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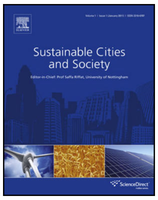

Assessing the effects of CO_2 reduction strategies on heat islands in urban areas

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ABSTRACT

There has been a wide range of low-carbon solutions proposed to mitigate climate change. However, such measures must be compatible with the local environment and living standards of residents to be brought to fruition. Measures that adversely affect residential environments will be difficult to implement, so the impacts of measures on the local environment must be taken into consideration during implementation. This study assessed the effects on urban heat islands of efforts to reduce CO_2 emissions, as one environmental impact associated with climate change. A simulated assessment was conducted, using an urban canopy model coupled with a building energy model (CM-BEM), to evaluate the effects of five specific measures: solar shading of windows using curtains and blinds, improvement of the thermal insulation of building walls and roof surfaces, implementation of energy-saving measures related to indoor appliances, installation of solar photovoltaic (PV) panels, and adjustment of preset cooling temperatures. The study focused on these effects as they occur within typical urban districts of office buildings, fire-resistant housing, and wooden housing. Results indicated that many of the energy-saving measures have slight temperature lowering effects, but solar panel installation and improved heat insulation, both associated with changes in surface heat balances, tend to raise daytime temperatures to some extent. However, effects on daytime temperatures were in the range of 0.1–0.2 °C and, as such, none of the CO_2 reduction measures considered was deemed a significant factor in raising urban temperatures.

1. Introduction

The need to reduce CO_2 emissions from daily activities has increased in urgency as global warming has become more severe (Murakami et al., 2006; “2050 Japan Low-Carbon Society” Scenario Team, 2009). Recent years have seen an increase in proposals to improve energy efficiency and introduce renewable energy technologies; however, atmospheric concentrations of CO_2 have continued to rise (World Data Centre for Greenhouse Gases, 2015) and further efforts to reduce emissions are required to stabilize the climate system. Following the Great East Japan Earthquake and subsequent tsunami disaster, Japan faces additional and important policy challenges, associated with securing stable energy supplies during disasters as well as lowering peak electricity demand, due to the shutdown of its nuclear power plants. This has led to an increased focus on the creation of regional distributed energy networks and the introduction of renewable energy technologies. However, numerous energy-saving proposals have proven extremely difficult to implement and current CO_2 reductions are far from adequate. Indeed, beyond the effects of the recent global financial crisis and the Great East Japan Earthquake, Japan's business and household sectors have seen an increase in CO_2 emissions during the 20 years since the signing of the UN Framework Convention on Climate Change (National Institute for Environmental Studies, 2015).

These circumstances call for proposals to reduce CO_2 emissions and for concrete research into how such reductions can be realistically achieved. Toward this end, it is our belief that responses to climate change that seek to protect the environment for future generations should align with proposals for urban environments that appeal to the current generation. Regardless of whether a specific CO_2 reduction measure benefits future generations, relevant decisions are made by the current generation such that any measures adversely affecting residential environments will be difficult to implement. Accordingly, the introduction of any measure must consider not only the future global environment but also

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any potential impacts on the immediate environment. Informed by this perspective, this study explored a co-benefit model of urban planning that balances CO_2 reductions with the comfort and convenience of residents in their immediate surroundings.

One particularly important aspect when considering this level of comfort relates to combating rising temperatures associated with increased urbanization, or, in other words, the heat island phenomenon (Ichinose, 2005; Rizwan, Dennis, & Liu, 2008; Santamouris, 2015). In Japan, with its blistering summer temperatures, heat islands are associated with a number of serious problems that require constant attention, such as increased energy consumption for air conditioning and peak electricity demand and discomfort caused by heat, heatstroke, and sleeping disorders. While it is widely known that increasing the albedo of buildings helps to prevent heat islands (Akbari & Matthews, 2012; Akbari, Konopacki, & Pomerantz, 1999; Akbari, 2003; Costanzo, Evola, Marletta, & Gagliano, 2014; Cotana et al., 2014; Georgakis, Zoras, & Santamouris, 2014; Kolokotsa, Diakaki, Papantoniou, & Vlissidis, 2011; Porritt, Cropper, Shao, & Goodier, 2012; Pisello, Rossi, & Cotana, 2014; Synnefa & Santamouris, 2012; Synnefa, Saliari, & Santamouris, 2012; Zinzi & Agnoli, 2012), installing solar photovoltaic (PV) panels, which have a low surface albedo, as a means to reduce CO_2 emissions may in fact exacerbate heat island effects. On these occasions, it is important to design for a comfortable urban environment by estimating the potential impacts on temperature, while avoiding – as much as possible – any negative effects on the thermal environment. Nonetheless, there is significant capacity for energy efficiency measures in urban settings to alleviate heat island effects from anthropogenic heat, in addition to achieving reductions in CO_2 emissions. If such impacts can be made achievable, then these measures should be actively introduced for their co-beneficial effects. This is important not only to improve the immediate environment of residents, but also to increase the feasibility of measures to reduce CO_2 emissions.

In terms of research related to heat islands, many studies have looked at the relationship between energy consumption and the outdoor thermal environment. However, most of these studies have sought to explain the effects of anthropogenic heat, caused by conventional energy consumption, on urban heat islands (Boehme, Berger, & Massier, 2015; Chen, Yang, & Zhu, 2014; Ichinose, Shimodozono, & Hanaki, 1999; Kimura & Takahashi, 1991), or the effects that heat islands have on the consumption of energy for air conditioning (Assimakopoulos, Mihalakakou, & Flocas, 2007; Hassid et al., 2000; Hirano & Fujita, 2012; Santamouris et al., 2001; Santamouris, Cartalis, Synnefa, & Kolokotsa, 2015; Santamouris, 2014). Previous studies have not evaluated the effects on heat islands of specific CO_2 reduction measures implemented to tackle global warming. Furthermore, while research has been carried out on urban heat island mitigation measures, with the aim of improving energy efficiency or reducing CO_2 emissions, the majority of this research has concentrated on measures to lower the energy consumption associated with air conditioning (Akbari, Pomerantz, & Taha, 2001; Akbari, 2002; Akbari & Konopacki, 2004, 2005; Rosenfeld, Akbari, Romm, & Pomerantz, 1995; Rosenfeld, Akbari, Romm, & Pomerantz, 1998; Taha, Akbari, Rosenfeld, & Huang, 1988; Sailor & Dietsch, 2007; Taha, Konopacki, & Gabersek, 1999). The direct effects of heat island mitigation measures, in terms of reducing air conditioning energy consumption as well as CO_2 emissions, are, of course, significant. Nonetheless, as mentioned, for a successful implementation it is essential that these measures be incorporated into broader CO_2 reduction strategies as a means to improve the lives of local residents. Existing studies do not reflect this particular viewpoint.

