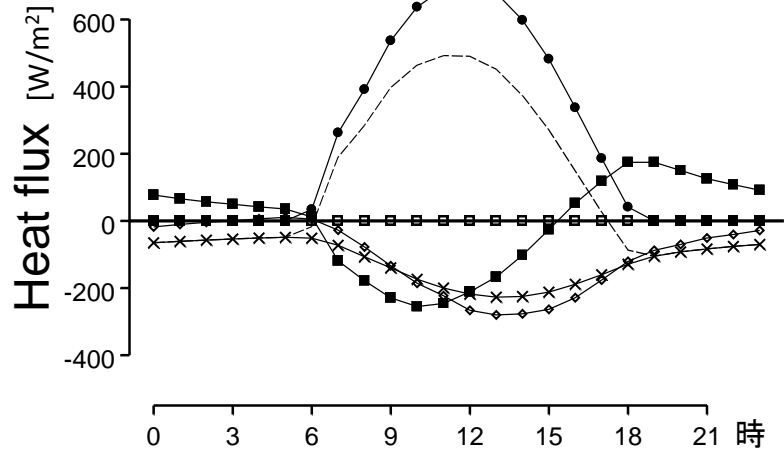


図2 屋上におけるコンクリートおよび植生の表面温度



(a) Case without greening (concrete)



(b) Case with 100% greening (vegetation)

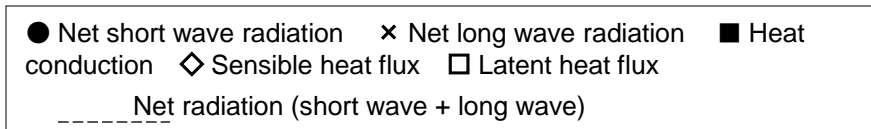
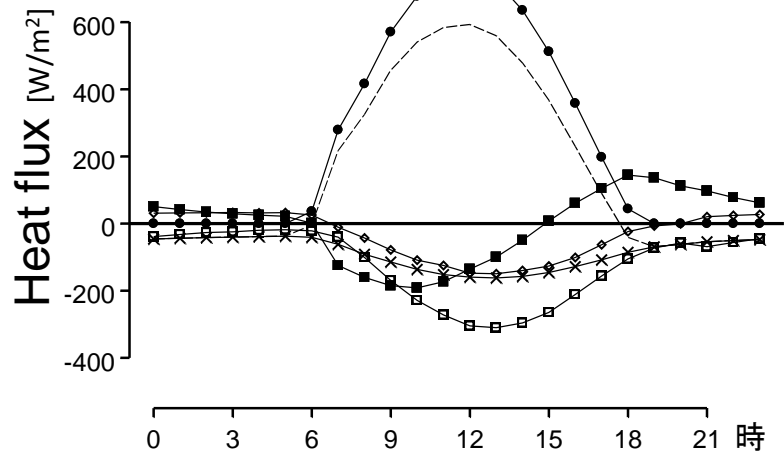


