Characteristics of Extreme Climate Sequences over Korea Using a Regional Climate Change Scenario

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Abstract
We investigate the characteristics and potential future change of extreme climate phenomena based on daily statistical properties. To assess the fine-scale climate change projection over Korea, an ECHO-G B2 scenario simulation has been dynamically downscaled by using the RegCM3 nesting system. Two sets of multi-decadal simulations are performed for the present day (1971–2000) and future climate (2021–2050). We analyze four categories of weather spells in terms of the sequences of dry/wet and frost/hot days from the nested domain simulation of 20 km grid spacing. In the validation of the reference scenario, the model shows a reasonable performance of reproducing both observed climatological and distinct characteristics of each spell. Regarding the projected extreme climate events, the results indicate not only a significant change in frequency and intensity, but also substantial change in the fine scale detail of the regional distribution of temperature-based as well as precipitation-based extreme events. A substantial increase of hot spells is found along with increasing of maximum temperature. Longer-period frost spells are projected to decrease, whereas relatively short-period frost spells are likely to increase due to breaks of long spells by greenhouse warming. Wet spells of long periods tend to be more frequent, showing a distinct variation across regions.

1. Introduction
One marked objective of regional climate models (RCMs) is to provide high-quality information with suitably fine scale for resolving complex topography, land-sea contrast, and detailed description of physical processes to impact assessment fields (Giorgi et al. 2001; Leung and Ghan 1999; Shin et al. 2006; Cocke and LaRow 2000). The potential users of climate information are often concerned with the characteristics of high-frequency weather at a particular location (Robertson et al. 2004). While the RCM evaluations of climatology in seasonal and monthly average demonstrate encouraging performance over various regions, there are more discrepancies between the observation and the simulation of the statistics of local climate based on daily data. Moreover, intensive examinations of daily properties appropriate for analyzing extreme events are relatively limited so far. To better understand the spatial and temporal characteristics of extreme events at regional scales remains as one of the major challenges.

In this study, we attempt the ‘series’ approach using daily data from a downscaled regional climate change scenario in terms of the sequences of wet/dry and frost/hot days. Because persistence of weather events may lead to extremes such as flood, drought and so on, successive duration is crucial for a realistic assessment in application of hydrological and agricultural models. Successive events of various durations can reveal significant structure of the frequency and intensity of extremes (Halenka et al. 2006).

We first evaluate the reference scenario against a dense observational network over the Korean territory. In order to obtain confidence in a future climate projection, it is necessary to demonstrate the ability of the regional model to adequately capture the characteristics of the observed regional climate. In addition, we address possible future changes of daily extreme events from the difference between future (2021–2050) and reference (1971–2000) scenarios. Considering a gradual warming experience throughout the 20th century, Korea will be strongly expected to be vulnerable to climate change (Oh et al. 2004; Boo et al. 2004; Boo et al. 2006). In particular, Korea is vulnerable where water resource is considered, since the geographical area is small and has complicated mountainous terrain, and since the climate of Korea is characterized by the occurrence of extreme precipitation episodes (Im et al. 2006b). A recent study using the outputs of the IPCC AR4 coupled climate models also reports a significant increase of summer monsoon precipitation and a possible increase in the length of the summer monsoon period over East Asia in particular over Korea (Kripalani et al. 2006). Hence it is important to quantify the influence of greenhouse-gas-induced climate change upon the frequency and intensity of extreme events at regional scale. We have focused mostly on the fine structure of the dry and wet spells induced by daily precipitation and frost and hot spells induced by daily minimum and maximum temperature of various durations.

