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Projection of future hot weather events and potential population exposure to this in South Korea

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ABSTRACT: Heat waves, often caused by consecutive severe hot weather events, are responsible for the majority of medical costs associated with climate change in South Korea. In this study, we obtained a regional climate change scenario (RCP4.5) for South Korea, with 7.5 × 7.5 km horizontal resolution and extending up to 2100, by dynamically downscaling from results of the Community Earth System Model (CESM) with the Weather Research and Forecasting (WRF) model. We analyzed hot weather events (daily maximum temperature >33°C) in summer (June–August), focusing on changes in extent and frequency. According to our analysis, the area exposed to hot weather events in August will expand to cover ~70% of the nation in the middle of this century, with a rate of increase of 0.24% yr^{-1}. We calculated the population exposed to hot weather events in Korea, considering both spatial coverage and number of event days. Population exposure was projected to increase almost 3-fold, from 26% of the national population during the 2010s to 72% during the 2090s. In particular, exposure of the elderly population (>65 yr old), who are particularly vulnerable, was expected to rapidly increase, with ~22% of the national population (~10.4 million people aged >65 yr) affected in the middle of this century when we considered the future projection of rapid aging of the South Korean population structure. Our projection of extensive hot weather events starting from the middle of the 21st century suggests the need for urgent government long-term measures and enforcement to ensure an early response to extreme weather events in Korea.

KEY WORDS: Climate change · Climate vulnerability · Hot weather · Korea · Population exposure · Representative Concentration Pathways · RCP scenarios

1. INTRODUCTION

Heat waves, which are generally defined as extreme weather conditions due to an extended period of unusually high air temperature, often lead to adverse health consequences (Robinson 2001) and great economic loss (Meehl et al. 2000, Beniston & Stephenson 2004, Kysely & Huth 2004, Knowlton et al. 2011). In the USA, 10 major droughts/heat wave events in 1980–2003 accounted for the largest economic loss (US$ 144 billion) among weather-related disasters (Ross & Lott 2003). In South Korea, 3384 people died due to an unusual heat wave in 1994 (KMA 2012, 2013). There has been a warming trend since the 20th century in Korea, as indicated by the increase in daily summer maximum temperature (Choi et al. 2007, Na 2015). Specifically, maximum temperature has increased over the major cities of South Korea from 1961 to 2000, with a rate of increase of more than twice that of the global average (0.028°C yr^{-1} for Seoul), which includes the impact of urbanization (Choi et al. 2007).

The number of heat wave days in Korea in the 1990s and 2000s has ranged from 5 to 20 days yr^{-1}

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under different heat wave definitions, and the occurrence of heat waves in Korea has increased over this period (Park et al. 2008, Son et al. 2012). In particular, heat waves have been more intense over southern provinces (including the Yong-Nam and Ho-Nam regions) (B. C. Choi et al. 2007, G. Y. Choi et al. 2008, Jeung et al. 2013, KMA 2013, Kim et al. 2014, Na 2015), and heat wave warnings or alerts were issued for most regions of Korea in summer 2013 (KMA 2013).

Heat waves in South Korea are most intense in late July through early August and the mortality rate is highest for people aged >65 yr due to their impaired ability to adapt to heat (Woodward & Scheraga 2003, Kim et al. 2006, Lee 2015). Not including the extreme heat wave disaster in 1994, the death toll due to heat waves has continued to rise since the 1990s (Park et al. 2008, Kim et al. 2014, Lee 2015).

Knowledge of potential extreme events in the future climate is necessary for the development of national plans for adaptation. According to the IPCC, global average surface temperature is projected to rise by 1.1–6.4°C by the 2090s (compared to 1980–1999; IPCC 2007). The frequency, intensity, and duration of heat waves will likely increase in the future (IPCC 2014). In addition, it has been reported that the adverse impacts on health of increased heat wave frequency in the future greatly outweigh the benefits of reduced cold spells associated with climate change (Kinney et al. 2012, Ebi & Mills 2013), due in part to the larger and more immediate rises in mortality caused by heat waves (Deschênes & Moretti 2009). For the USA, the Representative Concentration Pathway (RCP) scenarios suggest that mortality risks at the end of this century are expected to increase by an order of magnitude compared with the current risk (2002–2004) (Wu et al. 2014).

