Future projections of the impacts of global warming and urban planning on the thermal environments under hot-humid and hot-dry climate conditions in Jakarta, Indonesia

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In this study, future (the 2030s and 2050s) urban climate projections in Jakarta, Indonesia, were performed using dynamical downscaling simulations. We particularly focused on the impacts of global warming and urban planning on the urban thermal environment in the future projections. The 2030 city master plan for Jakarta was introduced as the future urban planning. In addition, for each of the two target periods, the projections under hot-humid and hot-dry climate conditions, which were selected based on a climate analysis conducted using a reanalysis data (the ERA5 data), were conducted.

1. Introduction

Jakarta is the capital city of Indonesia and a rapidly developing city. The city is hot due to two warming problems, i.e., global warming and urban heat island (UHI). In the future, both the progress of global warming and that of UHI in Jakarta will make the city hotter.

The change in land use associated with urban planning will affect the future UHI in Jakarta. City master plan is an appropriate scenario for the future land use change. In terms of projecting future urban climate or thermal environment, it is necessary to consider not only the UHI impact but also the future progress of global warming.

In this study, we performed dynamical downscaling simulations from a global scale to an urban scale in order to quantitatively assess the impacts of future global warming and urban planning on the thermal environment in Jakarta. The target periods for the future projections were the 2030s and 2050s. Here, a city master plan for Jakarta prepared by the DKI Jakarta (the special capital city region of Jakarta) provincial government was introduced as the future urban planning.

In addition, two climate conditions, i.e., hot-humid and hot-dry climate conditions, were considered in the future projections conducted in this study. Those climate conditions were selected based on a climate analysis conducted using a reanalysis data.

2. Jakarta's climatic characteristics

For each of the two target periods (the 2030s and 2050s) in the future projections using dynamical downscaling simulations (cf. Chapter 3), the cases with the representative months of hot-humid and hot-dry climates were conducted.

The representative months of both climates were selected based on a climate analysis conducted using the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) data. The data for 41 years (1980–2020) on daytime (from 11 a.m. to 2 p.m.) air temperature (at a height of 2 m), relative humidity (averaged over heights from 1000 hPa to 900 hPa or 0–1 km above sea level), and precipitation at the grid covering Jakarta were averaged monthly to analyze their monthly variations.

Fig. 1 shows the monthly variations of the air temperature, relative humidity, and precipitation. The target month for the hot-humid climate was selected based on higher temperature, high humidity, and high precipitation. In contrast, the target month for the hot-dry climate was determined based on higher temperature but low humidity and low precipitation.

The value in the 0.5 quantiles for each cumulative probability was selected as a threshold that determined the high and low value of each variable (dashed lines

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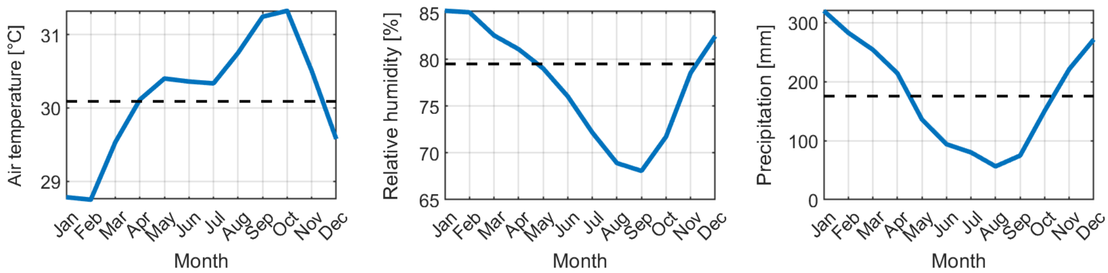

Fig 1. Monthly variations of air temperature, relative humidity, and precipitation averaged over the daytime (11 a.m. to 2 p.m.) for 41 years (1980–2020) using the grid data covering Jakarta of the ERA5 data.

in Fig. 1). The thresholds for temperature, relative humidity, and precipitation are 30.1°C, 79.5%, and 175.4 mm, respectively.

The month of April was selected as the target month for the hot-humid climate, as all values of temperature, relative humidity, and precipitation were above the thresholds. On the other hand, the month of September was selected as the target month for the hot-dry climate, as it had the lowest humidity and the second-highest temperature.