2. Data and method
For simulating the fine-scale climate change scenario, a one-way double-nested regional climate model system using ICTP Regional Climate Model, RegCM3 (Im et al. 2006a) has been applied to ECHO-G (ECHAM4/HOPE-G) global climate model of approximately 350 km horizontal resolution (Min et al. 2005) under forcing from the IPCC SRES B2 emission scenario (IPCC 2000). Two 30-year long experiments are performed, one for present day conditions (1971–2000) as a reference and the other for near future climate conditions (2021–2050). Changes in mean climate are intensively discussed for the 30-year period of 2021–2050 with respect to the reference period of 1971–2000 in Im et al. (2006c). For brevity, warming in the range of 1.71–2.24°C is found throughout the mean temperature change over Korea, and more pronounced over colder regions and seasons. Precipitation increase up to 30% in the winter season is also found. The datasets used in this study are daily maximum/minimum temperature and precipitation from the nested domain simulation focused on Korea at 20 km grid spacing. Further details...
occurs if the maximum temperature exceeds 30°C. In general, the model temperature in the frost/hot spells averaged over the season in the wet spells and daily minimum/maximum variation across durations between observation and reference scenario. The lines in Fig. 2 indicate the daily precipitation while the lines for the frost (hot) spell indicate the daily minimum (maximum) temperature averaged over the spells of each duration class. The regional averages were obtained by averaging the values at each grid point closest to the observation stations over Korea. The monthly mean duration of wet spells is invariably shorter than those of dry spells. Overall, the model results agree well with the observed monthly variation and characteristics of each spell. For comparison between dry and wet spells, the shape of both distributions are quite different, indicating that dry spells exhibit a much longer duration than the wet ones. The model reproduces dry spell characteristics not only for the relative ratio of the frequencies but also total number of frequency of various durations. In contrast to dry spells, all wet spells are longer than 3 days. The model shows a good performance in simulating the wet spells of duration less than 7 days, the model tends to overestimate rainy days for durations exceeding 7 days. Regarding the precipitation, although the frequency variation across durations between observation and simulation shows similarities, the averaged daily precipitation for each duration is severely underestimated. In particular, the model deficiency in precipitation is amplified as the duration lengths become longer. In this regard, the precipitation underestimate bias presented in this model (Im et al. 2006b) is probably not due to an underestimate of the frequencies, but to an underestimate of the intensities of events in the mid to high range (mostly during the summer season). Moving to the frost and hot spells, we can also notice that there are noticeable differences between both spells. The frequency of frost spells decreases more slowly as the interval length increases, with a heavier tail. While the model is capable of reproducing the frequency distribution characteristics, corresponding to the hot and frost spells, the model has the limitation of capturing the most extreme case. The extreme hot spells exceeding 17 days are severely underestimated, or entirely missed while the extreme frost spells exceeding 65 days are overestimated. In addition, maximum (minimum) temperature for a hot (frost) spell duration is also taken into consideration. In hot spells, the frequency is underestimated while the maximum temperature averaged during a hot spell is above observation. Conversely, the minimum temperature is systematically underestimated. The RegCM3 system applied in this study has previously been shown to have a cold bias in temperature, particularly in the cold season (Im et al. 2006b). The cold bias of the warm season is mainly due to the reduced frequency of extreme hot spells while the bias during the cold season is due to the combined effect of overestimated frequency of frost spells as well as overall lower temperatures.

of the high resolution climate change scenarios can be found in Im et al. (2006b, c).

For the validation of the reference scenario, we used climate observations from 57 stations maintained by the Korea Meteorological Administration (KMA) for the period of 1975 to 2004 throughout the southern part of Korea. The relatively high model resolution justifies the comparison between station data and model data at the grid point closest to the station location (Im et al. 2006a).

In this study, the four categories of spells are calculated as a number of consecutive days as follows. All spells are divided into 9 duration intervals. Each duration interval is empirically chosen based on the expected properties of the weather variables, as interval size gradually increases.

1. Dry and wet spells: A wet day is defined as a day with precipitation accumulation greater than or equal to 1.0 mm, whereas a dry day represents a day without precipitation or with too little precipitation (less than 1.0 mm) within a day. At least one dry (wet) day is referred to as a dry (wet) spell. It means there are alternating occurrences of wet and dry spells over the whole record.

2. Frost and hot spells: A frost day is defined as a minimum temperature less than 0°C, while a hot day occurs if the maximum temperature exceeds 30°C.

3. Results

3.1 Reference scenario (1971–2000)

We begin our analysis with a comparison of the annual cycle of dry and wet spells between observation and the reference scenario. Figure 1 shows the monthly mean duration of area-averaged dry and wet spells over Korea. The regional averages were obtained by averaging the values at each grid point closest to the observation stations over Korea. The monthly mean duration of wet spells is invariably shorter than those of dry spells. Overall, the model results agree well with the observed monthly variation and characteristics of each spell. However, some substantial differences between observed and simulated wet spells are found during summer season. The model overestimates wet spells duration in July and August, and this pattern contrasts with monthly precipitation amounts, which the model markedly underestimates during summer (Fig. 11 in Im et al. 2006b). These results thereby indicate that the model is likely to underestimate the summer precipitation intensity.

Basic characteristics of individual spells are summarized in Fig. 2. It describes the annual frequency distribution of four spells viz. dry, wet, hot, and frost of various durations between observation and reference scenario. The lines in Fig. 2 indicate the daily precipitation in the wet spells and daily minimum/maximum temperature in the frost/hot spells averaged over the spells of each duration class. In general, the model reasonably captures the annual (Fig. 2) as well as seasonal (not shown) frequency distribution characteristics as compared with observations for each spell category. For comparison between dry and wet spells, the shape of both distributions are quite different, indicating that dry spells exhibit a much longer duration than the wet ones. The model reproduces dry spell characteristics not only for the relative ratio of the frequencies but also total number of frequency of various durations. In contrast to dry spells, all wet spells are longer than 3 days. The model shows a good performance in simulating the wet spells of duration less than 7 days, the model tends to overestimate rainy days for durations exceeding 7 days. Regarding the precipitation, although the frequency variation across durations between observation and simulation shows similarities, the averaged daily precipitation for each duration is severely underestimated. In particular, the model deficiency in precipitation is amplified as the duration lengths become longer. In this regard, the precipitation underestimate bias presented in this model (Im et al. 2006b) is probably not due to an underestimate of the frequencies, but to an underestimate of the intensities of events in the mid to high range (mostly during the summer season).
Throughout the validation of reference scenario, we confirmed that the model shows a reasonable performance of reproducing both observed climatological and instinct characteristics of each spell, despite the biases described above.