A number of studies have been conducted regarding future hot weather patterns and the responses required for the vulnerable population in Korea. According to RCP-based climate scenarios, future hot weather is likely to occur in the metropolitan area over the central regions (e.g. Seoul Metropolitan Area [SMA] with a population of ~20 million) and the southern regions of Korea (Jeung et al. 2013, Park et al. 2013). Park et al. (2013) concluded that most regions of South Korea, except for the mountainous regions, will have >30 d of heat waves in 2070, based on RCP8.5. Mortality due to heat waves is also expected to increase accordingly, with the current rate of 0.7 deaths per 100 000 population in 2001–2010 increasing to 1.5 deaths per 100 000 population in 2040 (Yang & Ha 2013).

The present study used the RCP4.5 scenario, which represents relatively moderate greenhouse gas mitigation to stabilize radiative forcing at 4.5 W m^{-2} in this century, to analyze the future projection of hot weather events in Korea. Our RCP4.5 scenario for Korea is based on the Community Earth System Model (CESM) developed by the US National Center for Atmospheric Research (NCAR), and the global model results were downscaled by a regional-scale meteorological model (Weather Research and Forecasting [WRF]) to obtain a climate scenario with a horizontal resolution of 7.5 × 7.5 km over Korea.

With the estimated regional climate scenario for Korea, we investigated the projection of hot weather events regarding the spatial distribution and the cumulative number of days where a hot weather event is experienced in the 21st century. Additionally, this study investigated changes in the population exposed to hot weather events in Korea by estimating the population of affected administrative districts with corresponding model grids. Estimation of the exposed population can be used to gauge the potential health effects of hot weather events in the future, which is critical information for developing national adaptation measures to climate change in Korea.

The main objective of this study was to estimate the future population exposed to hot weather events in Korea based on the national-level climate scenario in order to support a long-term national policy.

2. DATA AND METHODOLOGY

2.1. Dynamical downscaling of global climate model results

We used the RCP4.5 scenario over Korea, which is based on results of the CESM model (www.cesm.ucar.edu/models) with a spatial resolution of 1.9° × 2.5°. CESM is a climate model that simulates the Earth's climate system and consists of submodels of the atmosphere (CAM), ocean (OCN), land (CLM), sea ice (CICE), and land ice (GLC). These submodels are connected through a coupler (CPL) that exchanges the feedbacks. We used CESM (v.1.0), developed by the NCAR and supported by the National Science Foundation (NSF) and Department of Energy (DOE), USA. WRF is a mesoscale numerical weather prediction model designed to support atmospheric forecasting and research by providing a variety of dynamic cores, with data assimilation and parallel computing (www.wrf-model.org/index.php/).

To dynamically downscale the CESM results, meteorological variables from the CESM model were used as the initial and boundary conditions for the WRF (v.3.3) model at 6 h intervals to produce regional-scale scenarios with a 7.5 × 7.5 km spatial resolution for the Korean Peninsula for 2006–2100. Detailed methodology for the dynamical downscaling has been reported previously by Seo et al. (2013). Fig. 1 shows the model domain for the CESM and the boundary of the WRF model for dynamic downscaling.

2.2. Bias correction based on ground observations

The climate model results inherently contain uncertainties, which can be amplified during the downscaling (Ho et al. 2011). It is agreed that downscaled surface variables, such as precipitation and temperature, should be comparable to observations to ascertain credibility in the projected scenarios (Lee et al. 2014).

Bias correction was estimated from the difference between simulated and observation data on a monthly basis from 2006 to 2014. The calculated bias correction was applied to the future climate projection, as in previous studies (delta change approach) (e.g. Graham et al. 2007, Sperna Weiland et al. 2010, Ho et al. 2012).

Observation data from ~400 nationwide ground stations were used for bias correction over South Korea. To undertake bias correction for temperature, we mapped the observational points with the corresponding model grid (7.5 × 7.5 km) considering geographical elevation. If the model grid contained a measurement station, bias was calculated directly. If the model grid did not contain a measurement station, data from the closest adjacent station were used to calculate bias over the shortest distance, which is similar to the gap-filling process for missing satellite observations where the interpolation of surrounding good-quality data is used to cover gaps (Zhao et al. 2011). This grid-based bias correction was applied to monthly temperatures from 2006 to 2014. The estimated bias for each grid was applied to the climate scenarios for the future projection of temperature.