図3 屋上面における表面熱収支

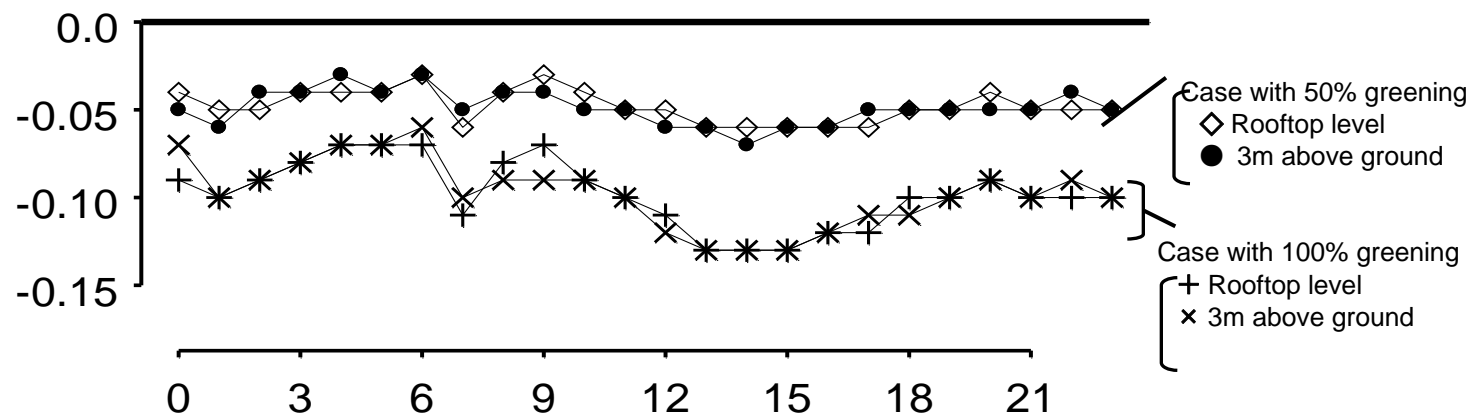
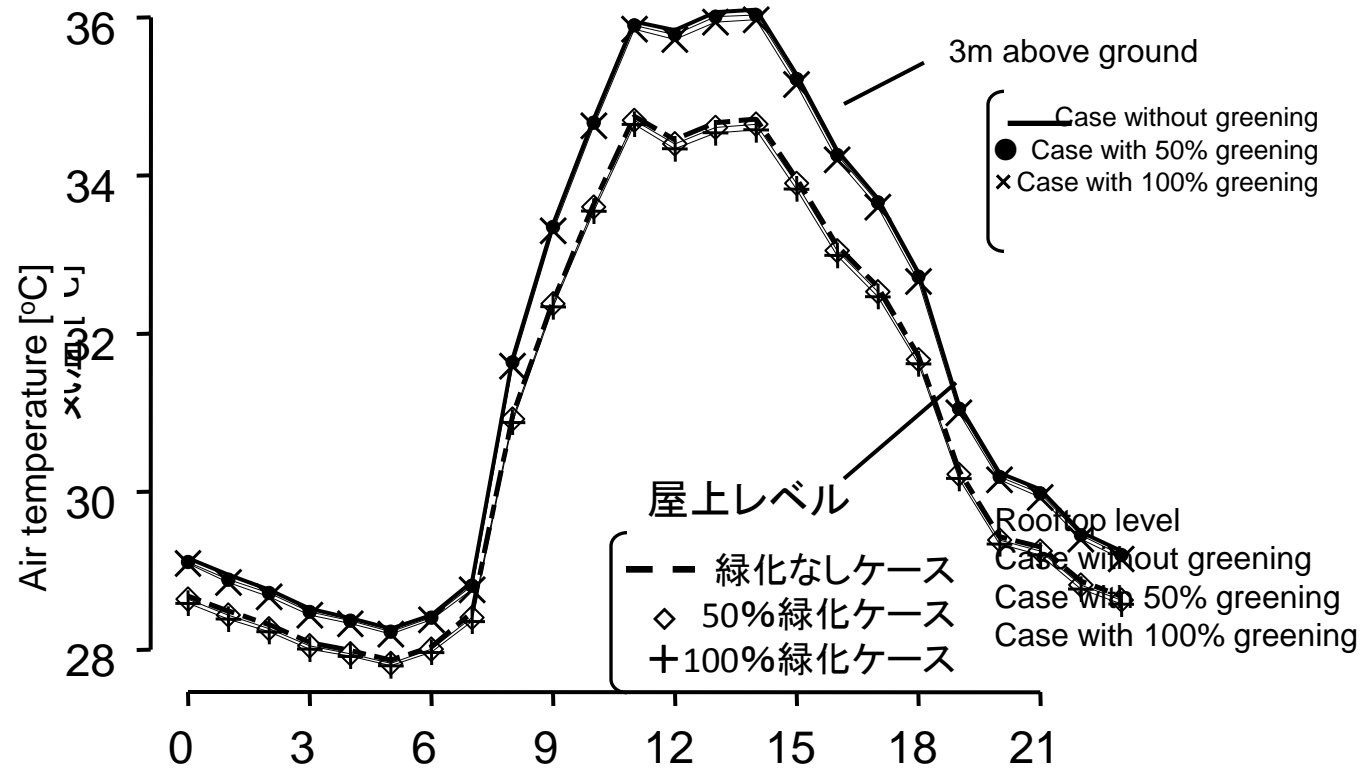


