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Future environmental assessment and urban planning by downscaling simulations

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ABSTRACT

The outline of a sophisticated downscaling simulation model developed by the author and colleagues and its application for projecting the future urban thermal environment during the progress of global warming are introduced in this paper. Examples of inevitable uncertainties in future projections brought by the choices of a greenhouse gas emissions scenario and general circulation model (GCM) data are also shown. Moreover, three examples of the environmental assessment for future urban planning, i.e., (1) disaster mitigation and prevention urban structure scenario, (2) compact city scenario, and (3) city master plan in a developing country, by the developed downscaling simulation model are presented. Downscaling simulation is a very powerful environmental assessment tool and is very useful for urban planning, especially in the inevitable future global warming period.

1. Introduction

As clearly stated in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (2014), "Warming of the climate system is unequivocal." The increase in the global mean surface air temperature (the globally averaged combined land and ocean surface temperature) for the last 100 years was about 0.6 °C (a warming of 0.85 °C over the period 1880 to 2012 (IPCC, 2014)). The small temperature change, which people cannot clearly recognize, causes various extreme weather events all over the world. Based on the results of various general circulation models (GCMs), it is likely that, in the future, the global mean surface air temperature will continue to rise more rapidly than ever. Under the highest greenhouse gas emissions scenario among the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011), i.e., RCP8.5, the increase in the surface air temperature by the end of this century (2081–2100) relative to 1986–2005 will likely be in the range of 2.6–4.8 °C (IPCC, 2014).

Currently, more than half of the world's population lives in urban areas (United Nations, 2018). In urban areas, air temperature increases can be attributed to global warming and urban heat islands. Increases in the annual mean air temperature in the major metropolises of Japan, such as Tokyo, Osaka, and Nagoya, for the last 100 years were about 3 °C (Japan Meteorological Agency, 2017). The temperature increases were mainly due to those cities' urban heat islands. Based on the above-mentioned fact that the temperature increase due to global warming for the last 100 years was about 0.6 °C, the impact of those urban heat islands was about four times greater than that of the past global warming.

However, in the future, the contribution of global warming will be larger than that of the urban heat island in many urban areas in developed countries, especially with population declining. In Japan, the population is declining as birth rates drop and the financial situation worsens. In this social situation, urban areas will not continue to expand as before, and the impact of urban heat islands will decrease. Nevertheless, future urban thermal environments will not improve due to the impact of future global warming. We should adapt the future thermal environments, especially in summers, to a certain degree. Not only mitigation measures but also adaptation measures are required to deal with the severe thermal environments of the future.

In Japan, research projects on climate change adaptation supported by the ministries started approximately 8 years ago. An interdisciplinary (climatology and meteorology, architectural and urban environmental engineering, civil engineering, and computer science) research group has been initiated by the author, and our group has tackled a pioneering research project on climate change adaptation named RECCA (Research Program on Climate Change Adaptation, 2010–2015) supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. Actually, many social implementations of adaptation (and also

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mitigation) measures are planned and will be performed on an urban or building scale. Appropriate and quantitative future projections of the thermal environments, especially in summers, on those spatial scales are crucial to considering suitable adaptation and mitigation measures. A downscaling simulation from a global scale to an urban or building scale is a very powerful tool for projecting the microscale thermal environments influenced by future global warming.

In this paper, first, the outline of a sophisticated downscaling simulation model developed by our interdisciplinary research group through the above-mentioned research project (RECCA) is introduced. Our simulation model is a kind of dynamical downscaling technique and consists of GCM data and a model based on Weather Research and Forecasting (WRF) (Skamarock et al., 2008) and large-eddy simulation (LES). The difficulty of merging WRF (a climate simulation model on regional and urban scales) and LES (a microclimate simulation model on a building scale) is also discussed.

Second, future projections of the changes in the urban thermal environment until around the end of this century using the developed downscaling simulation model are shown, and the uncertainties of future projections are discussed. To conduct future projections, various future scenarios (greenhouse gas emissions scenario, land-use and land-cover scenario, urban structure scenario, energy systems scenario, etc.) must be introduced. The choices of future scenarios and GCM data bring uncertainties to future projections.

Third, three examples of the environmental assessment for future urban planning by downscaling simulations are introduced. The final goal of these applications is social implementation. From the perspectives of environmental assessment and disaster mitigation and prevention, future urban structure scenarios for a major metropolitan area in Japan (the Nagoya metropolitan area) are discussed. In the context of future population decline and the global warming period, compact city scenarios for the same metropolitan area with a focus on mitigating the thermal environment are also discussed. Moreover, the environmental assessment of an actual city master plan in a developing country and investigation of some modifications by downscaling simulations are presented.