Thus, the purpose of this study was to assess the effects on urban heat islands of various CO_2 reduction measures at a building- and an urban district-scale. This goal was consistent with an impact assessment aimed at increasing the feasibility of such measures as well as improving the comfort of inhabitants. Specifically, this study undertook a simulation of thermal environments within typical urban districts to quantify the impacts of CO_2 emissions reduction measures on urban thermal environments. It also considered the main factors behind the observed effects based on estimations of atmospheric heat balance within city districts.

2. Research design

2.1. Modeling and urban districts used in calculations

The assessment was carried out using an urban canopy model coupled with a building energy model (CM-BEM; Hirano & Fujita, 2016; Ihara, Kikegawa, Asahi, Genchi, & Kondo, 2008; Kikegawa, Genchi, Yoshikado, & Kondo, 2003; Kikegawa, Genchi, Kondo, & Hanaki, 2006; Kikegawa, Tanaka, Ohashi, Ihara, & Shigeta, 2014; Kondo & Liu, 1998; Kondo et al., 2005; Ohashi et al., 2007; Ohashi, Kikegawa, Ihara, & Sugiyama, 2014; Ohashi, Ihara, Kikegawa, & Sugiyama, 2016). The CM-BEM combines a local meteorological model at the district-scale with a computational model of the air conditioning load. The urban canopy model is a multi-layer one-dimensional meteorological model at the district-scale; in the model, the average distance between buildings, average building width, and vertical floor density distribution were used as parameters to describe a district containing numerous buildings. The model calculates surface heat balances at different orientations, and considers blocking out and multi-layer reflection of sunlight by buildings, as well as temperature changes within the district. The building energy model is a computational model of air conditioning load, which can be coupled with the urban canopy model. Through the combination of models, it becomes possible to express interactions between ambient air and buildings, such as the increase in cooling due to temperature increases, and temperature increases caused by associated anthropogenic waste heat, to calculate a building's thermal load, air conditioning energy consumption and anthropogenic waste heat.

Districts of office buildings, fire-resistant housing, and wooden housing were selected as typical urban districts for use in the assessment. Conditions for the composition of wall and roof surfaces, heat-pump equipment for air conditioning, as well as operating schedules were calculated as per Kikegawa et al. (2003), Kikegawa et al. (2006) and Hirano and Fujita (2016).

2.2. Calculation days

The study was conducted under two weather conditions: standard conditions and fair weather conditions. If days of broadly average temperature and solar radiation were selected, there would have been significant irregular temporal variation, due to the changes in weather conditions owing to the fact that cloud coverage would not be 0%; therefore, the results would be difficult to interpret. Moreover, it is not always the case that hotter environments present the most acute conditions. Days of fair weather are more appropriate for revealing the mechanisms being examined because they exhibit fewer irregular weather variations and are valuable as case studies of acutely hot environmental conditions. Nonetheless, days with extremely high temperatures produce non-average values for air conditioning energy consumption and CO_2 emissions, and, hence, are not suitable for assessments representing average conditions. Thus, to represent these two conditions, we include results for both standard and fair weather conditions. In addition, the detailed examination of diurnal variations focused on results obtained under fair weather conditions.

Table 1
CO_2 reduction measure settings.

Window shading	Change in total solar transmission rate, using blinds or curtains (office buildings: 0.3 → 0.1; residential buildings: 0.5 → 0.2)
Improved insulation	Insulation of roof and external walls to Japanese Next Generation Energy Efficiency Standards (for actual values see Hirano and Fujita (2016))
Indoor energy savings	Twenty percent reduction in energy consumption by indoor appliances (heat generated by appliances and lighting, excluding air conditioning)
PV panels	Installation of PV panels over 60% of building rooftops
Adjustment of preset air-conditioning temperature	Increase of preset cooling temperature by 1 °C (office buildings: 26 °C → 27 °C; residential buildings: 27 °C → 28 °C)

PV—photovoltaic.

Data from two summer days of roughly average solar radiation and clear and sunny were selected for this analysis: July 29, 2002 (standard conditions), and August 10, 2002 (fair weather conditions). Our detailed observation within urban districts was conducted on these days (Ohashi et al., 2007). For both days, we conducted detailed meteorological observations in the urban canopy, and captured diurnal variations in air temperatures inside the canopy. We also measured the shortwave and long wave downward radiation, and used these measurements for the calculations in this study. Approach calculations were made for two more days leading up to both target days (i.e., July 27–28 for standard conditions, and August 8–9 for fair weather conditions). All parameters related to buildings were set using workday conditions.

For each of these days, we had already conducted hourly mobile meteorological observations within urban districts, and verified the reproducibility of outdoor meteorological factors by CM-BEM based on these observations (Ohashi et al., 2007). Simulations focusing on heat island mitigation measures were carried out under the standard conditions analyzed in this study (Hirano & Fujita, 2016). The business as usual (BAU) simulation under standard conditions in this study contained the same calculation conditions as the standard case simulation conducted by Hirano and Fujita (2016).

2.3. Summary of cases in which CO_2 reduction measures were used

We assessed five specific CO_2 reduction measures: solar shading of window surfaces, PV panel installation, increased thermal insulation of walls and roofs, energy-saving operation of indoor appliances, and adjustment of preset cooling temperatures. The relevant settings for each of these measures are listed in Table 1. These are typical CO_2 reduction measures, and numerous efforts to increase the awareness of such measures among Japan's citizens have already been implemented. In addition, these five measures have different physical mechanisms: 1. solar shading of windows reduces the transmission of solar radiation, 2. improving the thermal insulation of the external walls and roof surfaces decreases the transmission of heat, 3. indoor energy savings reduce internal heat generation, 4. installation of PV panels generates electric power and provides shielding from solar radiation, and 5. alteration of preset temperatures in the air-conditioning units reduces the operating load of indoor cooling appliances. These measures were selected for the case study to compare how each measure influences the outdoor thermal environment.