図4 各ケースにおける気温およびその緑化なしケースとの差

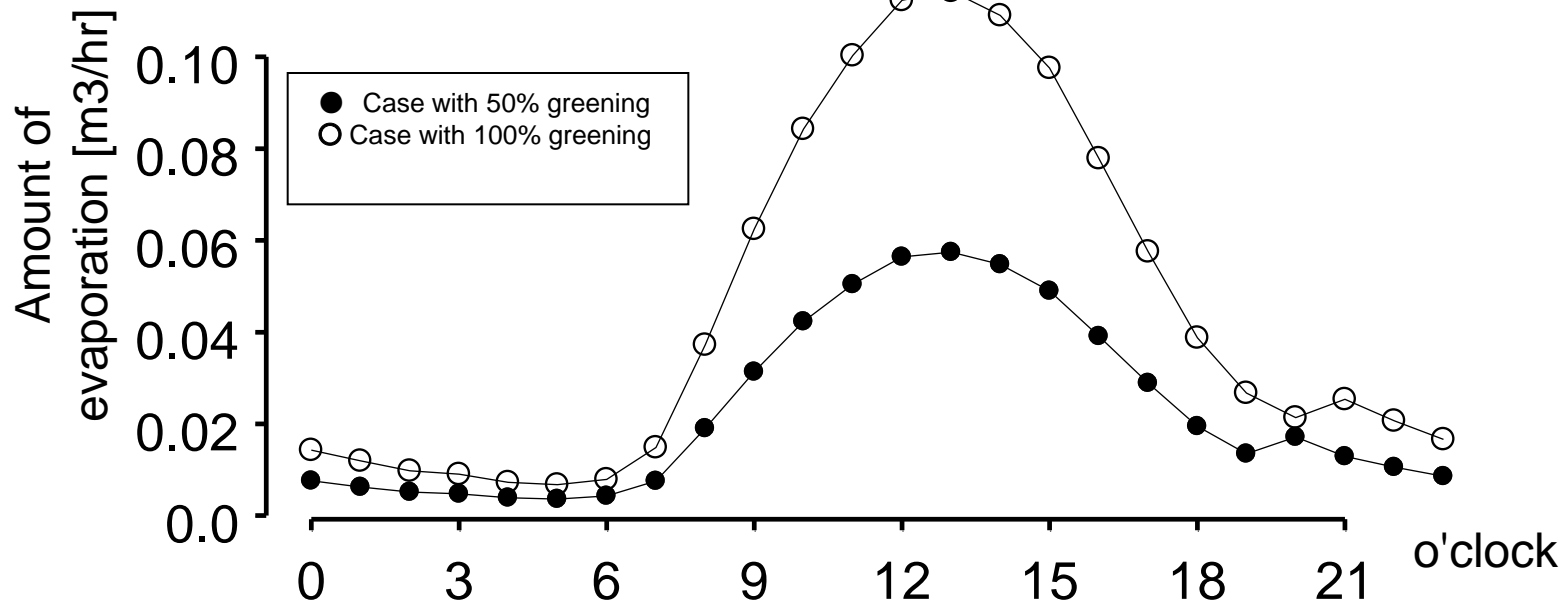


図5 各緑化ケースにおける蒸発量