Although there are many definitions of heat waves, we adopted the current official definition used by the Korea Meteorological Administration (KMA), i.e. a daily maximum temperature >33°C, based on regional information for health impacts (KMA 2013, Park et al. 2013). Because this definition simply classifies single days based on a predefined temperature threshold, we adopted the term 'hot weather events' for clarity. Hot weather events in Korea mostly occur in July and August, with the number of hot weather days being highest in August (Park et al. 2008, Kim et al. 2014). Based on the frequency of national hot weather events for the last 20 yr, we analyzed hot weather events in the Korean summer months (June–August).

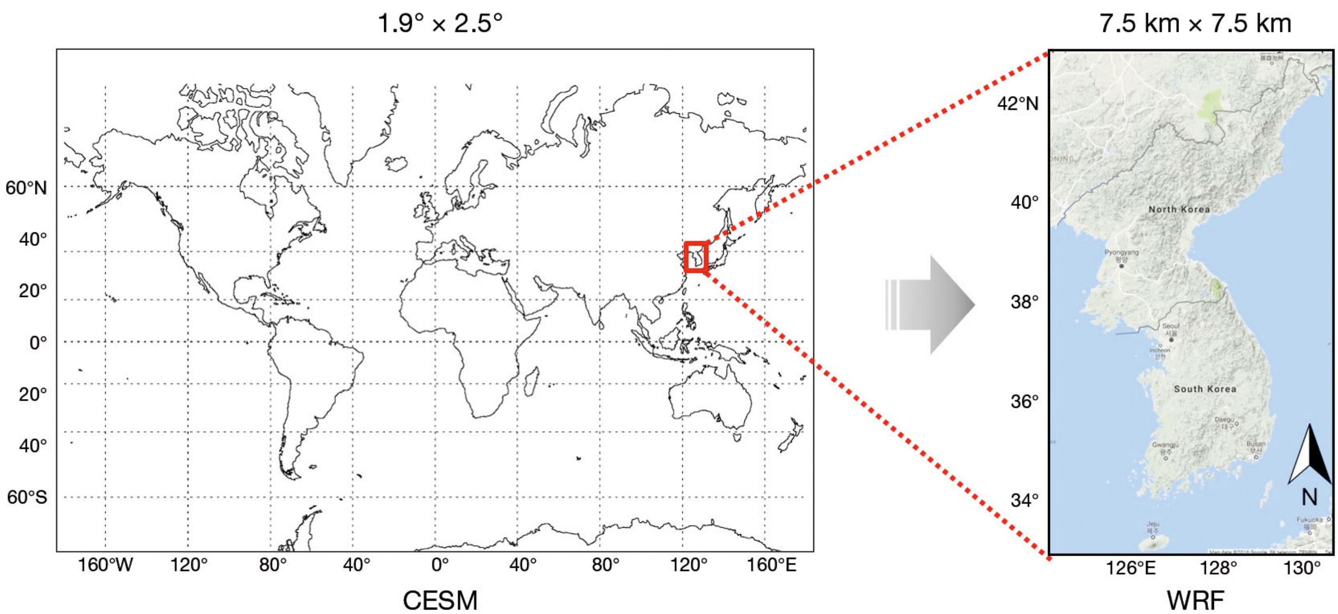

Fig. 1. Model domain for dynamic downscaling of climate scenarios from the global scale climate model Community Earth System Model (CESM; 1.9° × 2.5° spatial resolution) (left) by the Weather Research and Forecasting model (WRF; 7.5 × 7.5 km horizontal resolution) (right)

2.3. Considering both area and frequency of hot weather events

We evaluate the national impact of hot weather events in terms of both area and frequency by integrating the area and frequency (IAF, %) of hot weather events. IAF is defined here to evaluate the spatiotemporal extent of hot weather events. IAF is obtained by the integration of each unit of area with a hot weather event multiplied by the frequency (number of days), which is then divided by the area of the entire nation multiplied by the total number of days in the month, as follows:

$$\mathrm{IAF}(\%) = \frac{\sum_{\mathrm{i}=1}^{h} A_{\mathrm{i}} d_{\mathrm{i}} \times 100}{\sum_{\mathrm{i}=1}^{t} A_{\mathrm{i}} D} \tag{1}$$

where A is the area of grid i with a hot weather event, h is the total number of grids with hot weather events, d is the number of heat wave days in grid i, t is the total number of grids over South Korea, and D is the total number of days per month (~30 d). For example, an IAF of 100% indicates that the entire area of South Korea is exposed to hot weather events every day during that month.