In the window shading case, the total solar transmission rate changed; it was assumed that blinds or curtains were employed to block solar radiation. The PV panel scenario assumed coverage of 60% of a building rooftop. Following the settings associated with PV panels from a previous study (Genchi et al., 2003), this study included deductions of heat generated from the surface heat balance, as well as decreased building cooling loads due to solar blocking by panels and reduced anthropogenic heat from air conditioning energy consumption. The generation efficiency of PV panels was assumed to be 10%, as given in Genchi et al. (2003). This generation efficiency value was based on actual measurements (Genchi et al., 2002). The insulation scenario assumed improvements in wall and roof heat insulation to meet the Next Generation Energy Efficiency Standards, while volumetric heat capacity and thermal conductivity parameters kept the same settings as in Kikegawa et al. (2003), Kikegawa et al. (2006) and Hirano and Fujita (2016). The application of indoor energy efficiency measures assumed a 20% reduction in heat production by indoor appliances, excluding air conditioners. Reductions in indoor generated heat, as well as anthropogenic heat, caused by a lower consumption of cooling energy were included. The air conditioning temperature adjustment scenario assumed a 1 °C increase in the preset cooling temperature.

3. Methods

CM-BEM allows for the simultaneous calculation of radiation within the district. Factors include multiple reflections by the buildings and road, heat balance between building surfaces, air-conditioning unit loads for each building according to height, and energy consumption of buildings based on air-conditioning load. Other factors include wasted heat from the cooling units, heat balance of the wasted heat from the cooling units, the building surface, and the heat balance within the district, where the balance of radiation has been taken into account as well as a one-dimensional component of vertical diffusion of air.

In this research, it was necessary to calculate the interactions between the outdoor thermal environment and the indoor energy consumption by air-conditioning units. Whereas there are many general types of meteorological and computational models to calculate the air-conditioning load, for the purpose of this research, it was necessary to combine both model types to calculate such interactions simultaneously. There are only a limited number of simulation models that have the capability of calculating such interactions and, among those models, the CM-BEM is the only one to incorporate PV panels; therefore, the CM-BEM was selected for this study.

To understand the overall flow of energy across an entire district in an integrated manner by using CM-BEM, the shape of the buildings needed to be simplified. Thus, the buildings were represented as squares with a fixed average width and average distance between buildings. In addition, the height distribution was defined by setting building density at each height, constructing vertical one-dimensional model layers.

To define the average building width, the average building spacing, and the vertical distribution of building heights, we used the geographic information system (GIS) data for urban planning in the city of Kawasaki. Based on the building polygon data pertaining to building usage and structure, which was included among the GIS data, the major types of buildings, including office buildings, fire-resistant housing, and wooden housing were selected as study targets, in the same way as Hirano and Fujita (2016). First, the entire city of Kawasaki was divided into approximately 500 m × 500 m grids using the GIS data. We then identified the grids as typical office building districts, fire-resistant housing districts, or wooden housing districts, based on the information on building usage in each grid. Subsequently, we calculated the average width of each building, and average the distance between them once they were

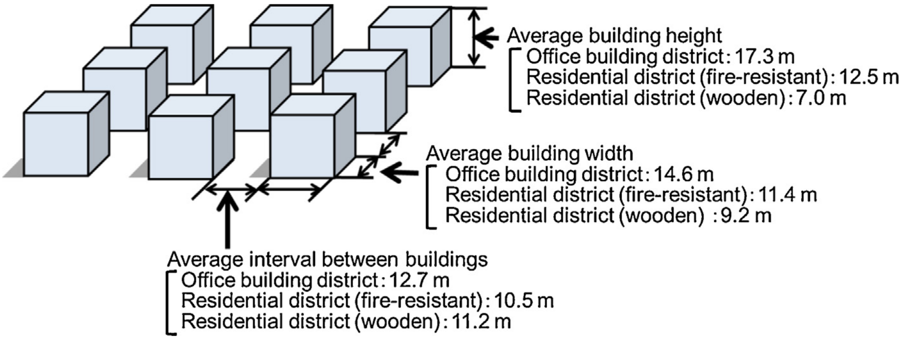


Fig. 1. Composition of typical urban districts.

rearranged into a column of squares, while maintaining the coverage and number of buildings. District specifications are shown in Fig. 1.

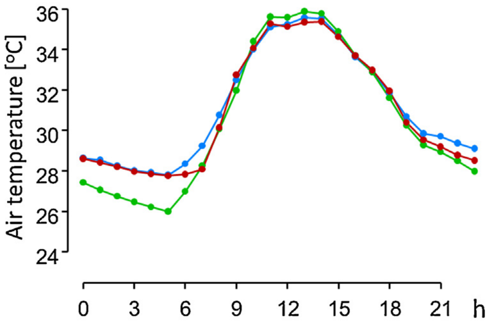
To confirm the accuracy of this model, Kikegawa et al. (2003) compared the modelled temperature sensitivity of electricity demand within an urban block of office buildings with actual electricity supply data; the results were used to validate the model. Furthermore, Kikegawa et al. (2006) compared calculations from a building energy model with calculations by general air-conditioning load calculation software for residential buildings, and confirmed the correspondence of those calculation results. Ohashi et al. (2007) conducted detailed meteorological observations within city blocks, and confirmed the reproducibility of outdoor meteorological elements. Hirano, Ohashi, Kikegawa, Kondo, and Genchi (2005) compared daily variation patterns of cooling energy calculated by this model with hourly data on energy consumption intensity, and confirmed correspondence of the characteristics of variation patterns. Hirano, Kikegawa, Genchi, and Kondo (2006) conducted inter-comparison among methods, including this model, for estimating the temperature sensitivity of energy consumption; the results were confirmed to be consistent.

