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Projection of temperature over Korea using an MM5 regional climate simulation

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ABSTRACT: The present study dealt with the projection of future temperatures over Korea, using MM5 dynamic-downscaling simulation, for the period 1971–2100. MM5 simulations were based on the IPCC's (Intergovernmental Panel on Climate Change) A1B scenario, which has been described in detail in the Special Report on Emissions Scenarios. Regional climate projection showed that the annual mean value of daily mean temperatures will increase by 3.8°C between now and the 2071–2100 period. Comparing minimum and maximum temperatures, the change in minimum temperatures is expected to be larger (4.0°C) than that in maximum temperatures (3.5°C). Seasonally, the increase is projected to be greater in winter than in summer. Inter-annual variability is also projected to be higher in winter than in summer. In the troposphere, a rise in temperature shows a tendency to be greater with height; thus, increases are projected to reach a peak value of +4.5°C at 400 hPa. Frequency distributions of daily mean temperatures, showing an increase in the mean value without a change in variance, will reflect a change in temperature extremes. Hot events, based on the 95th percentile of the daily maximum temperatures, are expected to be intensified by 2.3°C and to be 5 times more frequent in the 2071–2100 period than in the 1971–2000 period. Cold events, based on the 5th percentile of daily minimum temperatures, are predicted to become warmer by 5.3°C, and the number of days involved will be reduced by 99%. The rise in temperature is projected to be associated with an increase in relative humidity of 2% and specific humidity of 29% near the surface over Korea by the end of the 21st century. The projections show consistency between temperature and humidity changes, at a rate of about 7% K^{-1} of the moisture holding capacity.

KEY WORDS: Global warming · Future projection · MM5 · A1B scenario

1. INTRODUCTION

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) reported that the global mean surface temperature rose by 0.74°C between 1906 and 2005 (IPCC 2007). A warming of about 0.2°C per decade is projected for the next few decades according to a range of scenarios outlined in the IPCC's Special Report on Emissions Scenarios (SRES) (IPCC 2007). By the end of the 21st century, global temperature is expected to have risen by 1.8 to 4.0°C under various SRES scenarios. In addition to projected global warming, it is also important to predict possible consequences of climate change at a regional scale, requiring the use of techniques such as downscaling (using regional climate models, RCMs).

RCMs are valuable dynamic-downscaling tools that provide regional details based on large-scale climate information from global climate models (GCMs) or from reanalysis. Studies of RCMs nested within GCMs or reanalysis data have been applied for most regions in the world, particularly regions where the effects of complex orography or coastlines regulate the spatial and temporal variations of important climate variables (e.g. Walsh & McGregor 1995, Kim & Lee 2003). It has been demonstrated that RCMs driven by coarse resolution global data can generally generate reliable descriptions of regional-scale water and energy cycles

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(Giorgi et al. 1993a,b). Multi-year or multi-decadal climate simulations, both in hindcast and prediction models, have provided estimates of global climate change impacts on East Asian regional climate characteristics (Lee & Suh 2000, Im et al. 2006, Kim et al. 2008). Usually, to overcome the resolution limitations of GCMs, 1-way nested RCMs are used (Giorgi & Mearns 1999). Recently, double-nesting methods have been utilized to reduce the lateral boundary problems due to grid disparities (Im et al. 2007, 2008). However, according to Castro et al. (2005) and Denis et al. (2003), the downscaling method can be used, in addition to the double-nesting approach, without detracting from the features of the global model.

To provide a feasible projection of the conditions over Korea, the National Institute of Meteorological Research (NIMR) performed high-resolution regional climate simulation under the IPCC SRES A1B scenario (NIMR 2006). This work was a continuation of previous work (NIMR 2004 and Boo et al. 2006), and used the IPCC SRES AZ. In the present study our aim was to further investigate future changes in temperature over Korea based on the NIMR (2006) simulation results. Regional climate projection was carried out with the RCM MM5 over Korea. Furthermore, the greenhouse-gas-induced warming of the Asia-Pacific region may explain the increase in heat mortality, the reduction in cold-temperature morbidity and the spread of respiratory diseases related to increased urban pollution (Griffiths et al. 2005). In order to consider the regional-scale temperature extremes in global warming, the present study also provided an analysis of the changes in temperature extremes (i.e. hot and cold events).