2.4. Estimating population exposed to hot weather events

One of the main objectives of this study was to estimate the future population that will be exposed to hot weather events in Korea. Estimation of the exposed population was undertaken by mapping the 228 administrative districts (vector data) containing population information to the geographical information on the corresponding model grid (7.5 × 7.5 km, raster data). The area used for sampling was the model grid with total number of hot weather days per year >11 d, which was the average number of hot weather days over a 30 yr period (1981–2010; Na 2015). Population data, with age groups, for each administrative district, was based on 2010 data from the Korea Statistical Information Service (KOSIS) (http://kosis.kr/statHtml/statHtml.do?orgId=101&tblId=DT_1IN0001_ENG&conn_path=I3).

For mapping, we used ArcGIS (v.10.1) software, with the zonal statistics method. If one administrative district matched multiple grids, we selected the median value of temperature, which would show a more realistic current hot weather distribution than the mean value (not shown). Our estimation of total population exposure is based on data from 2010, which is not expected to change substantially until the middle of this century due to the low national birthrate and the limited residential area in Korea (~65% of the nation is mountainous) (KOSIS 2015). However, changes in population structure are considered by 2060, reflecting a rapidly aging society (KOSIS 2015).

3. RESULTS

3.1. Distribution and frequency of hot weather events

Fig. 2 displays the spatial distribution of the projection of daily maximum temperature (T_{max}) in summer with the RCP4.5 climate scenario on a monthly mean basis. Differences of future projection of T_{max} compared to the 2010s are presented in Fig. 3. While T_{max} was not expected to increase greatly over northwestern Korea in June until the 2050s, T_{max} over southeastern Korea increased markedly in the 2050s (Figs. 2 & 3). T_{max} was projected to increase over most regions of South Korea in the last decade of the 21st century, which was a similar pattern to the summer months over Korea (Figs. 2 & 3). An increase in T_{max} over the western coast and southeastern Korea in July in the 2050s and 2090s was noticeable (Figs. 2 & 3), which was also reported previously by Choi et al. (2008), based on observations made over several decades. In particular, a generally higher T_{max} in August (>35°C) was expected in the 2090s (Fig. 2), which is fairly remarkable considering that the projection was made with the RCP4.5 scenario that represents relatively moderate climate change.

Projection of the distribution of hot weather frequency (total number of hot weather days) over South Korea is shown in Fig. 4, and differences in the projected frequency compared to the 2010s are in Fig. 5. Similar to T_{max}, the area affected by hot weather events was expected to expand over southeastern Korea (Young-Nam region) in the 2090s (Fig. 4). In addition to expansion of the area affected by hot weather events in July and August, the higher number of hot weather days (>15 d mo^{-1}) over the western and southeastern regions of Korea are expected in the last decade of the 21st century (in July and August; Figs. 4 & 5). Similar projections were also made by Jeung et al. (2013) and Park et al. (2013), although with different extreme weather definitions and using different climate scenarios.

To investigate hot weather event projection, we focused on 2 factors: expansion of the area affected by hot weather events, and frequency (number of days).