4. Results and discussion

4.1. Results under business as usual (BAU)

Calculations of outdoor air temperatures and indoor heat balances under BAU and fair weather conditions are shown in Figs. 2 and 3. As mentioned, results under standard conditions were the same as those obtained in the standard case of Hirano and Fujita (2016). As Fig. 2 illustrates, office and fire-resistant housing districts showed less variation in diurnal temperature than the timber housing, and their nighttime temperatures were particularly high. These higher nighttime temperatures are attributed to the accumulation of heat and the obstruction of radiative cooling by the different building structures, and clearly suggest heat island effects. These trends largely match those in the standard case (Hirano & Fujita, 2016); however, under fair weather conditions, the daytime temperature reached around 36 °C, producing extremely hot weather conditions that differed from those in the standard case. Indoor heat balances (Fig. 3) were largely in line with those of the standard case; however, as there was little irregular dispersion of solar radiation penetrating windows, the indoor heat balance displayed a clear, double-peaked pattern. This is a logical result, given that solar radiation more easily penetrates windows during times of low solar elevation.

(a) Fair weather conditions



(b) Standard conditions

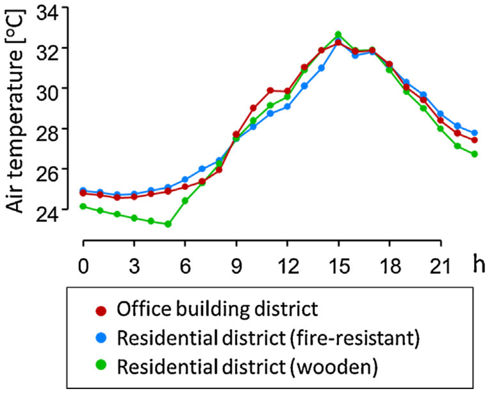


Fig. 2. Outdoor air temperatures under business as usual (BAU) (fair weather conditions).

The amount of removed sensible and latent heat, shown in Fig. 3, refers to the quantity of heat removed from building interiors by air conditioning equipment. In the building energy analysis model, we calculated the amount of energy consumed for cooling purposes using the values for removed heat and the efficiency of air conditioning equipment. Fig. 4 shows the energy for cooling consumed per unit of floor area, under fair weather and standard conditions. In both cases, the most elevated results were from office building districts during the day. While office buildings are less susceptible to the effects of outside air when compared to residential buildings, the larger quantities of heat generated by indoor appliances and occupants, as well as their higher rates of air conditioner operation during the day, means that solar radiation from windows rapidly adds to their air conditioning load. Also, the relatively large difference between office and residential districts under fair weather, compared to standard conditions, was due to a higher susceptibility to the effects of indoor heat generation compared to those of outside air. Considering the residential districts, we noted the particularly high daytime energy consumption of wooden residential districts under fair weather conditions. This is mainly due to the effects of heat transfer from roof and wall surfaces and solar radiation through windows. Wooden housing has a lower thermal

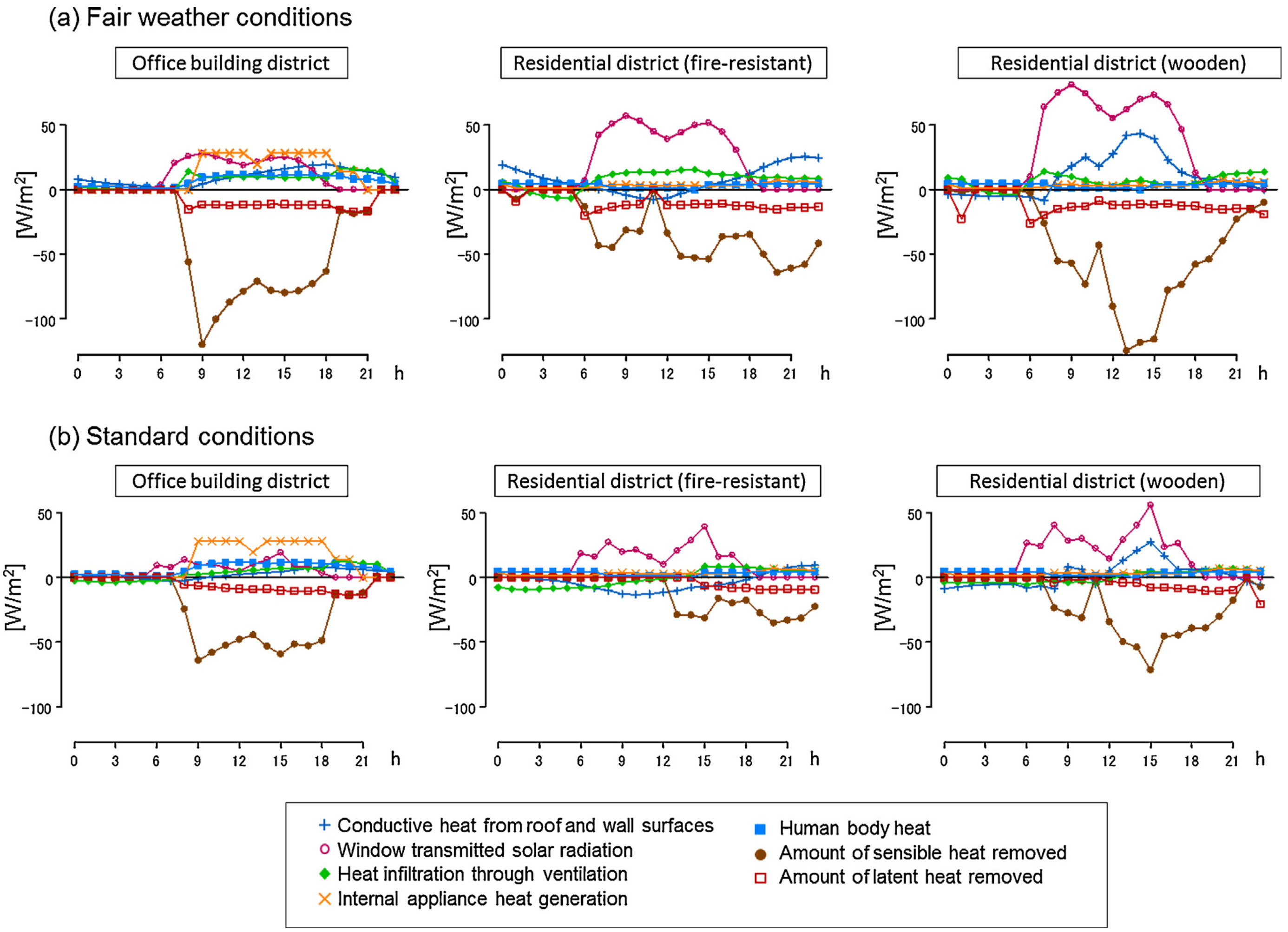


Fig. 3. Indoor heat balances under BAU (fair weather conditions).