2. Development of a downscaling simulation model from a global scale to a building scale

2.1. Downscaling techniques

Downscaling techniques have been developed mainly by researchers who specialize in climatology and meteorology. The purposes are to fully grasp the impact of global warming on environments on smaller spatial scales and to consider mitigation and adaptation measures on those spatial scales. Downscaling techniques are broadly divided into two categories: dynamical downscaling (e.g., Wang et al., 2004) and statistical downscaling (e.g., Wilby et al., 2004). The dynamical downscaling technique is a kind of interpolation of GCM data using a regional climate model (RCM). By introducing an RCM, the dynamics and physical processes on regional and urban scales are sufficiently taken into account; however, the computational load becomes large. The statistical downscaling technique is based on statistical relationships between past or present climatic elements on broader scales and those on local scales. The technique is simple to use, and its computational load is small. However, it is difficult to apply the statistical downscaling technique based on past or present climate data to future projections with the progress of global warming.

The downscaling simulation model developed by our interdisciplinary research group and introduced in this paper is based on a dynamical downscaling technique, as shown in Fig. 1. Almost all downscaling simulation models work from a global scale to a regional or urban scale and cannot be applied to a finer spatial scale, i.e., a building scale. In contrast, our model can downscale to a building scale. This is the most significant feature of the model.

The dynamical downscaling technique is divided into two methods: a direct downscaling method and a pseudo global warming method (Kimura and Kitoh, 2007). In the direct downscaling method, GCM data are given to an RCM directly as the initial and boundary conditions. Therefore, the errors and biases of the GCM used are also given to the RCM. Moreover, the processing of all spatial-temporal GCM data is very complicated.

The pseudo global warming method proposed by Kimura and Kitoh (2007) can avoid the problems of the direct downscaling method. In their method, first, the difference between the 10–30-year average of future climatic elements and that of present climatic elements is calculated based on GCM data. Then, the linear coupling of the climatic differences and reanalysis data is given to an RCM as the initial and boundary conditions. The pseudo global warming method is adopted in our downscaling simulation model.

2.2. Difficulty in the development of a downscaling simulation model

As described in Section 2.1, our downscaling simulation model can downscale to a building scale, which is the most significant feature of the model. The downscaling simulation model consists of GCM data and a model based on WRF (Skamarock et al., 2008) and LES. WRF is introduced as the climate simulation model on regional and urban scales, and LES is applied as the microclimate simulation model on a building scale.

One of the biggest difficulties in developing our downscaling simulation model was merging WRF on an urban scale and LES on a building scale. Needless to say, a simulation model on a larger scale cannot capture the fluctuations of climatic elements such as velocity and temperature on a smaller scale. Especially on a building scale, small-scale velocity fluctuations largely affect flow, temperature, and other scalar fields around buildings. Therefore, the boundary conditions of LES, especially the inflow boundary condition, cannot be given by a simple nesting of the WRF results. To successfully downscale to a building scale, appropriate small-scale velocity fluctuations for the inflow boundary condition (inflow turbulence) of LES should be generated separately and incorporated into the WRF results.

Artificial generation methods based on the inverse Fourier transform of prescribed spectra (Lee et al., 1992; Kondo et al., 1997; Iizuka et al., 1999) and the Cholesky decomposition of the Reynolds stresses (Lund et al., 1998; Xie and Castro, 2008) are effective for making appropriate inflow turbulence of LES. No flow simulation is required in those methods; thus, there is little additional computational load. The biggest problem of artificial generation methods is the rapid and unphysical decay of the generated turbulence just behind the inflow boundary. This is because the artificially generated inflow turbulence does not satisfy the governing equations (the continuity and momentum equations), and it changes to satisfy them when it flows downstream.

Our downscaling simulation model introduces an artificial method of generating the inflow turbulence of LES based on the Cholesky decomposition of the Reynolds stresses (Xie and Castro, 2008). Inflow turbulence is expressed as the combination of the mean velocity component and its deviation. By obtaining the mean velocity components and the Reynolds stresses from the WRF results, the WRF and LES simulations are merged. The artificial generation method also has a problem that the generated turbulence is rapidly and unphysically attenuated when it flows downstream. We proposed a modified method in which the inflow turbulence generated can satisfy the continuity equation by using Taylor's hypothesis of frozen turbulence and generalized curvilinear coordinate transformation (Xuan and Iizuka, 2014; Iizuka and Xuan, 2016). Unfortunately, the decay of turbulence was not remarkably improved by our modification. In the present stage, for practical applications, inflow turbulence should be generated with consideration of the increment to offset the rapid and unphysical decay of the generated turbulence. Further efforts to solve the common problem of artificial methods of generating the inflow turbulence of LES are required.