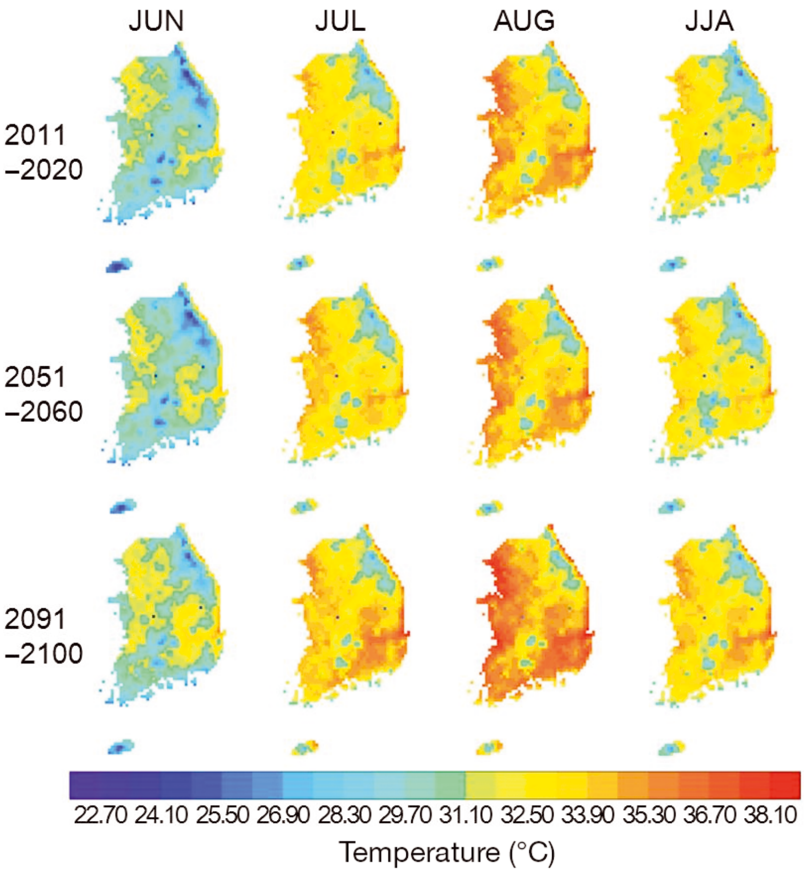

Fig. 2. Distribution of daily maximum temperature (T_{max}) of South Korea in June, July, August, and the summer mean (average of JJA), for 3 decadal bins (2011–2020, 2051–2060, and 2091–2100)

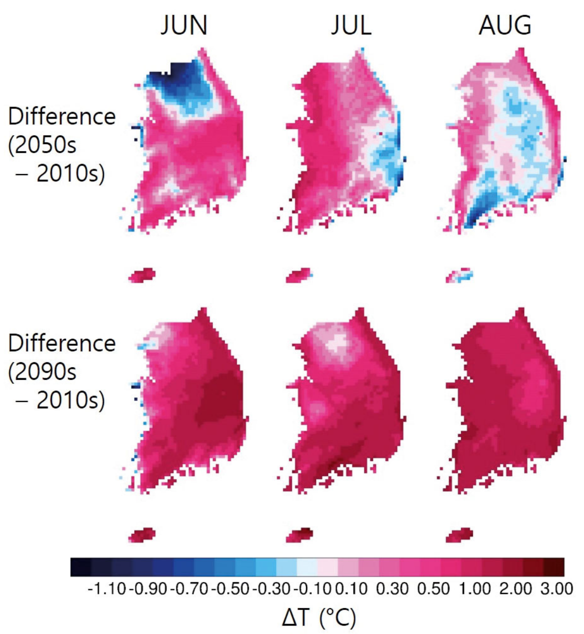

Fig. 3. Distribution of daily maximum temperature (T_{max}) of South Korea in June, July, and August, showing the differences between the 2050s and 2010s and the 2090s and 2010s

We estimated expansion of the area affected by hot weather events by defining it as the area exposed to hot weather events more than once in a month. Fig. 6 shows the decadal trend of expansion of the area affected by hot weather events for each summer month, with the area affected by hot weather events expressed as a fraction (%) of the total area of the country.

Although the area currently affected by hot weather events was not extensive in June (<10%), it was projected to increase to almost 25% before 2040, which is similar to the current area affected by hot weather events in July (~30%) (Fig. 6). The fastest expansion of the area affected by hot weather events occurred in July (Fig. 6). The current extent of the area affected by hot weather events (30%) almost doubled by the end of this century, and the rate of increase was 0.29% yr^{-1} (Fig. 6). In particular, a large expansion in the area affected by hot weather events in the 2060s was noticeable (Fig. 6). The area affected by hot weather events was largest in August and expanded at an average rate of 0.24% yr^{-1}, resulting in 70% of South Korea being exposed to hot weather events in the 2060s (Fig. 6).

Expansion of hot weather events in the 21st century is not linear with time, with instant drops predicted in the 2050s and 2080s (Figs. 6 & 7). This is likely due to the complex geophysical response to external forcing and internal climate variability in the simulation (Manabe et al. 1990, Hall 2004, Seneviratne et al. 2010, Deser et al. 2012, Ishizaki et al. 2012, Good et al. 2015).

In addition to the area affected by hot weather events, we also considered the frequency of hot weather events by integrating the area and frequency of hot weather events (IAF, %) (defined in Section 2.3). The nationwide IAF is currently <5% in July, but was projected to increase to 10% in the 2060s (Fig. 7). IAF in August is a more serious concern. It was projected to increase sharply and reach ~20% in the 2040s (Fig. 7). In the 2040s, IAF will reach 25%, with an average rate of increase of 0.15% yr^{-1} (Fig. 7). Our analysis indicated that the national frequency of hot weather events and the population's exposure to them will be severe in August, with a large potential mor-

