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Mechanism of early-summer low-temperature extremes in Japan projected by a nonhydrostatic regional climate model

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ABSTRACT

We investigated the mechanisms associated with projected early-summer low-temperature extremes in Japan at the end of the 21st century by means of a well-developed nonhydrostatic regional climate model under the A1B scenario provided by the Intergovernmental Panel on Climate Change-Special Report on Emission Scenario. The projected surface air temperature reveals that even in a climate warmer than that at present, extremely low daily minimum temperatures in early summer are comparable to those in the present climate at several locations. At locations where future low temperatures are remarkable, the temperature drop at night is larger in the future than at present. This temperature drop results from mainly two heat fluxes: upward longwave radiation and latent heat flux. In the future climate, upward longwave radiation increases owing to high temperature at the surface around the time of the sunset. In addition, the upward flux of latent heat increases owing to low relative humidity just above the surface. These dryer conditions are associated with lower relative humidity at 850 hPa, suggesting the effects of synoptic systems. These two fluxes act to reduce the surface temperature, and hence surface air temperature.

1. Introduction

Temperature change is one of the central issues surrounding future projections of the climate. Projections of future temperature associated with anthropogenic global warming are important for every branch of human activities and natural systems: human health, ecosystems, and a variety of industries, such as agriculture, energy, and insurance.

Although climate warming projections usually present mean temperature increases, recently, extreme temperatures have been projected because human activities will be significantly affected not only by changes in mean temperatures, but also changes in extreme temperatures. Global warming might induce regional- or local-scale temperature extremes. According to (Anderson (2011, 2012), even with an increase in the global-mean temperature of only 2 K, broad areas of the globe could experience maximum seasonal-mean temperatures exceeding historical extremes. Projections of extreme temperatures on regional scales are needed; to achieve this, we need regional climate models (RCM) that capture finer-scale changes in temperature over space and time (e.g., Kurihara et al., 2005; Rummukainen, 2010; Arritt and Rummukainen, 2011).

Previous studies at regional scales primarily focused on higher temperature extremes such as changes to the daily maximum temperature in summer; for example, using the simulation projected by the A1B scenario provided by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenario (SRES) (IPCC, 2000), Murata et al. (2012) examined future changes in summertime temperature extremes over Japan projected by an RCM with a high spatial resolution of 5 km. Projected changes in extreme daily maximum and minimum temperatures were relatively large over several areas leeward of mountains. Using two state-of-the-art RCMs, Frías et al. (2012) found that in the future climate under the A1B scenario during spring and summer in Southern Europe, the extremes are two or three times the increases in mean seasonal temperatures. Rangwala et al. (2012) projected temperature extremes in mid-21st century in the southern Colorado Rocky Mountains by using RCMs under the A2 scenario provided by the IPCC-SRES; at higher elevations mean daily maximum temperature during summer increases more than 3 K in addition to increases of around 2 K for all seasons.

In addition to high temperature extremes, projections of future low temperature extremes are also important because many human activities are vulnerable to cold extremes, regardless of overall climate warming. For example, some crops are vulnerable to extremely low temperatures. Luo (2011) reviewed temperature thresholds for a variety of crops to provide a basis for estimating the probability of exceeding temperature thresholds. Among these

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thresholds, base temperature and lethal minimum temperature were defined: the former is the temperatures below which grain yield fails to zero and the latter is the temperature below which recovery of function is impossible. Other human activities and natural systems vulnerable to cold extremes have also been examined, such as human health (Patz et al., 2005; Handmer et al., 2012) and ecosystems (Handmer et al., 2012; Inouye, 2000).

Few studies have investigated the changes to low-temperature extremes associated with global warming, although such extreme events may significantly impact human activities. Kodra et al. (2011) is a rare example; they analyzed projections provided by GCMs and found that cold extremes could persist even under 21st-century warming scenarios. Their results indicate that in many regions of the globe, the intensity and duration of cold extremes would be comparable to those under current typical conditions. Park et al. (2011) examined the changes to cold extreme events over East Asia by using projections provided by GCMs. The projections showed frequent occurrences of cold surges even in the future climate; these surges are comparable to those in the present climate, and Park et al. pointed out that living things in the future climate would suffer the impact of cold surges. Their results were primarily focused on synoptic-scale systems and indicate that the minor changes to the frequency of cold surges are due to the nearly constant magnitude of the Siberian High during the time between the present and future. However, local-scale effects on cold extreme events were not investigated in these previous studies because local-scale phenomena are not adequately resolved by GCMs.