2. DATA

Data sets in the present study were produced with a dynamic-downscaling method using the RCM MM5, at 27 km horizontal resolution. The model domain was centered at 38° N, 126° E and extended over an area of East Asia that included Korea. The model domain is shown in Fig. 1, along with the topography and the sub-region analyzed. The initial and boundary conditions for the MM5 were provided by the long-term simulation of the ECHO-G global coupled model. The atmospheric component of ECHO-G is ECHAM4 (Roeckner et al. 1996), and the oceanic component is HOPE-G (Legutke & Maier-Reimer 1999). The horizontal and vertical resolution of ECHO-G was defined by a spectral T30 grid (~3.75°). Model integration covered the 130 yr from 1971 to 2100, based on the IPCC SRES A1B emission scenario. The present study used the monthly temperatures at 2 m height simulated by MM5 for the period 1971–2100. Observational data,

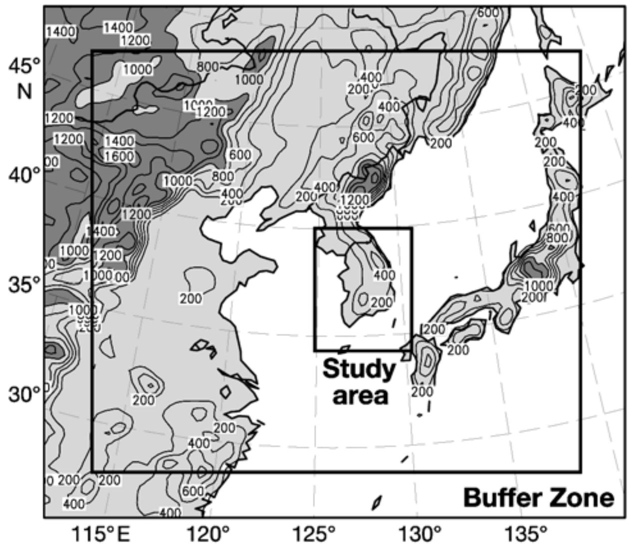

Fig. 1. Domain with terrain heights (m) for the model simulation in the present study. The sub-region for analysis and buffer zone are also indicated. Dark gray: land >1000 m

which were used for model climate validation, were the mean temperatures from 1971 to 2000 given in the CRU TS 2.1 data set (Mitchell & Jones 2005) provided by the Climatic Research Unit (CRU, University of East Anglia, Norwich, UK). Observed relative humidity data from 24 stations managed by the Korea Meteorological Administration (KMA) were used.

3. RESULTS

3.1. Projection of the surface air temperature

To validate the simulations carried out in the present study, temperature simulated by MM5 was compared with the CRU data set. The MM5-simulated temperatures for the period 1971–2000 realistically reflected the topographic features to the east of Korea, an area characterized by complex mountain regions. Obviously, the inclusion of orography in the RCMs helps to simulate more realistic surface temperatures, particularly over mountains (Kasahara & Warren 1971). The simulated horizontal distribution of temperatures was similar to that indicated by the CRU data set, with a bias of about 2°C colder temperatures over Korea (Fig. 2). According to Fu et al. (2005), the bias in regional climate simulations appears, not only in the MM5 simulation, but also in other RCMs. The present study showed that simulated temperature biases in the summer ranged from –3°C to +2°C across models, and the amplitude of the bias increased in winter. The spatial distributions of 30 yr annual mean surface temper-