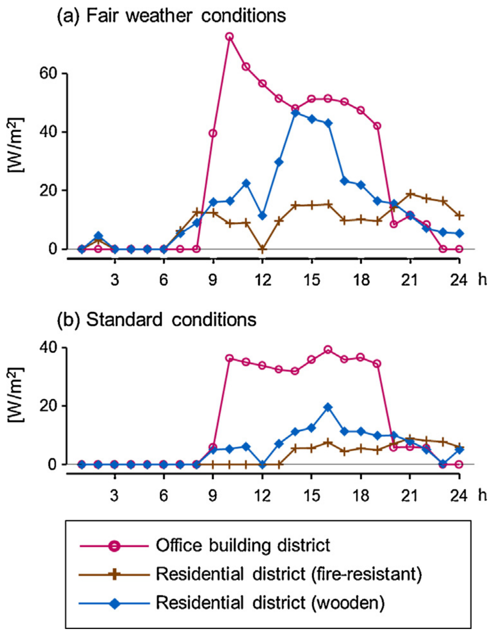


Fig. 4. Consumption of cooling energy under BAU.

insulation performance than fire-resistant housing and, due to its smaller structural scale, has a higher ratio of surface area to volume, making it more susceptible to the effects of outside air. This accounts for the larger amounts of cooling energy consumed per unit of floor area.

4.2. Results of CO_2 emission reduction measures

Fig. 5 shows the differences in CO_2 emissions per unit of floor area under BAU and with reduction measures applied. As the figure shows, in office building districts, indoor energy efficiency measures had the largest impact in reducing CO_2 emissions, while in residential districts, the installation of PV panels had the largest impact. However, as we did not establish settings that would allow each measure to be compared on equal terms, we could not conduct a comparative assessment of the effect of each countermeasure. For example, in the energy efficiency case, a straightforward fixed proportional value was given for the rate of reduction in indoor energy consumption, so that office districts, which consume significant amounts of energy for indoor appliances, showed a large reduction in CO_2 emissions. Furthermore, due to lower building height in residential districts compared to office districts, residential districts have a larger roof area relative to floor area and hence a large effect of PV panels per unit of floor area. Thus, both out-

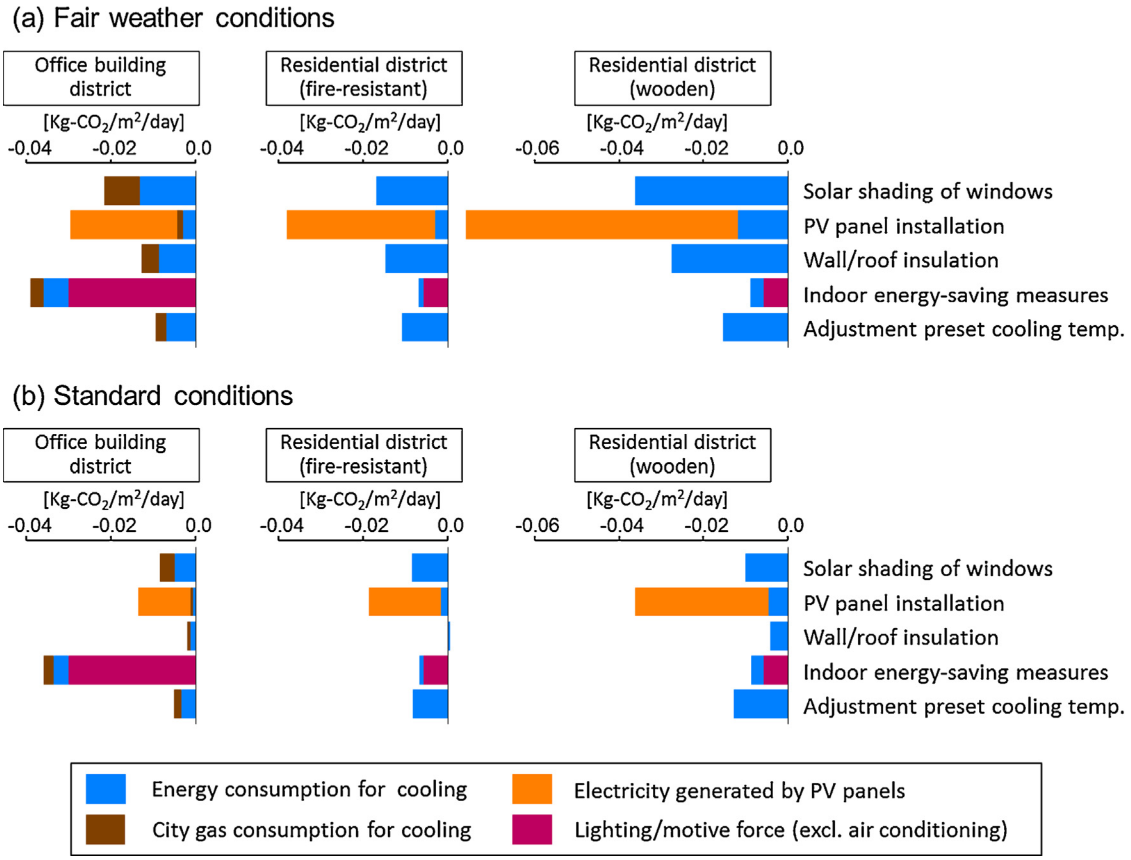


Fig. 5. CO_2 emission reductions achieved under each reduction measure (measure case—BAU case).

comes were highly contingent on the settings for each emissions reduction scenario and may not be generalizable. Nevertheless, the aim of this study was to assess the effects of each countermeasure on outdoor air temperatures and not on CO_2 emissions; therefore, assessments were based on these reduction scenarios. Further research is needed to establish scenario values to allow each measure to be compared on an equal basis, for example by using the cost of application.