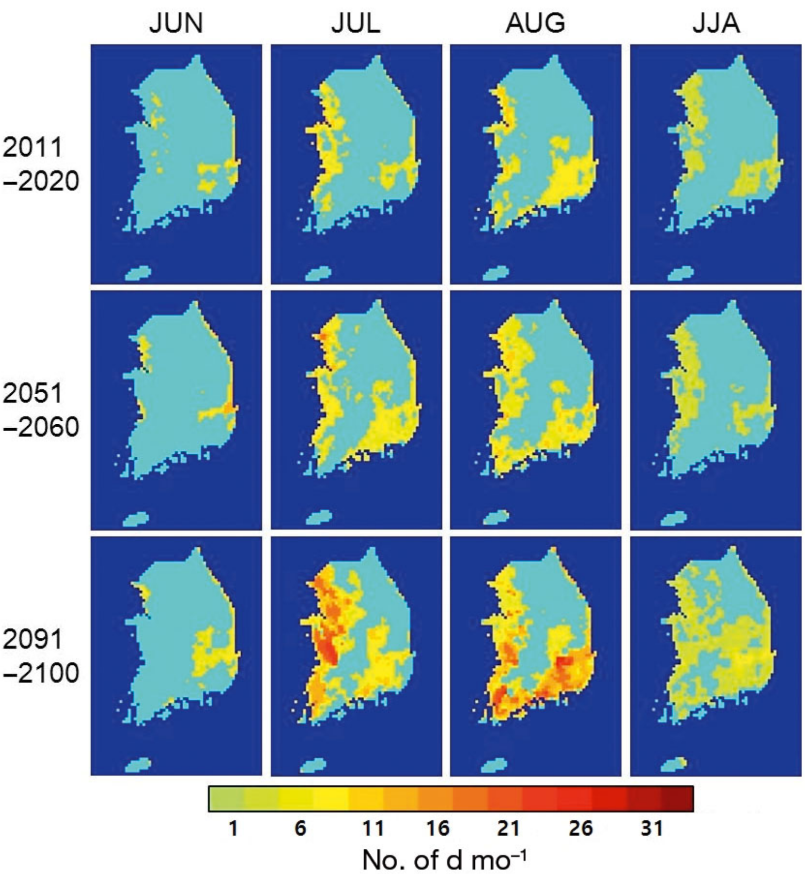

Fig. 4. Projection of hot weather frequency in South Korea in June, July, August, and the summer mean (JJA), for 3 decadal bins (2011–2020, 2051–2060, and 2091–2100)

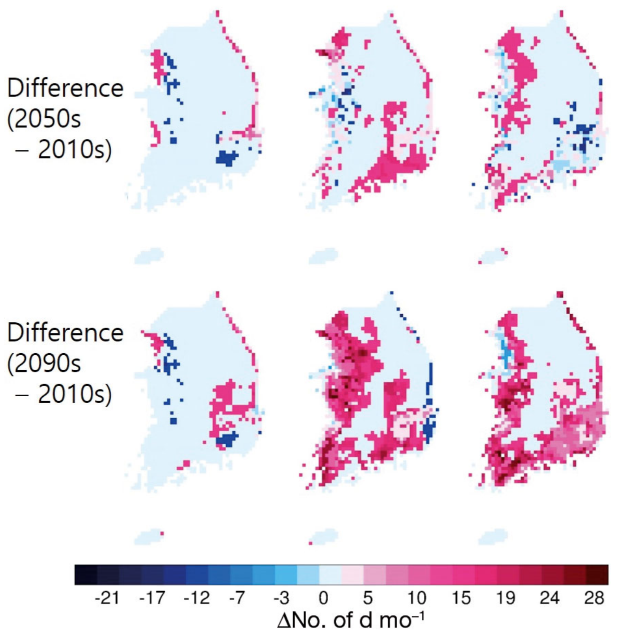

Fig. 5. Projection of hot weather frequency (number of days per month) in South Korea in June, July, and August, for the difference from the 2050s to 2010s and the 2090s to 2010s

tality associated with the increased hot weather intensity in Korea.