3. Outline of dynamical downscaling simulations

3.1 Simulation model

For the future (the 2030s and 2050s) projections of the impacts of global warming and urban planning on the thermal environments under hot-humid and hot-dry climate conditions in Jakarta, we conducted dynamical downscaling simulations based on the pseudo-global warming method proposed by Kimura and Kitoh (2007).

We used the WRF model version 4.0 (Skamarock et al., 2019) to perform the future projections on country, regional, and urban scales. As shown in Fig. 2, three nested domains, Domains 1, 2, and 3, were used in the WRF projections. The domain sizes and horizontal grid resolutions were 1225 km × 1225 km × 20 km and 25 km (Domain 1), 325 km × 325 km × 20 km and 5 km (Domain 2), and 140 km × 135 km × 20 km and 1 km (Domain 3). Table 1 summarizes the physics options in the WRF configuration.

In the pseudo-global warming method, the data obtained by adding a past objective analysis data/reanalysis data and the differences of future and past climatic elements projected/analyzed by a GCM were applied for the initial conditions of all WRF domains (Domains 1–3) and the boundary conditions

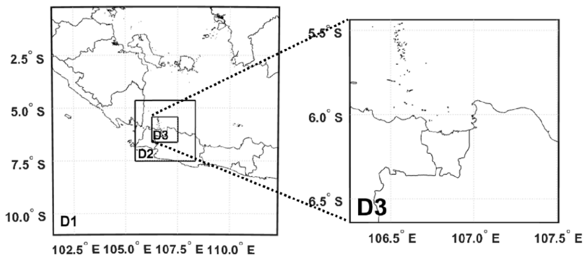

Fig. 2. Three nested WRF domains.

Table 1. Physics options in the WRF configuration.

Microphysics option	WSM 3-class simple ice scheme
Cumulus option	Grell-Devenyi ensemble scheme
Longwave radiation option	RRTM scheme
Shortwave radiation option	Dudhia scheme
Boundary-layer option	YSU scheme
Surface-layer option	Revised MM5 Monin-Obukhov scheme
Land-surface option	Unified Noah land-surface model Single-layer urban canopy model

of Domain 1. Horizontal winds, air temperature, relative humidity, geopotential height, and surface temperatures (skin temperature on the ground and sea surface temperature) were used as climatic elements in the pseudo global warming method. The NCEP Final Operational Global Analysis data for April 2015 and September 2015 (https://doi.org/10.5065/D6M043C6) were used as the objective analysis data.

The climatic differences required in the pseudo global warming method were calculated using the results of two GCMs, GFDL-CM3 and GISS-E2-R. Moreover, the GCM results based on two future GHG emissions scenarios, RCP2.6, and RCP8.5, were used in this study.

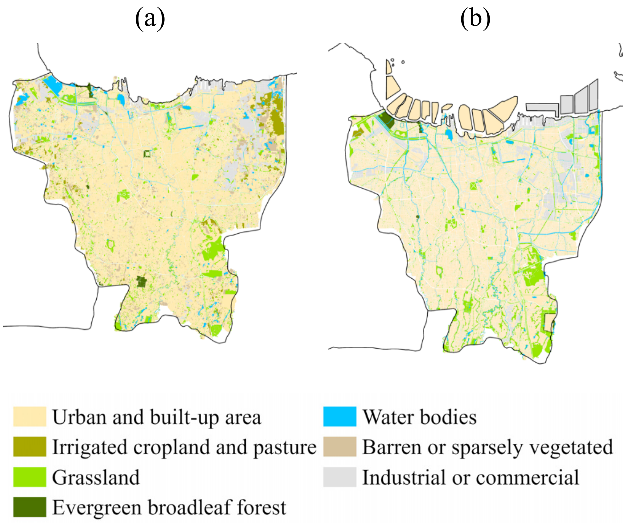

Fig. 3. Jakarta's land use distributions: (a) Present land use in 2020, (b) City master plan for 2030.

3.2 Land use distribution

Fig. 3(a) shows Jakarta's present land use distribution; it is dominated by urban and built-up areas with several industrial and commercial areas, especially in the northeast part of the city, and few green spaces.

Fig. 3(b) depicts the future land use distribution corresponding to the 2030s city master plan for Jakarta. As compared with the present land use, "grassland", "water bodies", "industrial or commercial", and "urban and built-up area" increased. On the other hand, "irrigated cropland and pasture" and "barren or sparsely vegetated" decreased significantly in the city master plan.