Next, we assessed the impacts of each measure on outdoor air temperature. As stated, the scenario settings did not allow for comparison of each measure on an equal basis; thus, we have shown the relationship between the effects of CO_2 reduction and temperature change in scatterplots (Fig. 6). Despite significant variation according to conditions, many cases indicated reductions in air temperature. Nevertheless, the average daytime effect on temperature among the CO_2 reduction measures considered was less than 0.1 °C, which is not significant.

Looking at each case in turn, shading solar radiation from windows, indoor energy-saving measures and changing preset cooling temperatures all reduced CO_2 emissions by lowering the energy consumption of air conditioners and appliances and, in many cases, a small reduction in air temperature was produced. This is most likely caused by a reduction in anthropogenic heat resulting from lower energy use. Conversely, PV panel installation in many cases produced an increase in air temperature. This implies that, despite electricity generation and blocking of solar radiation lowering air temperatures, the low albedo of PV panels cancels out these effects. In the case of improved insulation, the range of variation in surface temperatures differed significantly due to the lowered heat capacity of buildings, with impacts varying depending on conditions. In these cases, it is difficult to consider them in detail based on daily average values. Therefore, we conducted a detailed analysis based on daily variations, focusing on fair weather conditions, in Section 4.3.

4.3. *Analysis of sensible heat balances within districts*

Fig. 7 shows diurnal variations in air temperature and differences against BAU for each case under fair weather conditions. Fig. 8 shows atmospheric sensible heat balances within the urban canopy and differences against BAU for each case, also under fair weather conditions. For atmospheric sensible heat balances, sensible heat inflows into the urban canopy from each factor are shown as positive, and outflows as negative. Accordingly, if the total of each factor (shown by the black line in Fig. 8) is positive, this indicates a rise in temperature, and likewise a drop in temperature if negative. Fig. 8 shows column amounts totaled to the top of the urban canopy. The total for each factor cannot be compared across the different district types owing to their different canopy heights.

From Fig. 7, we can observe that despite significant variations according to conditions, solar shading of windows, indoor energy efficiency measures and adjustment of preset cooling temperatures generally produced slight reductions in air temperature. As mentioned, all of these measures reduce CO_2 emissions by lowering energy consumption, and, hence, the main cause of these temperature reductions was the decrease in anthropogenic heat as a consequence of lower energy consumption. Fig. 8 shows that, in all cases, waste heat from air conditioning equipment was lower compared to BAU, confirming a reduction in waste heat via the application of the relevant measures (Fig. 8b, e, f). In addition, as sensible heat flux via turbulent heat dispersion has a negative value, in the figures showing differences a positive value indicates a reduction in heat flux. Accordingly, as the difference against BAU was positive in the case of solar shading of windows, indoor energy effi-

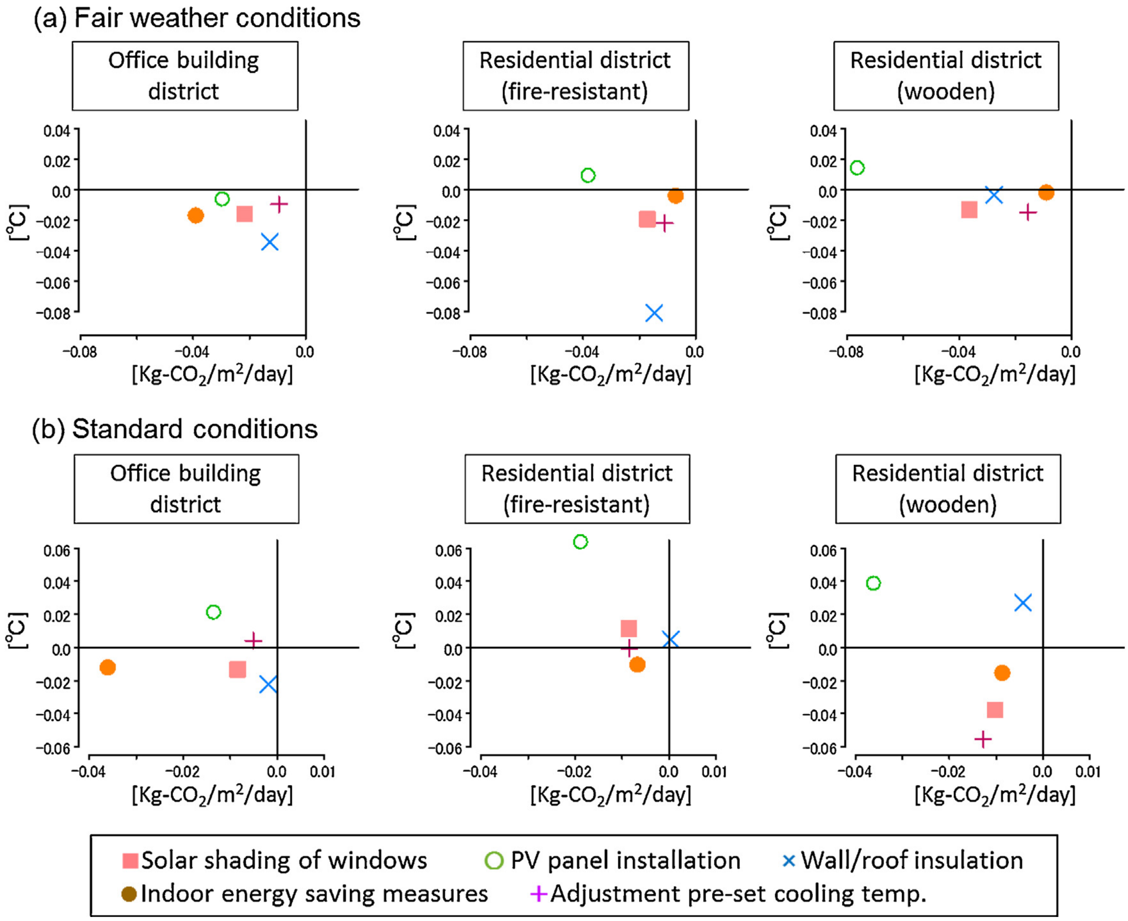


Fig. 6. Differences in CO$_2$ emission (measure case—BAU case) and differences in daily average air temperature (measure case—BAU case).