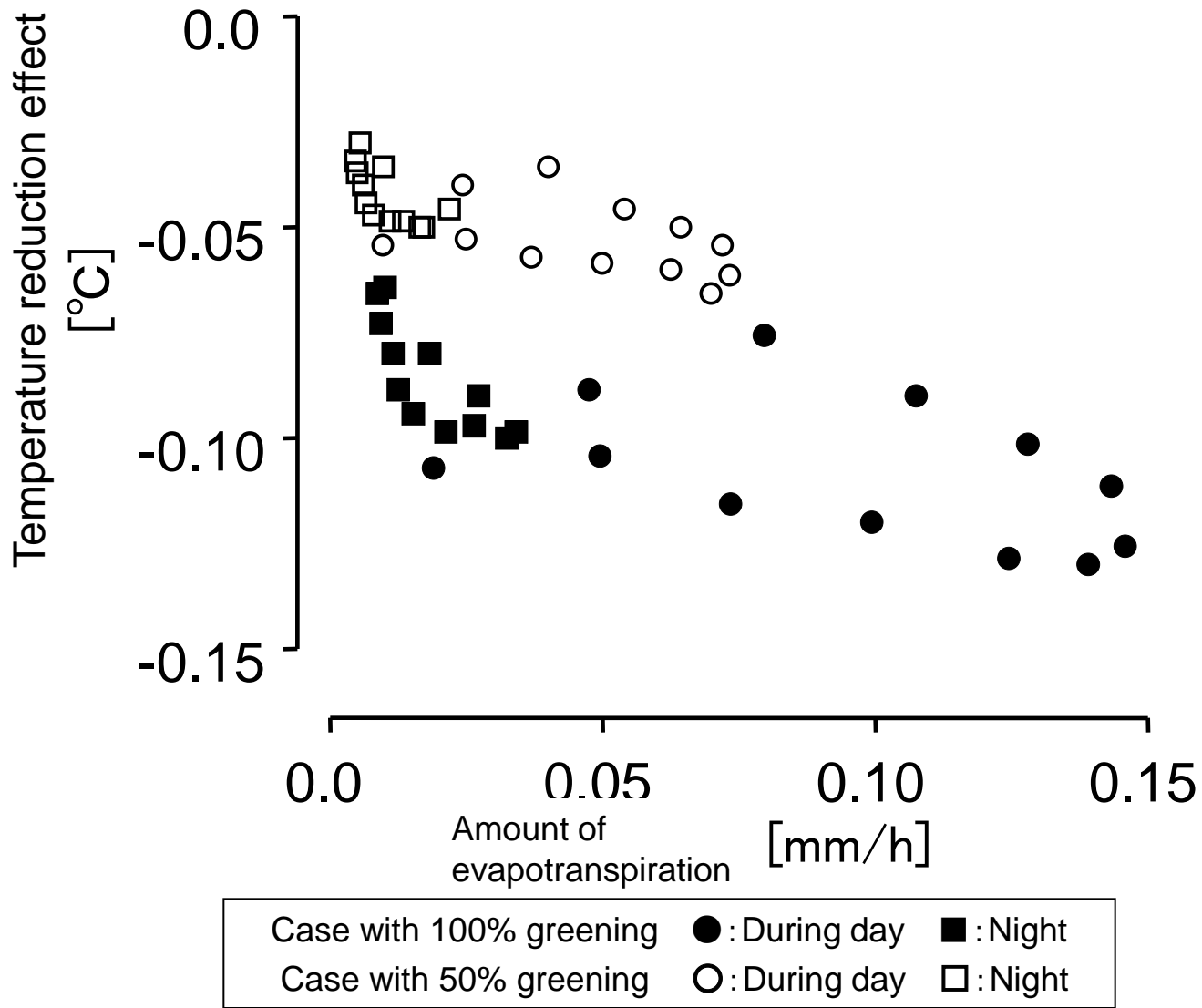


図6 蒸発散量と気温低下効果の関係

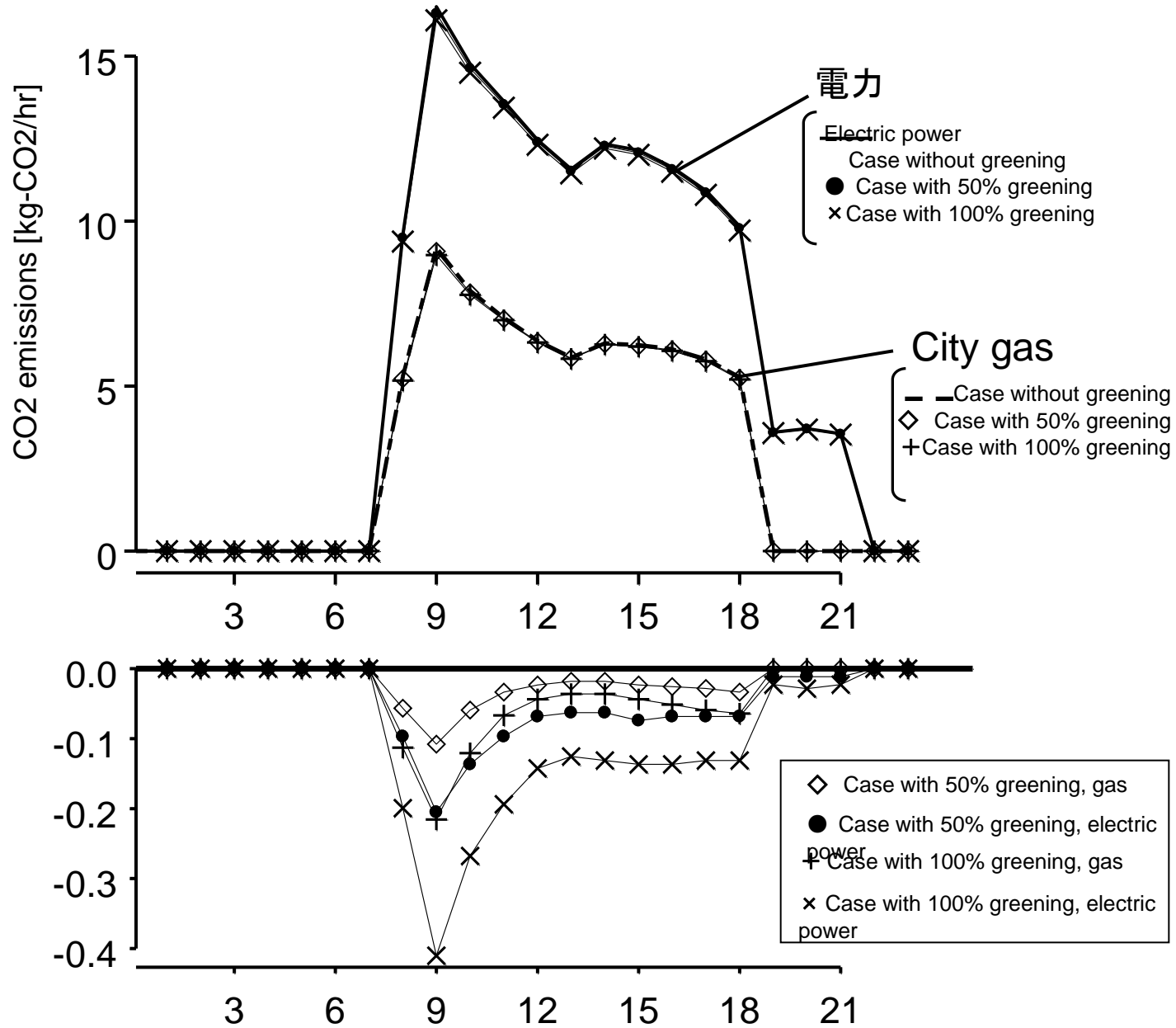