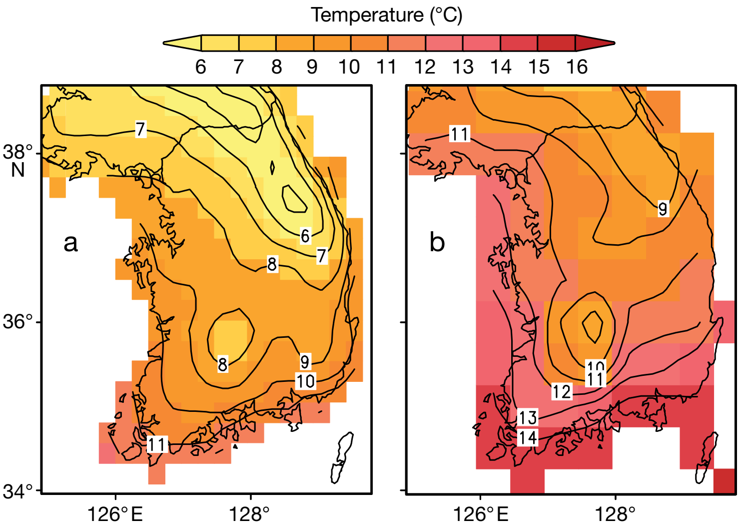

Fig. 2. Comparison of the horizontal distributions of annual mean temperatures (°C) using (a) MM5 simulation and (b) Climatic Research Unit (University of East Anglia) observed data for the 30 yr period 1971–2000

atures over the southern Korean Peninsula for the periods 2021–2050 and 2071–2100 are shown in Fig. 3. Annual mean temperatures in the MM5 simulation for the period 2021–2050 rose by approximately 1.3°C relative to the 30 yr mean (1971–2000) over Korea (Fig. 3a). Seasonally, the temperature rise was largest in summer and autumn (~1.5°C) (Fig. 3b), while that in winter was 1.1°C (Fig. 3c). The temperature increase at the end of the 21st century was similar to that in the middle of the 21st century, except with different amplitudes. The annual temperature was projected to increase by 3.8°C between 2071 and 2100 (Fig. 3d). Seasonally, temperature changed in the summer by 3.8°C (Fig. 3e), but the winter temperature increase at the end of the 21st century was ~4.0°C (Fig. 3f). In a latitudinal direction, the increase in the