3.3 Simulated cases

A total of six cases were conducted in this study. All cases included simulations of the target month for the hot-humid climate (April) and that for the hot-dry climate (September) (cf. Chapter 2). Cases 2 and 3 were future projections, while Cases 0 and 1 were 2015 analyses. Cases 0 and 1 were conducted for comparison.

4. Results

4.1 Impacts of urban planning and global warming

As an example showing the impact of introducing urban planning, Fig. 4 compares the monthly averaged (for April 2015) and spatially averaged (over the grids covering the whole region of Jakarta: 106.71°E–106.94°E and 6.10°S–6.34°S) diurnal variations of air

Table 2. Simulated cases.

	Target year/period	Land use distribution
Case 0	2015 analysis	Present land use
Case 1	2015 analysis	2030 city master plan
Case 2a	2030s projection based on RCP2.6	2030 city master plan
Case 2b	2050s projection based on RCP2.6	2030 city master plan
Case 3a	2030s projection based on RCP8.5	2030 city master plan
Case 3b	2050s projection based on RCP8.5	2030 city master plan

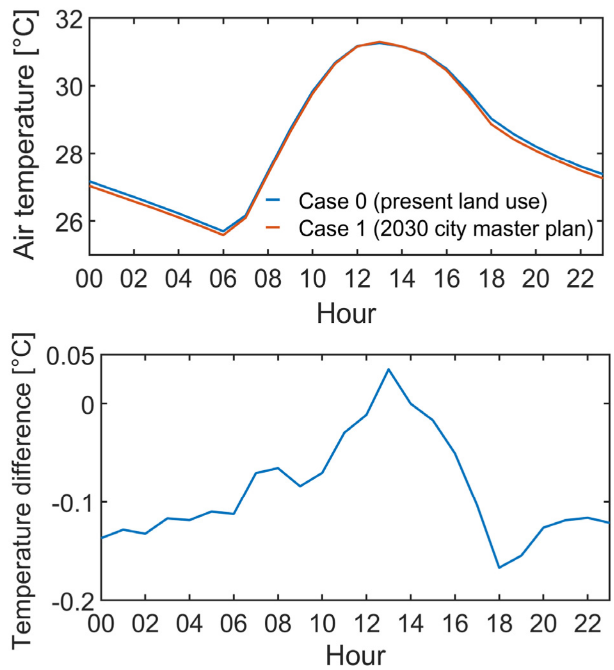

Fig. 4. Monthly averaged (for April 2015) and spatially averaged (over the whole region of Jakarta) diurnal variations of air temperature at a height of 2 m in Cases 0 and 1 (upper) and the difference between the cases (lower).

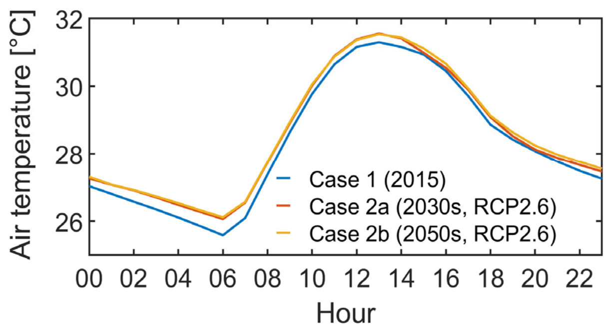

Fig. 5. Monthly averaged (for April) and spatially averaged (over the whole region of Jakarta) diurnal variations of air temperature at a height of 2 m in Cases 1 and 2.

temperature at a height of 2 m between Cases 0 and 1. Although Case 1 gives slightly cooler temperatures from the evening to the early morning, generally, the difference between both cases is small. The highest temperature difference is only 0.16°C at 6 p.m.

Fig. 5 shows the comparison of the monthly average (for April) and spatially averaged (over the grids covering the whole region of Jakarta) diurnal variations of air temperature at a height of 2 m among Cases 1 (2015) and 2 (the 2030s and 2050s with RCP2.6 and the GFDL-CM3 result).

Even in the cases with the relatively low GHG emissions scenario, i.e., RCP2.6, the magnitudes of temperature changes in Cases 2a and 2b against Case 1, which are due to the future progress of global warming, are larger than the above-mentioned magnitude of temperature change between Cases 0 and 1 by the introduction of future urban planning. The maximum temperature rises in Case 2a and 2b with respect to Case 1 are 0.48°C at 6 a.m. and 0.53°C at 6 a.m., respectively.