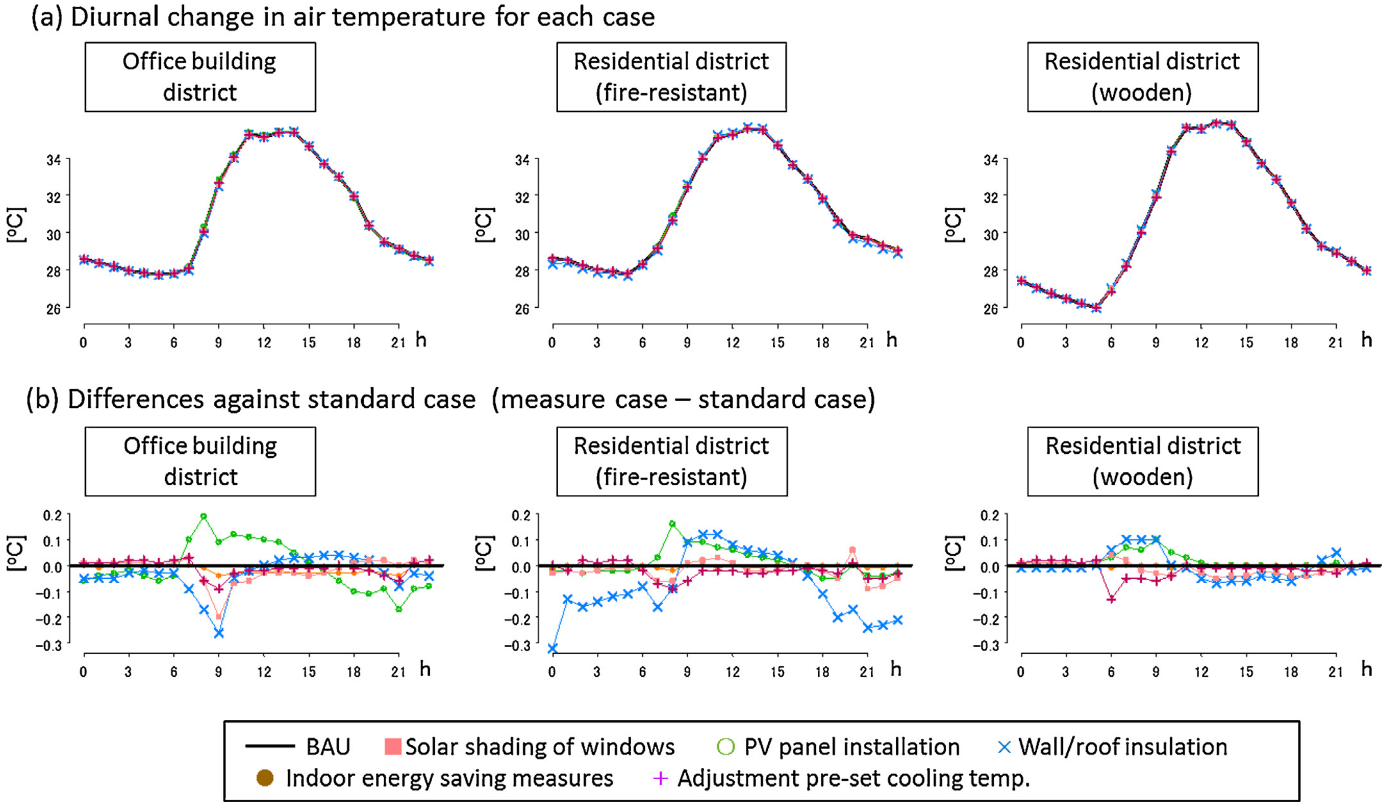


Fig. 7. Air temperature calculations for each case and differences against BAU.