3.2. Population exposed to hot weather events

As explained in Section 2.4, we estimated the population exposed to hot weather events in the summer months based on the mapping of local administrative districts and the model grid. Currently (2010), a quarter of the Korean population (~12.5 million people) is exposed to hot weather events (Fig. 8). However, the exposed population was projected to rapidly increase to more than half of the total population (58%, 27.9 million) in the middle of this century (2050; Fig. 8), which is closely associated with the expansion of the area affected by hot weather events into the SMA and southeastern region, where there is higher population density (Figs. 4 & 5). In the last decade of this century, the population exposed to hot weather events was projected to reach 72% of the total population, indicating that the majority of the nation's population will be exposed to hot weather events by the end of this century. Furthermore, the population structure in Korea is expected to change significantly. The Korean population is continuously aging and has been considered an 'aging society' since 2000 (Gong & Jang 2010). The elderly population is projected to increase rapidly in the future (KOSIS 2015), and this portion of the population is particularly vulnerable to heat waves (McGeehin & Mirabelli 2001, Schifano et al. 2009, Huang et al. 2010, Son et al. 2012), having significantly higher mortality from heat waves in South Korea, especially those >65 yr of age (Lee 2015). Thus, we estimated the population exposure for the elderly (>65 yr old) to hot weather events. Currently (2010), the population of >65 yr olds is about 5.5 million, accounting for ~11% of the total population of South Korea.

If we apply the future changes in national population structure with the same spatial distribution of the population in 2010, our estimation shows that the ~1.4 million elderly exposed to hot weather events (~3% of the national population) in 2010 could rapidly increase to ~10.4 million (~22% of the national population) in 2050 (Fig. 8).

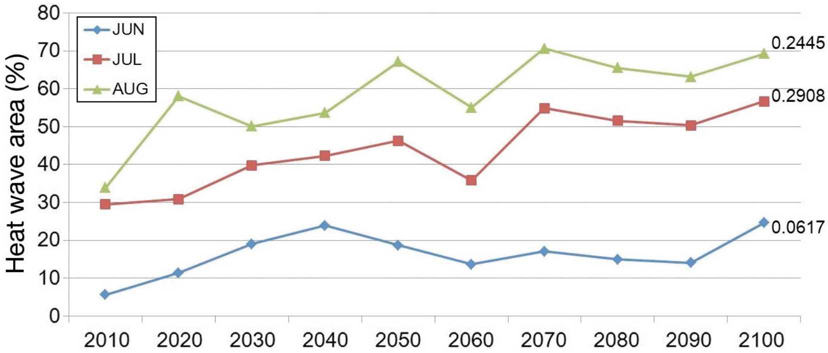

Fig. 6. Projection of area affected by hot weather events (%) in South Korea, defined as the sum of the area experiencing ≥1 hot weather event in each summer month (June–August), divided by the area of the entire nation. Numbers on the right side are the rate of increase (% area per year) for each month

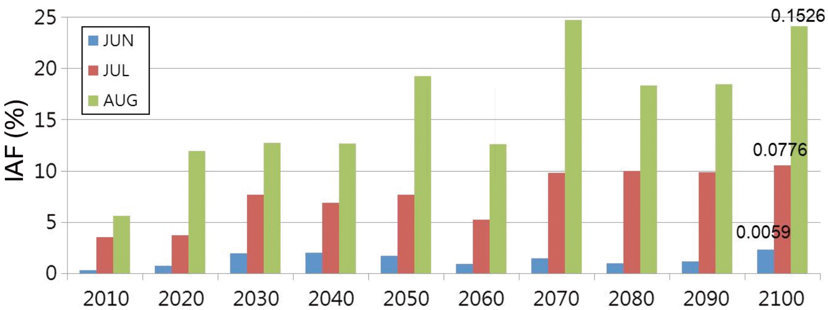

Fig. 7. Projection of integration of area and frequency (IAF) of hot weather events in South Korea (see Section 2.3 and Eq. 1 for definition). Numbers above bars for 2100 are the rate of increase of IAF (% per year) for each month

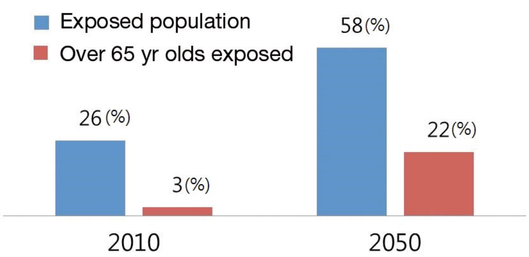

Fig. 8. Projection of population (overall and elderly) exposed to summer hot weather events in South Korea. A projection of the national population structure was used. Note that the population of >65 yr olds is considered to have significantly higher heat wave mortality in Korea

Although our estimation contains uncertainty from the assumption of a static population distribution due to lack of future data available at the local administrative district level, the uncertainty would be small, because the changes in the population structure at the regional administrative district level are small (KOSIS 2015). Our results therefore have important implications for future national security associated with climate change.