No studies have, so far, investigated local- or regional-scale low-temperature extremes across Japan under global warming conditions although such extremes may severely impact human activities in Japan. Because Japan has complex topography and coastlines, which lead to considerable climate variability, the necessary projections of low-temperature extremes should be prepared at fine spatial scales (local or regional). To capture low-temperature extremes at the local- or regional-scale, it will be necessary to use a high-resolution RCM with grids fine enough to capture such small spatial and temporal variations. Recently, a high-resolution nonhydrostatic RCM (called NHRCM), developed from a nonhydrostatic mesoscale model, has been used to simulate regional climates in Japan (e.g., Murata et al., 2012; Sasaki et al., 2008; Kanada et al., 2008; Nakano et al., 2012; Bai et al., 2013). In particular, Sasaki et al. (2011, 2012) conducted high-resolution regional climate simulations for all seasons in Japan and reported on the superior performance of the NHRCM over that of a GCM. Using this dataset, several studies of regional climates in Japan were conducted (Sasaki et al., 2013; Hanafusa et al., 2013; Murata et al., 2013).

In this study, we used data obtained from NHRCM simulations to perform a detailed assessment of local-scale low-temperature extremes in Japan under the future climate; we found extremely low temperatures in early summer. Therefore, our focus is on low-temperature extremes in early summer, when suitable conditions are crucial for a variety of crops because early summer corresponds to the growing season.

The aim of this study was to estimate future changes in local-scale low-temperature extremes in early summer across Japan by means of a well-developed high-resolution RCM (i.e., NHRCM) and to identify possible factors that control such changes. To do this, we explored the mechanisms for projected low-temperature extremes by using budget analysis of heat fluxes at the ground surface, which are linked to surface air temperature. Few studies have investigated local-scale heat budgets in projected future climate.

Section 2 describes the data and the methods for numerical simulations obtained with the NHRCM. Section 3 evaluates the performance of the NHRCM with respect to low-temperature extremes in the present climate. Section 4 investigates the simulated data on low-temperature extremes in the future climate. Section 5 identifies the atmospheric situations that give rise to extremely low temperatures and examines the key factors that govern the occurrence of low-temperature extremes. Section 6 assesses uncertainties in projected low-temperature extremes by employing the bootstrapping approach. Finally, section 7 presents the discussion and conclusions.

2. Data and methods

2.1. Data

2.1.1. Model data

The NHRCM developed by Sasaki et al. (2008) is a climate extension of the Japan Meteorological Agency Nonhydrostatic Model (JMA-NHM) (Saito et al., 2006, 2007), which is one of the numerical weather-prediction models operated by the JMA. The NHRCM has fully compressible equations with a map factor and uses a semi-implicit time integration scheme. It includes the bulk-type cloud microphysics (Ikawa et al., 1991; Lin et al., 1983; Murakami 1990; Murakami et al., 1994). The Kain–Fritsch convection scheme (Kain and Fritsch 1990; Kain 2004; Kato et al., 2010) is included as a cumulus scheme. For a planetary boundary layer scheme, the Mellor–Yamada–Nakanishi–Niino Level 3 scheme (Nakanishi and Niino, 2004) is employed. For radiation, a clear-sky radiation scheme (Yabu et al., 2005) and a cloud radiation scheme (Kitagawa, 2000) are used. The land-surface scheme by Hirai and Oh'izumi (2004), improved from the simple biosphere model (Sellers et al., 1986), is included. Land-cover classification is derived from the global land-cover characterization for the simple biosphere model from the U.S. Geological Survey land-use classification. Surface air temperature (1.5 m height) is diagnosed from the surface skin temperature and the temperature of the lowest atmospheric layer, based on the Monin–Obukhov similarity theory (Beljaars and Holtslag, 1991).

For long-term climate simulation, the NHRCM includes a spectral boundary coupling scheme (Kida et al., 1991; Sasaki et al., 2000). In this scheme, large-scale components produced by the outer model are merged into smaller-scale components in the inner model. Consequently, no contradiction in the large-scale components exists between the inner and outer models, thereby enabling us to integrate the inner model steadily for a long period.

The NHRCM has been used successfully to simulate regional climates in Japan. For example, Sasaki et al. (2011), using the NHRCM with 5 km grid spacing, performed a 20-year integration with predicted boundary conditions and demonstrated that the annual mean surface air temperature and precipitation in the present climate are reproduced well. Sasaki et al. (2012) performed a 20-year integration (from 2076 to 2096) for the end of the 21st century and showed a 3 K rise in surface air temperature averaged over Japan for each month (99% confidence level), compared with the temperature in the present (from 1980 to 2000). Using data obtained from Sasaki et al. (2011), Murata et al. (2013) pointed out negative biases in daily mean, maximum, and minimum temperatures in urban areas; they demonstrated that these biases are useful for estimating urban heat island intensity.

Data obtained from Sasaki et al. (2011, 2012) are utilized in this study. The grid-nesting strategy for numerical simulations is as follows. The model domain (211×661 grid points) of the NHRCM with a grid spacing of 5 km (NHRCM05) is set to cover Japan. Boundary conditions for the NHRCM05 are derived from a