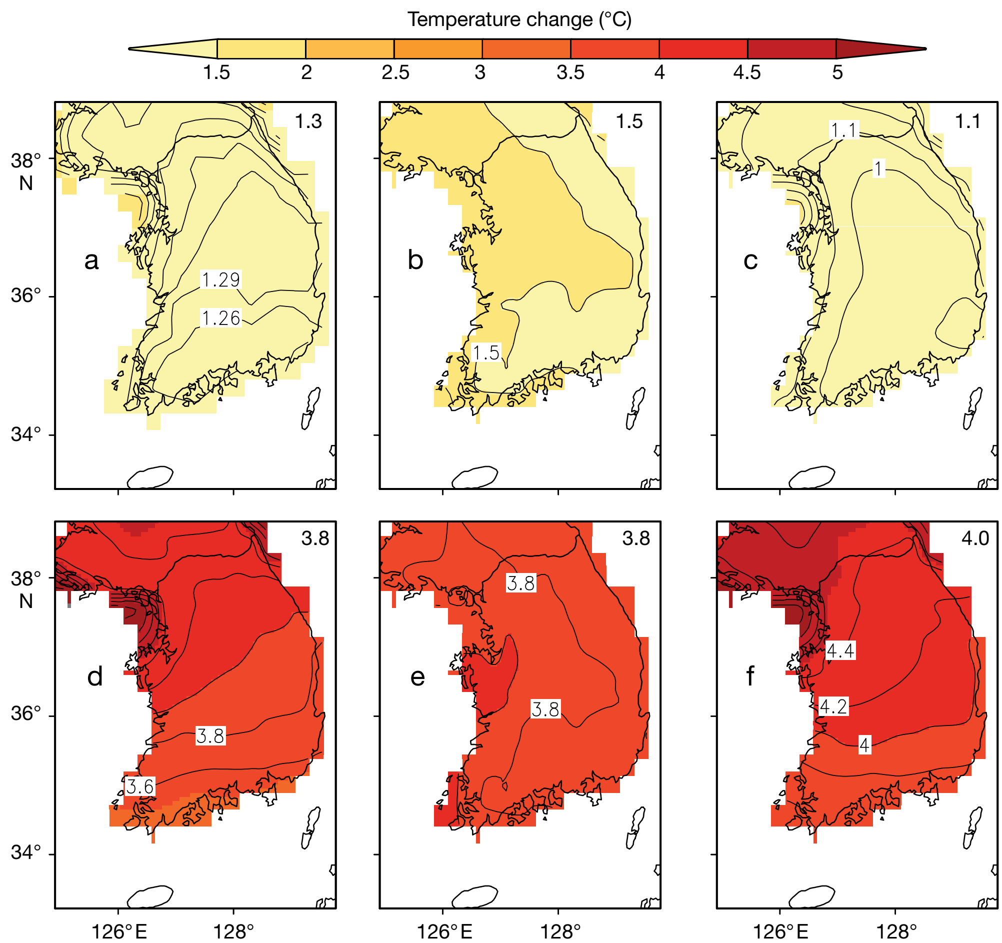

Fig. 3. Changes in daily mean temperatures (°C) for the periods (a,b,c) 2021–2050 and (d,e,f) 2071–2100 relative to the 1971–2000 period determined in MM5 simulations based on the Special Report on Emissions Scenarios A1B scenario. Left, middle and right panels indicate annual, summer and winter mean temperatures, respectively. Numbers in top-right of panels: area-averaged temperature changes (°C) over land

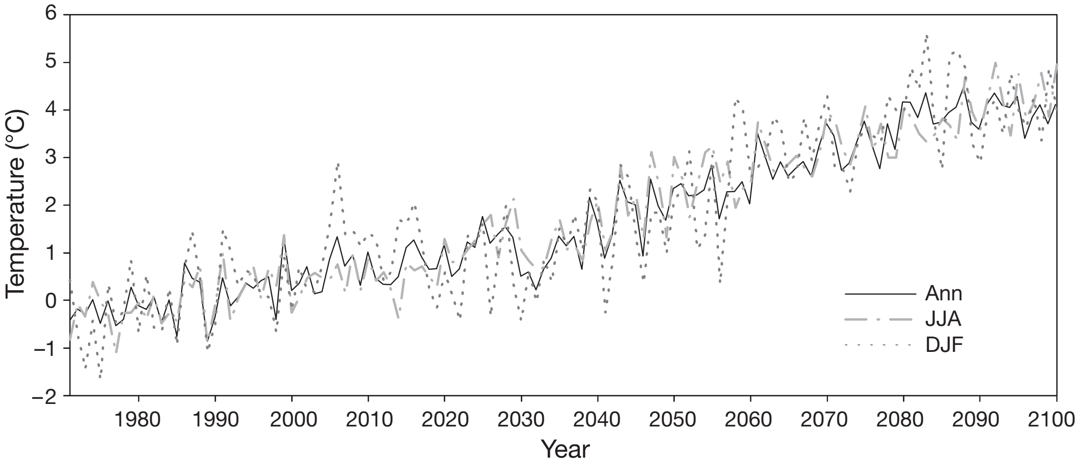

Fig. 4. Time series of daily mean temperature changes with respect to the 30 yr mean values (1971–2000) over Korea in the MM5 A1B simulation. Ann: annual; JJA: June, July, August; DJF: December, January, February

surface air temperature over Korea was greater towards the north. The amplitude of latitudinal difference increased at the end of the 21st century and the latitudinal changes were distinct in winter (Fig. 3f). Compared to winter, the increase in summer did not show a similar latitudinal change (Fig. 3b,e).

The results here were based on the SRES A1B scenario. The horizontal distribution of temperature increases was similar to the projection based on the SRES A2 scenario, except for the amplitude, as described by Boo et al. (2006). They reported that annual temperatures were projected to increase by 5.5°C by the end of the 21st century according to the SRES A2 scenario; the projection in the present study was 2.0°C lower.

Fig. 4 shows the annual time series of daily mean temperatures with respect to the mean value for the 1971–2000 period. The variation in winter temperatures was larger than that in summer temperatures, while the variation in summer temperatures had a similar amplitude to that in annual temperatures. The amplitude was especially large for the middle of the 21st century.