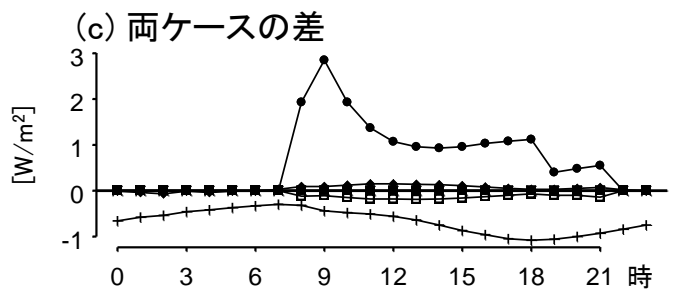
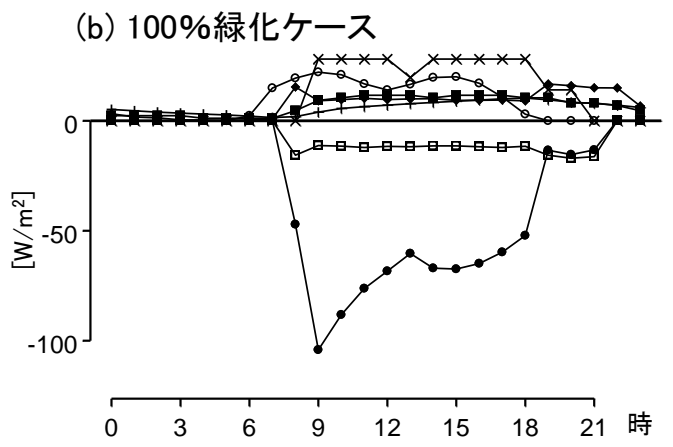
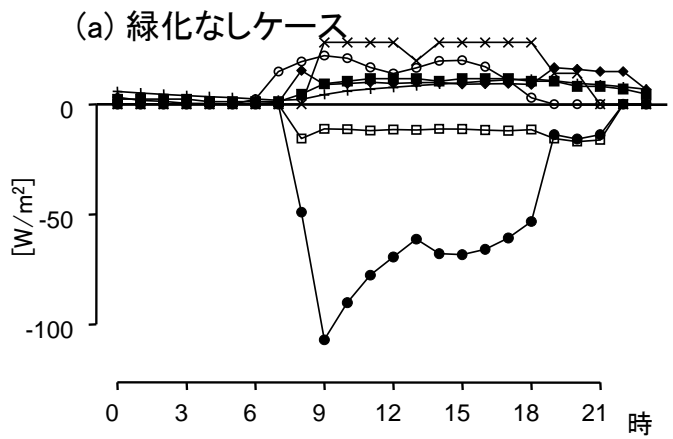