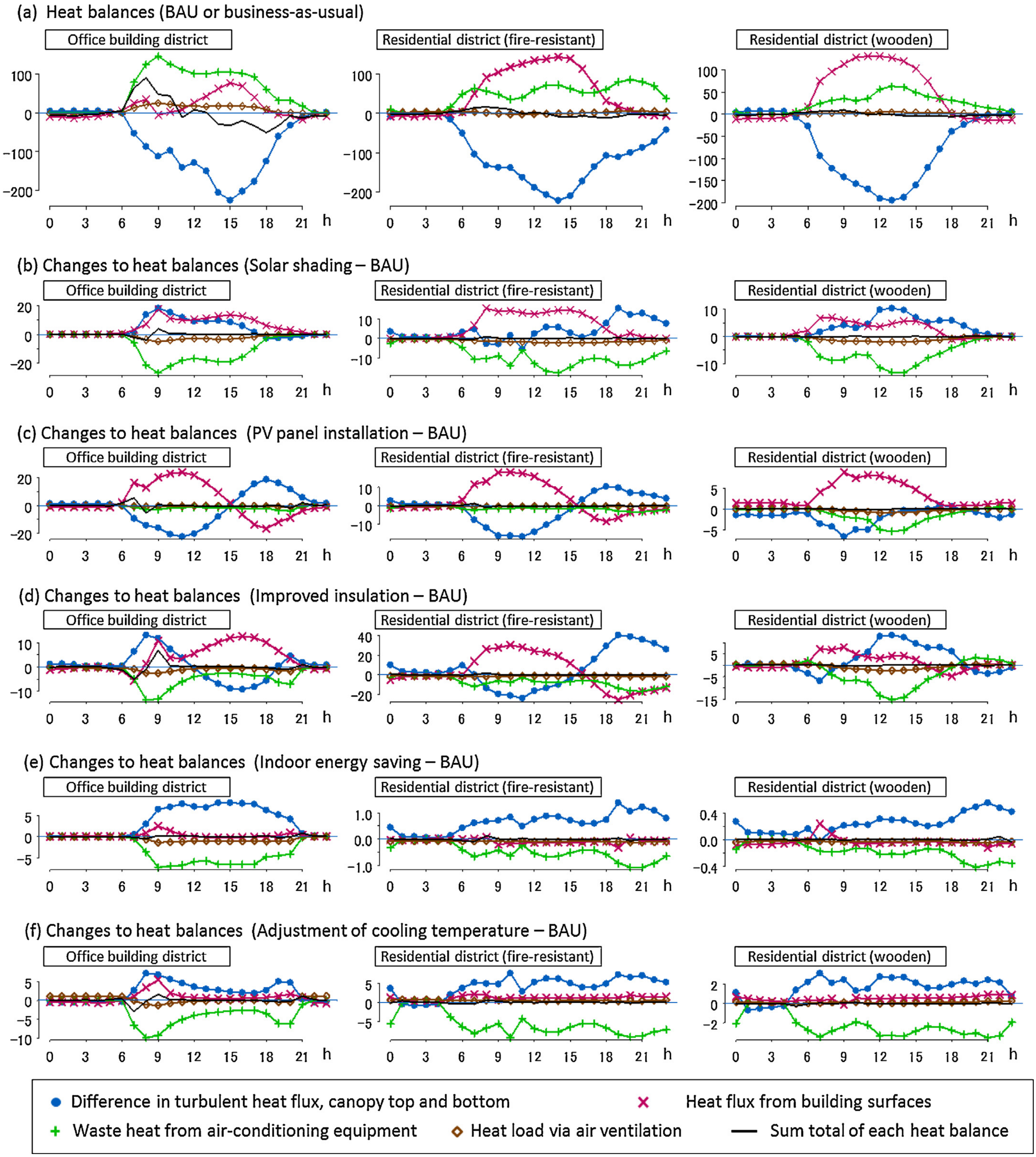


Fig. 8. District sensible heat balances for each case and differences against BAU.

ciency measures, and adjustment of preset cooling temperatures (Fig. 8b, e, f), sensible heat flux from the top of the urban canopy was reduced as air temperatures fell. Sensible heat flux from building surfaces during the daytime increased in the case of solar shading of windows (Fig. 8b). This is due to the increased absorption of heat into the canopy atmosphere proportional to the reduction of solar radiation that would have penetrated windows absent any shading. Nonetheless, during many time periods the reduction in waste heat from air conditioning equipment surpassed this amount, resulting in a slight drop in air temperature.

Conversely, the installation of PV panels tended to produce an increase in daytime air temperature (Fig. 8c). The main cause of this increase was the low albedo of PV panel surfaces and their tendency to increase in temperature. Fig. 8 shows increasing heat flux from building surfaces in each of the different districts during morning hours, highlighting the effect of rising surface temperatures. However, evening values for office and fire-resistant residential districts were negative, indicating a slight drop in air temperature. This is due to the reduction in accumulated heat by concrete roof surfaces, which have a large heat capacity, caused by the low heat capacity of PV panels and their blocking of solar radiation. Conversely, wooden housing has a small heat capacity compared to reinforced concrete structures, and hence does not produce this type of reduction in heat flux. Also, due to the low insulation performance of wooden housing, the effects of reduced air conditioning load due to blocking of solar radiation are relatively large. For this reason, within wooden housing, the increase in heat flux and the reduction in waste heat from air conditioning during the evening largely offset each other, such that the air temperature remained essentially unchanged against BAU.

In the case of improved thermal insulation (Fig. 8d), we can see a number of time periods over which air temperatures rose or fell, determined by the balance between increasing building surface temperatures and reductions in waste heat from air conditioning. For office districts, which have high air conditioner operation rates, the reduction of heat penetration during operational hours had a significant effect, while heat flux from building surfaces increased. Nevertheless, as air conditioning increased during morning hours, the effect of reduced waste heat from air conditioning equipment was greater, producing a temporary reduction in air temperature. For residential buildings, the lower heat capacity of building surfaces created by insulation resulted in an increase in heat flux from building surfaces during the day and a reduction during the night. This effect was particularly pronounced for fire-resistant residential districts, which have a high heat capacity to begin with, and a clear reduction in nighttime air temperature was observed. Wooden residences have low insulation performance and sensitive cooling loads, thus, improved insulation produced a slight increase in air temperature, caused by increased heat flux from building surfaces during the morning. However, the reduction in waste heat from air conditioning in the afternoon resulted in a slight drop in air temperature.

5. Conclusions

In this study, we have assessed the effects on urban heat islands of a range of measures aimed at reducing CO_2 emissions. We conducted a simulation of the summertime thermal environment to test CO_2 reduction measures at the district- and building-scale using an urban canopy model coupled with a building energy analysis model (CM-BEM). The purpose of this study was to provide an impact assessment of CO_2 emissions reductions strategies, not simply to improve the comfort of residents but also to enhance the feasibility of future measures aimed at ameliorating global warming.

We found that measures to reduce CO_2 emissions via energy-savings on the whole resulted in reductions in air temperatures, while measures involving changes to a building's heat capacity or albedo, such as improving insulation or installing PV panels, resulted in higher daytime air temperatures. However, in many of these cases the effects on daytime air temperature were in the range of 0.1–0.2 °C, and we concluded that such measures were not major factors in increasing temperatures in urban areas. At the same time, the incentive to introduce these CO_2 reduction measures, according to any co-beneficial effects, is surely limited.

While not considered by this study, emissions of cold air from heat-pump water heaters and the displacement of atmospheric heat emissions by ground source heat pumps may be significant in terms of heat island mitigation. As these factors could contribute more directly to alleviating district thermal environments, conducting a similar assessment of these measures in the future is considered worthwhile. Furthermore, while this study only considered measures at the district- and building-scales, many CO_2 emissions reduction strategies that have been proposed may have more large-scale impacts on urban thermal environments. These include transferring untapped energy from industrial waste heat to cities, as well as urban distributed generation and cogenerated heat supplies, which produce waste heat from electricity generation. Moreover, the increasing shift towards compact cities, with higher concentrations of people and buildings, will become a factor in increasing the exposure of inhabitants to these potential impacts. Accordingly, similar assessments will be required for measures involving supply-side solutions and modifications to city structures.

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