The probability density function (PDF) can be a convenient way of condensing a vast amount of data to express the probability of occurrence of an event (Brankovic & Palmer 1997). Therefore, to investigate the possible changes in the frequencies of temperatures, we investigated the frequency distributions of the daily mean, maximum and minimum temperatures over Korea for the entire length of the data record. In Fig. 5, simulated daily mean temperatures for the period 1971–2000 were projected to show a shift in distribution of mean values in the future. The simulated daily mean temperatures for the period 2021–2050 and 2071–2100 were increased by about 1.3 and 3.8°C, respectively, compared to the values for the period 1971–2000. The change in the standard deviation was negligible, which is consistent with the results of Boo et al. (2006). Similar to the daily mean temperatures, the daily maximum (minimum) temperatures for the period 1971–2000 were projected to show shifts in the distribution of the mean of about 1.2 (1.4)°C and 3.5 (4.0)°C for the periods 2021–2050 and 2071–2100, respectively (not shown). The increase in the minimum temperature was slightly larger than that of the maximum temperature.

The rise in temperature showed different magnitudes according to the height in the troposphere. Fig. 6 shows that changes in the projected temperatures over Korea increased with height, and the highest values were near the tropopause. Temperature increases were within 1.2–1.6°C for the period 2021–2050. At the end of the 21st century, the rising temperatures showed large differences between the surface and the 400 hPa level. The vertical profiles in Fig. 6 were similar to previous results based on ECHO-G simulations according to IPCC A2 and B2 scenarios (Koo et al. 2005). That is, the temperature change in the upper troposphere was greater than at the surface.

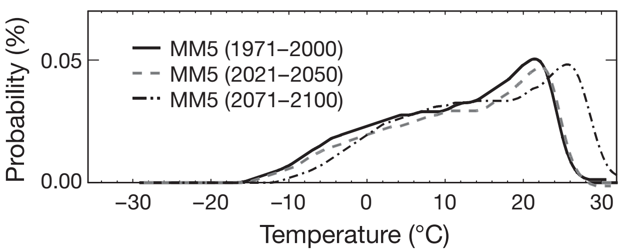

Fig. 5. Probability density function of projected daily mean temperatures over Korea. Lines according to the key indicate the MM5 simulations for the periods 1971–2000, 2021–2050 and 2071–2100, respectively

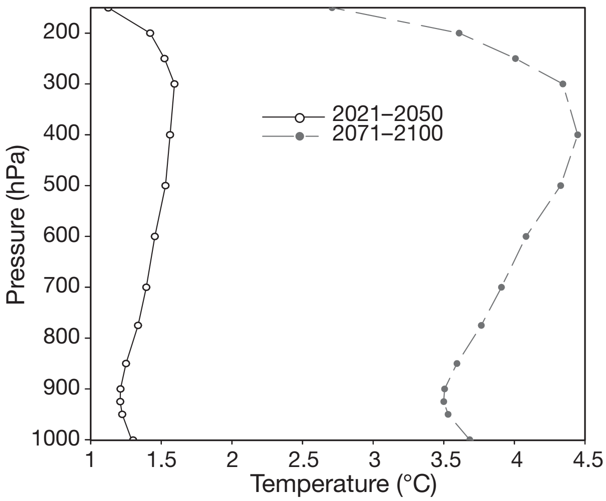

Fig. 6. Vertical profiles of projected changes in temperature for the periods 2021–2050 and 2071–2100, with respect to the 1971–2000 period over Korea

3.2. Changes in indices during extreme temperature events

Simulated future warming would have considerable implications for our daily lives (Dai et al. 2001). To estimate these consequences, we need to examine the details of change at sub-continental scales (Dai et al. 2001). In addition, changes in several indices of extreme events may have profound impacts on particular sectors of society or ecosystems (Alexander et al. 2006, Tebaldi et al. 2006). The indices of extremes in the previous studies were based on fixed values or percentiles. This study addresses intensity of temperature extremes, and uses percentiles of daily temperature. To estimate the change in intensity of temperature extremes, we defined the intensity and frequency of hot and cold events with the 95th percentile of daily maximum temperatures in summer and the 5th percentile of daily minimum temperatures in winter, respectively. The horizontal distribution of the 95th percentile of daily maximum temperatures showed that the percentile value was high in inland regions (Fig. 7a). The 95th percentile of daily maximum temperatures increased by about 2.3°C between 1971–2000 and 2071–2100 (Fig. 7b). The 5th percentile of daily minimum temperatures increased by about 5.3°C (Fig. 7d). Fig. 7 suggests the change in intensity of cold events was greater than that of hot events. The increases in the percentiles in the present study were smaller than the results according to the SRES A2 scenario, since Boo et al. (2006) presented a 4 to 5°C change in the 95th percentile and a 7 to 9°C increase in the 5th percentile.