図7 各ケースにおけるCO<sub>2</sub>排出量およびその緑化なしケースとの差



+ : Transmitted heat from roof and walls  
 ○ : Transmitted solar insolation at window surface  
 ◆ : Heat introduced through ventilation heat  
 × : Heat produced by equipment etc.  
 ■ : Heat produced by human bodies  
 ● : Removed sensible  
 □ : Removed latent heat

(a) Case without greening  
 (b) Case with 100% greening  
 (c) Difference between two cases

図8 緑化なしケースおよび100%緑化ケースにおける室内熱収支の計算結果および両ケースの差

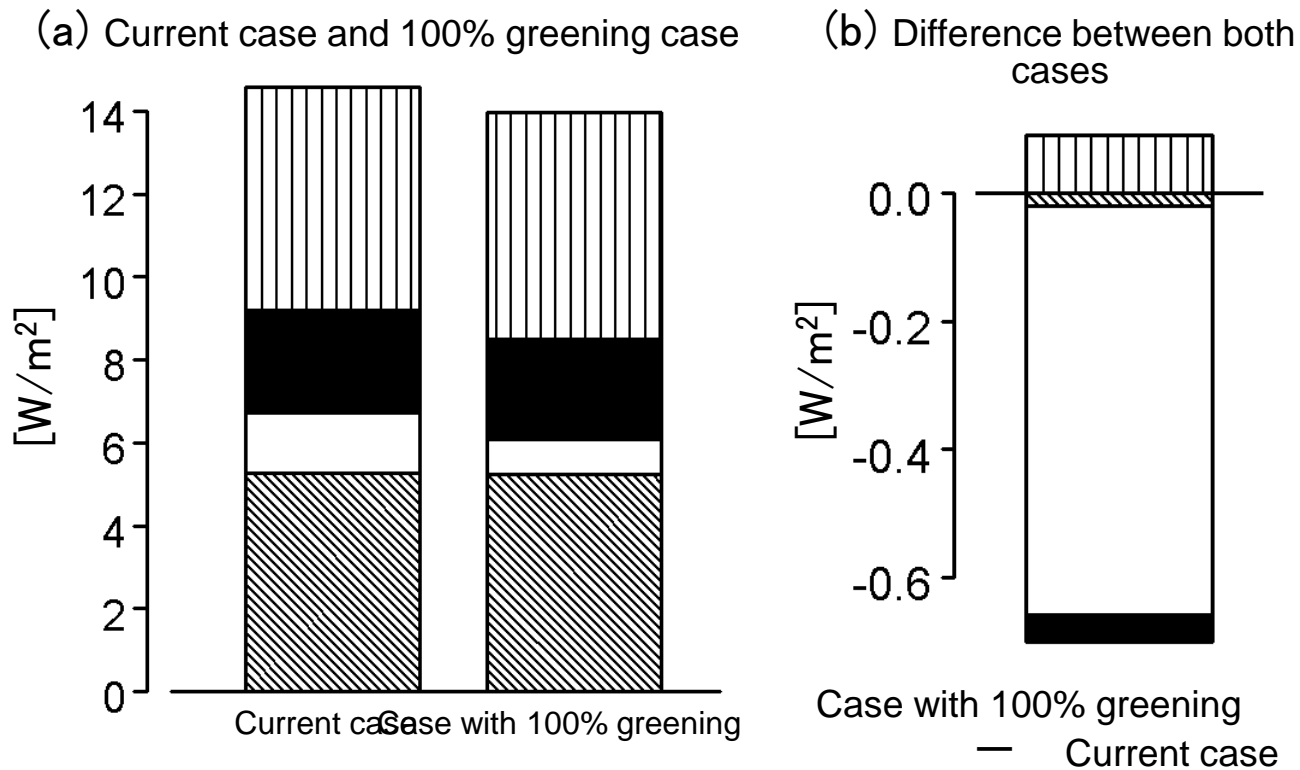


図9 貫流熱および換気侵入熱の詳細比較(日平均, 床面積あたり)