In the next section, we turn our attention to the future projection of extreme climate events.

3.2 Future scenario (2021–2050)
Figure 3 presents the potential future change of frequency and intensity of the extreme events. Dry spell change does not reveal any significant trend due to anthropogenic forcing. On the other hand, wet spell change is characterized by the reduction in events less than 3 days and enhancement in events exceeding 4 days. As indicated by the averaged daily precipitation for each duration, an increase of precipitation intensity is projected in the future except for the 12–24 day duration. In this duration, total precipitation amounts increase, but the frequency also increases. Thus the intensity tends to slightly decrease. The results suggest the possibility that precipitation intensity in the future may increase in response to the anthropogenic forcings, and appears in line with results found in other regional climate change projections for the 21st century (Boo et al. 2006; Gao et al. 2006a; Kimoto et al. 2005).

As global warming undergoes, an increase in the number of hot days has been projected over Korea, along with increasing mean maximum temperature except for the 13–16 day duration. At the same time, episodes of severely successive cold days may become less frequent, along the lines of those found in Mizuta et al. (2005). However, relatively short period frost spells are likely to increase due to breaks of long spells by greenhouse warming. A substantial increase of minimum temperature is found throughout the whole duration. The increasing trend of projected temperature due to anthropogenic forcing is associated with an increase (decrease) in the number of hot (frost) days as well as corresponding maximum/minimum temperature.

As an attempt to assess the regional distribution of the potential changes of extreme events, we examine the spatial distribution of the longest duration difference in the four types of spells (Fig. 4). These are calculated by finding the maximum duration of the four spells in each simulated year and then averaging them over the 30 simulated years at each grid point closest to the observation stations over Korea. We then carried out a two-tailed t-test to calculate the statistical significance of these changes. In Figs. 4 (a) and (b) shading in dry and wet spell indicates areas where the change is statistically significant at the 90% confidence level while the entire analysis area for frost and hot spells is statistically significant at the 95% confidence level (not indicated by shading). The change of temperature-based extremes shows a substantial warming signal induced by anthropogenic forcing in terms of a decrease of frost spells and an increase of hot spells, indicating robustness of the projected changes. By comparing the change in pattern between hot and frost spells, a more pronounced decrease of frost spells in the cold season is found. The spatial pattern of frost spell change is similar to that of the lowest minimum temperature change (Im et al. 2006c). The distribution is modulated by local geographical features with northward gradient of warming across Korea in response to a notable increase of minimum winter temperature. For hot spell change, we find a maximum distribution with the center around 36 °N in the southern parts of Korea, and its location is consistent with the area of maximum decreased wet spells. Especially, the area of maximum change of increased hot spells and decreased wet spells coincided with the location of the negative peaks in the Palmer Drought Severity Index (PDSI) anomalies during 2031–2060 relative to 1971–2000 using the downscaled ECHO-G A2 scenario reported by Boo et al. (2004). In contrast to the temperature change, the projected change of precipitation-based extremes shows low statistical confidence, likely because of the large natural variability of this variable. The fine scale detail in the change distribution found across Korea indicates the need of high resolution climate simulations over the region.
4. Discussion and conclusions

To estimate the characteristics and potential future change of the extreme climate phenomenon over Korea based on daily statistical properties, we analyzed the downscaled regional projection data from the RegCM3 nested simulation at 20 km grid under forcing from the SRES B2 emission scenario.

Simulated monthly averaged dry and wet spell durations reproduce reasonably well the observed seasonal variation and characteristics even though there is a tendency of the model to underestimate precipitation intensity in summer. The model is also capable of capturing the frequency distribution of various durations, which shows a distinct characteristic shape across each of the four categories of spells. The simulated daily temperature and precipitation reproduce each spell characteristics not only for the relative ratio of the frequencies but also absolute number of frequency of various durations. Throughout the evaluation against station observations, despite some limitations, the simulated frequencies as well as intensity of extreme sequences generally show an encouraging performance over Korea, whose monsoon-dominated climate has been traditionally very difficult to simulate with global climate models (e.g., Gao et al. 2006b).

The projected change signal shows significant potential impacts over Korea, not only in terms of the frequency change, but also in terms of shifts in the distribution for vulnerable regions. While dry spell change does not reveal any significant trend due to anthropogenic forcing, wet periods become more frequent, showing an increase of total precipitation amounts as depicted by the IPCC AR4 coupled models (Kripalani et al. 2006). The warming in the future scenario run mostly manifests itself with an increase of both maximum and minimum temperatures. A substantial increase of hot spells is found throughout whole duration, but frost spells decrease for the extremely longest duration class exceeding one month. Large-scale forcing caused by global warming may locally change the distribution of extreme climate sequences over Korea, which is typified by complex topography and coastlines.

This study provides strong evidence that the substantial fine scale detail in the climate change pattern is found across Korea, which justifies the need of high resolution modeling over the region. We plan to produce ensembles of simulation using different emission scenarios to evaluate the uncertainty and reliability associated with surface climate change projections over Korea.

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