Intensity changes during extremes were accompanied with changes in frequency. Fig. 8 shows the frequency changes in the 95th and 5th percentiles of daily maximum and minimum temperatures. In the period 2071–2100, the frequency of hot events was about 5-fold

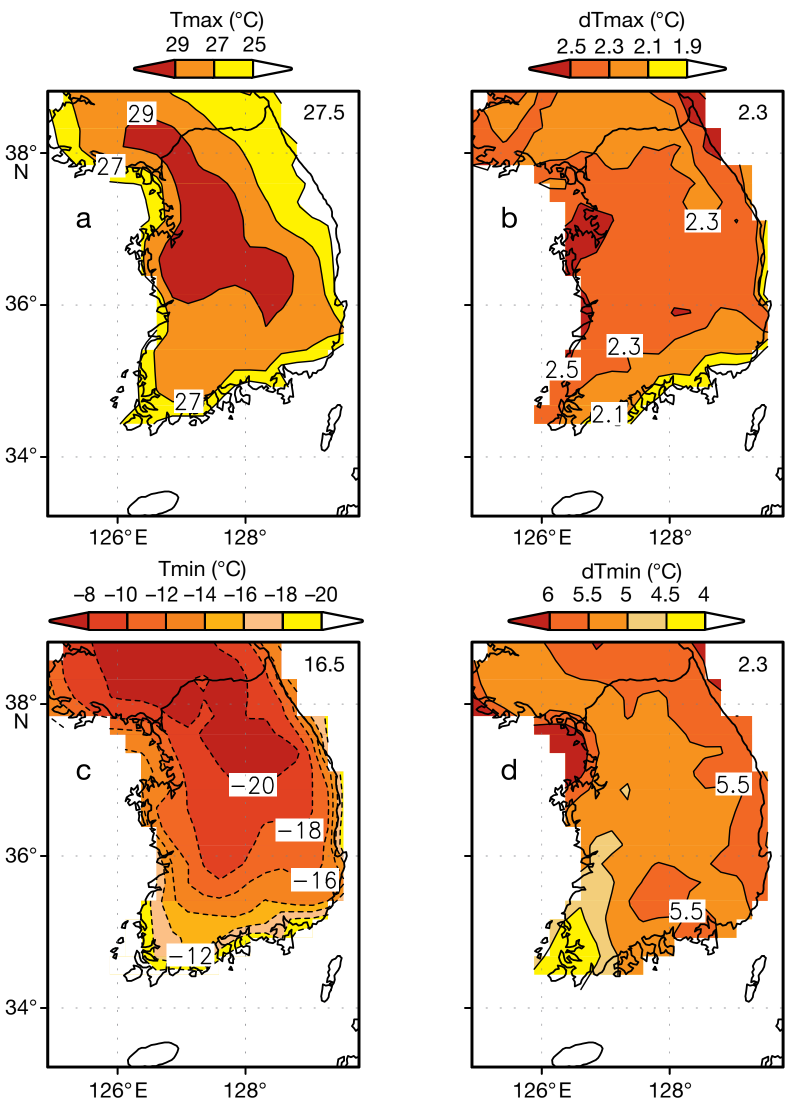

Fig. 7. (a) The 95th percentile of daily maximum temperatures (Tmax) in summer and (c) the 5th percentile of daily minimum temperatures (Tmin) in winter, for the period 1971–2000 in the MM5 A1B simulation. (b,d) Changes in the percentiles in Panels (a) and (c) (dTmax and dTmin, respectively) for the periods 1971–2000 and 2071–2100. Numbers in top-right of panels: area-averaged temperatures over land