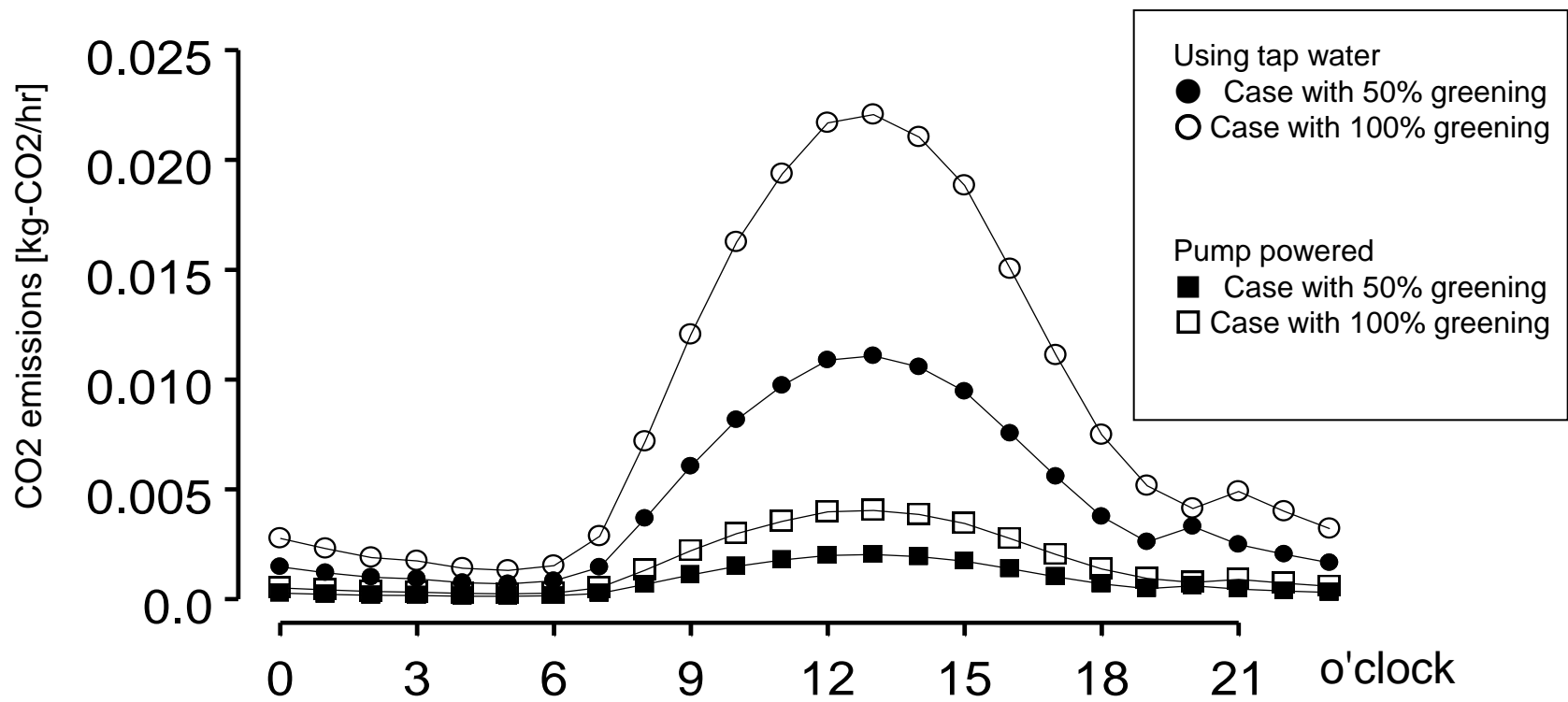
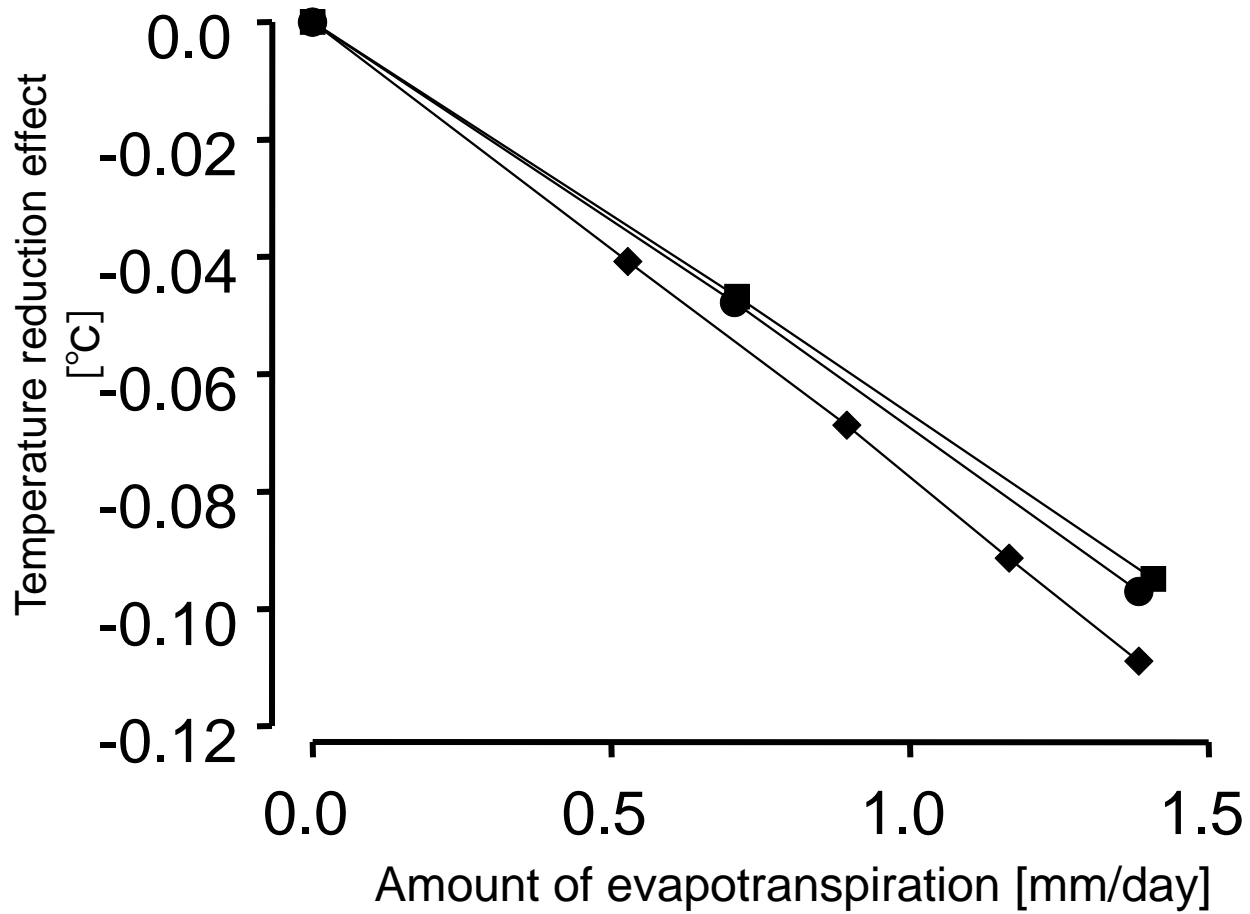