In the cases with the high GHG emissions scenario, i.e., RCP8.5 (figure omitted), the temperature changes due to future global warming are significantly greater than the temperature change caused by the introduction of future urban planning. Even for a rapidly developing city such as Jakarta, the impact of future global warming on the urban thermal environment is more serious than that of the temperature change caused by urban development.

4.2 Difference in hot-humid and hot-dry climate conditions

Fig. 6 shows the horizontal distributions of air temperature at a height of 2 m and velocity vectors at a height of 10 m at 1 p.m. in Cases 3a and 3b (RCP8.5 and the GISS-E2-R result case group).

An interesting feature is that, especially in the inland areas (the southern part of Jakarta), the daytime air temperature during the hot-dry climate condition is higher than that during the hot-humid climate condition. In a dry climate condition, there are many sunny days; thus, the ground surface becomes dry and hot. As a result, the hot surface heats the air above it. In addition, the heated air is transported to the inland areas by sea breezes, and the temperature in the inland

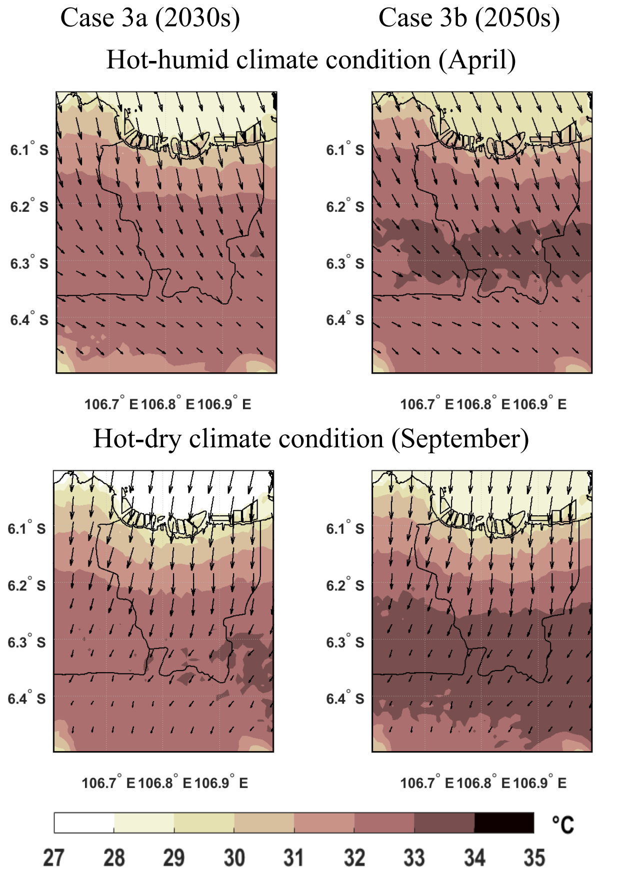

Fig. 6. Horizontal distributions of the monthly averaged air temperature at a height of 2 m and velocity vectors at a height of 10 m at 1 p.m. in Cases 3a and 3b.

areas rise. The same tendency can be seen in RCP8.5 and the GFDL-CM3 result case group, although the temperatures are higher across the target region (figure omitted).

5. Conclusion

In this study, the impacts of future (the 2030s and 2050s) global warming and the urban planning on the thermal environment in Jakarta, a developing city with rapid economic and population growth, were quantitatively assessed by dynamical downscaling simulations. In order to investigate the impact of the future urban planning, the 2030 city master plan for Jakarta prepared by the DKI Jakarta provincial government was introduced. In addition, two different climate conditions, hot-humid and hot-dry climate conditions, were considered in the future projections.

As compared with the impact of the future progress of global warming, the introduction of future urban planning, i.e., the 2030 city master plan for

Jakarta, did not give a significant impact on the thermal environment in Jakarta.

In the comparison between the hot-humid climate (April) and hot-dry climate (September) conditions, especially inland, i.e., the southern part of Jakarta, the daytime air temperature in the hot-dry climate condition was higher than that in the hot-humid climate condition. The convective heat transfer from the coastal areas by sea breezes contributed to the temperature rise inland. The situation was more remarkable in the hot-dry climate condition.

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