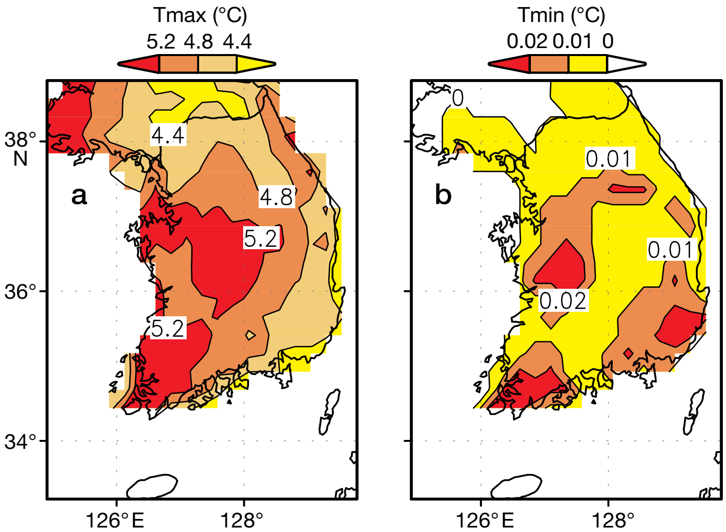

Fig. 8. Ratio of the future frequencies of (a) the 95th percentile of daily maximum temperatures (Tmax) in summer and (b) the 5th percentile of daily minimum temperatures (Tmin) in winter, for the period 2071–2100, with respect to the frequency in the 1971–2000 period

that in the 1971–2000 period (Fig. 8a). The frequency of cold events, defined by the 5th percentile for the period 1971–2000, was projected to be reduced by 99% (Fig. 8b).

3.3. Humidity

In association with warmer climate, a previous study projected that relative humidity would remain fairly constant, leading to an increase in specific humidity (Willett et al. 2007). We compared mean annual relative surface humidity between the KMA observations from 24 surface stations and the MM5 simulation for the period 1971–2000. The magnitudes were similar in both data sets. Averaged over Korea, the MM5 relative humidity showed a slight bias of +0.06%. Projections in the present study showed similar spatial patterns of relative surface humidity, except in the magnitudes, as time went on (Fig. 9).

Relative humidity is expected to increase by about 2% over Korea by the end of the 21st century. According to Willett et al. (2007), a larger response of specific humidity is expected for a given change in temperature in warmer regions, as a result of the approximately exponential dependence of saturation vapor pressure on temperature. The relationship between specific humidity and height showed distinct changes near the surface, as illustrated in Fig. 10. In the upper troposphere, specific humidity did not change. Therefore, the vertical profile of the 2071–2100 period differed from that of the 1971–2000 period only for the lower troposphere. Specific humidity increased in response to rising temperatures (Willett et al. 2007). Specific humidity at the surface increased by 0.0018 g kg^{-1} in the 2071–2100 period relative to the 1971–2000 period. Future atmospheric water vapor content increased by 29% at the surface compared with that of the 1971–2000 period. Assuming the projected warming of 3.8°C for the 2071–2100 period, simulated water vapor content near the surface changed at an increasing rate of 7% K^{-1}. The water-holding capacity of the atmosphere is related to rainfall intensity (Trenberth et al. 2003). The related change in rainfall rate over Korea needs further study.