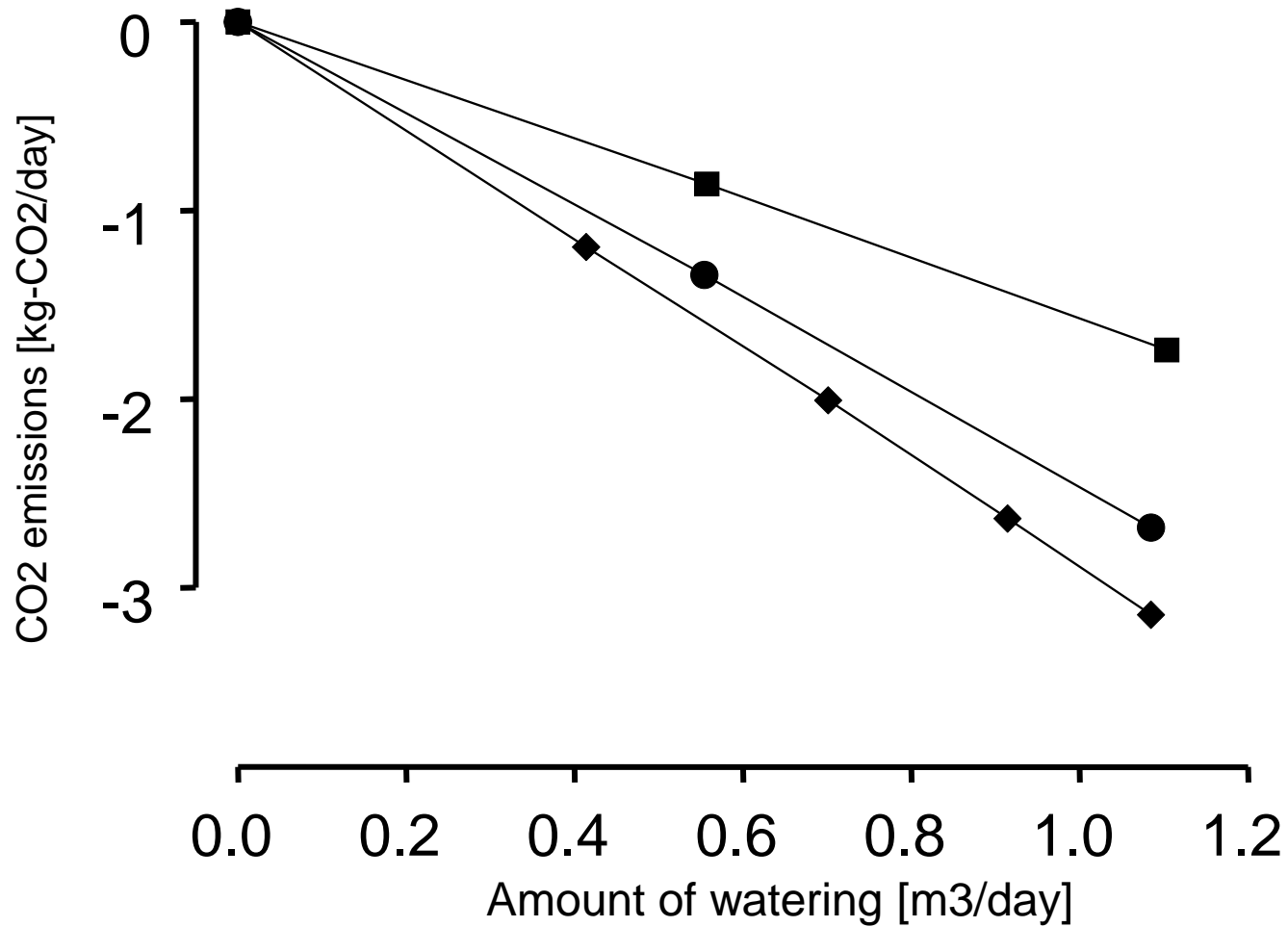
図10 各ケースにおける灌水によるCO<sub>2</sub>排出量





● : Standard conditions    ■ : Highly insulated conditions  
◆ : Conditions with reduced evaporation efficiency

図11 蒸発散量と気温低下効果の関係



● : Standard conditions    ■ : Highly insulated conditions  
 ◆ : Conditions with reduced evaporation efficiency

図12 散水量とCO2削減量の関係(1棟あたり)