4. DISCUSSION AND CONCLUSIONS

Here, we discuss the projections of hot weather events and the potential population exposure over South Korea in the 21st century. The regional RCP4.5 scenario, with a 7.5 × 7.5 km horizontal resolution, was calculated by dynamical downscaling of CESM model results, in which the estimated temperature was validated by ground observations, and the mean bias was applied for future temperature projection.

This study first presented quantitative information on future projections of hot weather events in Korea with information on changes in the area affected and frequency for the entire nation. This study also estimated future nationwide population exposure to hot weather events, which is essential information for preparing national climate change adaptation policy.

Our analysis showed that the area affected by hot weather events will increase to cover ~70% of the nation in August in the middle of this century, with an overall rate of increase of 0.24% yr^{-1}. In terms of frequency, the larger number of hot weather days (>15 d mo^{-1}) in the western and southeastern regions of Korea in the last decade of the 21st century is critical because the majority of the Korean population, nearly 30 million people, reside in these regions, which includes the SMA and Busan.

We introduced the index of integration of area and frequency (IAF, %), which is a summation of the area affected by hot weather events multiplied by the number of heat wave days for each area. According to the IAF results, a quarter of the nation will be exposed to daily hot weather events in August during the 2060s and 2090s, which is almost a 500% increase compared with the 2000s. An IAF of 25% can cause a great impact on the nation since it is statistically equivalent to a quarter of the nation being exposed to hot weather events every day of a month, or all of the nation being exposed to hot weather events for about 7.5 d mo^{-1}. IAF contains frequency information associated with hot weather intensity and duration, which is closely related to mortality (Son et al. 2012). Ho et al. (2011) also estimated the projection of heat waves.

Although they used a different definition and the Special Report on Emissions Scenarios (SRES), they concluded that heat wave frequency will increase by 583% in the A1FI scenario, implying that our analysis with RCP4.5 was almost as serious as the previous analysis using the A1FI scenario.

In addition, we estimated the population exposed to hot weather events by mapping population data from the nation's administrative districts with the model grid. Despite the limitations and uncertainty in the projection of future population, the exposed population was projected to increase almost 3-fold, from 26% during the 2010s to 72% during the 2090s. In particular, the exposure of the elderly population (>65 yr old), who are particularly vulnerable to heat waves, was expected to reach ~22% of the national population (~10.4 million) in the middle of this century if we apply the projection of an aging population to our results. It is important to note that those results are only based on the RCP4.5 scenario, implying that even more severe hot weather events could be expected under a possible business-as-usual scenario (e.g. RCP8.5).

The Korean government has taken actions against heat waves with an annual national plan for heat waves coordinated by the Ministry of Public Safety and Security (MPSS) and a national adaptation plan to climate change coordinated by the Ministry of Environment (MOE). However, cross-sectoral collaboration and engagement for regional-specific plans need to be improved (Ha et al. 2014). In particular, our results strongly suggest the need for long-term measures to mitigate the effects of heat waves, for which there are no current provisions (Ha et al. 2014).

This study may contain uncertainties for the following reasons. (1) Bias correction over a relatively short period (9 yr) can ignore long-term interannual climate variability. We further estimated that the difference in monthly bias between the 9 yr period 2006–2014 and 30 yr period 1985–2014 ranges from −0.04 to 0.45°C (national mean). Applying the bias correction over a 30 yr period could reduce the number of total grids with hot weather events in summer by 16% (2015–2100), leading to reductions in population exposure of 50% (total population) and 19% (elderly population) in 2050 (corresponding to Fig. 8). Although the application of the same approaches to bias correction with a 30 yr period was not possible due to the much smaller number of ground stations (~70), these facts imply the possibility of the overestimated projections.

(2) There are uncertainties associated with the climate model schemes and downscaling method, which requires further study, including comparisons with multi-model scenarios, including those from the KMA (Jeung et al. 2013, Park et al. 2013), because the projection of heat wave mortality could be highly variable, depending on the exact climate model used (Ho et al. 2011, Peng et al. 2011).

(3) Heat waves earlier in the year can produce higher mortality than later heat waves (Son et al. 2012), and the Korean government has already issued heat wave alerts several times in May 2016 (Kim 2016), while the occurrence of heat waves in Korea used to be rare (<10 in the last 20 yr; Kim et al. 2014). Thus, studies of early heat waves and their impacts on health are necessary.

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