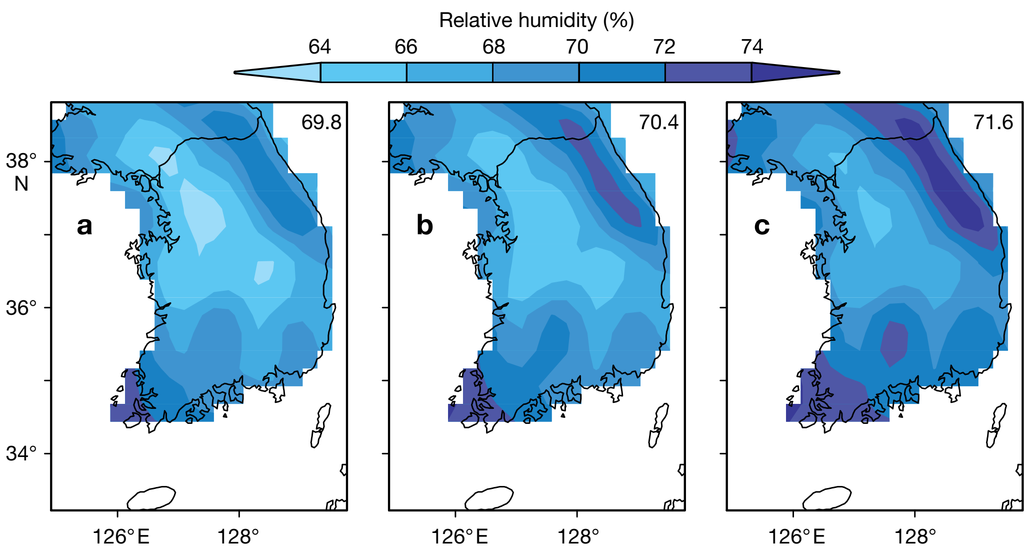

Fig. 9. Horizontal distributions of the simulated surface relative humidity for the periods (a) 1971–2000, (b) 2021–2050 and (c) 2071–2100. Numbers in top-right of panels: area-averaged relative humidity (%) over land

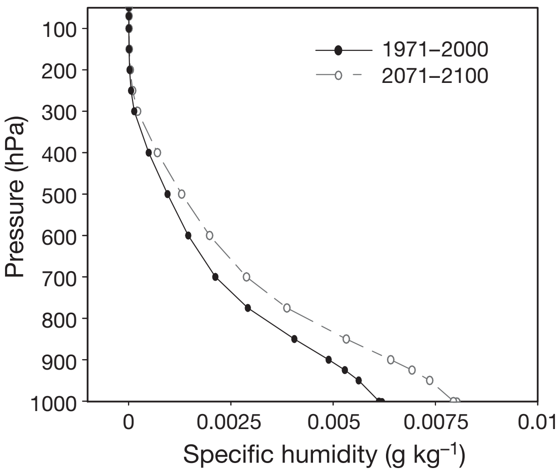

Fig. 10. Vertical profiles of annual mean specific humidity changes (g kg^{-1}) for the periods 1971–2000 and 2071–2100, using MM5 simulations

4. DISCUSSION AND SUMMARY

To provide information on future regional climate change over a region of complex topography like Korea, MM5 downscaling simulation was performed at 27 km horizontal resolution. The downscaled temperature realistically reproduced the features over Korea. According to the A1B scenario, the annual mean temperature over Korea was projected to increase by 1.3°C between the 1971–2000 and 2021–2050 periods. The warming trend became even stronger in the second half of the 21st century and led to an increase of 3.8°C by the 2071–2100 period. Considering minimum and maximum temperatures, the change in minimum temperatures was larger (4.0°C) than the increase in maximum temperatures (3.5°C). These results are consistent with the regional projection for East Asia by the IPCC (2007). Moreover, the troposphere temperatures determined in the present study by regional projection show consistency with the global climate projections of the IPCC (2007).

Temperature increases resulting from global warming tend to be greater for higher latitude regions (IPCC 2007). The latitudinal difference appears to be about 0.6°C over South Korea. Seasonally, the latitudinal difference appears to be larger in winter (1°C) than in summer. The amplitude of the inter-annual variability was also larger in winter than in summer.

A change in mean temperature accompanies a change in the frequency and intensity of temperature extremes. Analysis of the 95th percentile of daily maximum temperatures projected that hot events would be stronger and more frequent at the end of the 21st century. Changes in the 5th percentile projected weaker and rarer cold events.

In the present study, we were able to estimate the changes in temperatures and temperature extremes over Korea, as they would be affected by the different CO_2 concentrations integrated into the A2 versus the A1B scenario for the period 2071–2100. These results are part of a continuing simulation effort by the NIMR (2004) to support climate change impact assessment. Between these two scenarios a 2°C difference in mean temperature increase was determined; changes in the intensities of hot and cold extremes were similar.

The analysis of humidity demonstrated a regional-scale pattern when global warming was thermodynamically balanced. Consequently, the projections in the present study make it feasible to estimate potential regional climate change, including seasonal features and extremes over Korea.

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