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REVIEW

Changes in Weather and Climate Extremes over Korea and Possible Causes: A Review

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Abstract: Weather and climate extremes exert devastating influence on human society and ecosystem around the world. Recent observations show increase in frequency and intensity of climate extremes around the world including East Asia. In order to assess current status of the observed changes in weather and climate extremes and discuss possible mechanisms, this study provides an overview of recent analyses on such extremes over Korea and East Asia. It is found that the temperature extremes over the Korean Peninsula exhibit long-term warming trends with more frequent hot events and less frequent cold events, along with sizeable interannual and decadal variabilities. The comprehensive review on the previous literature further suggests that the weather and climate extremes over East Asia can be affected by several climate factors of external and internal origins. It has been assessed that greenhouse warming leads to increase in warm extremes and decrease in cold extremes over East Asia, but recent Arctic sea-ice melting and associated warming tends to bring cold snaps to East Asia during winter. Internal climate variability such as tropical intraseasonal oscillation and El Niño-Southern Oscillation can also exert considerable impacts on weather and climate extremes over Korea and East Asia. It is, however, noted that our current understanding is far behind to estimate the effect of these climate factors on local weather and climate extremes in a quantitative sense.

Key words: Weather extremes, climate extremes, climate variability and change, Korea and East Asia

1. Introduction

During recent years, a large number of weather and climate extreme events (hereafter extreme events without separation of weather and climate) have occurred across the world, causing severe damage to human society and the environment (IPCC 2012, 2013). There is observational evidence of long-term changes in such extremes across the globe with significance dependent on variables, regions, and seasons (IPCC 2012, 2013; Peterson et al., 2012, 2013; Herring et al., 2014). For global changes in temperature extremes, the Intergovernmental Panel on Climate Change (IPCC) concludes that "it is *very likely* (assessed likelihood of 90-100%) that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased globally since about 1950". For the continental scale trends, however, it concludes that "it is *likely* (66-100% likelihood) that heatwave frequency has increased in large parts of Europe, Asia and Australia". The observed changes in precipitation extremes are assessed even with lower confidence - "it is *likely* that the number of heavy precipitation events over land has increased in more regions than it has decreased". This indicates that extreme events would have larger uncertainties with less predictability because they are rare and also develop locally on a short time scale (Peterson et al., 2012).

In recent years, East Asia has been experiencing increasing number of extreme events such as record-setting heat waves and flooding. However, much smaller geographical domain of East Asia and the increased level of internal variability hinder proper attribution of such changes to any internal and/or external factors. It has been known that many internal and external factors interplay to affect East Asian climate, making it harder to identify exact causes of the observed changes in extreme events. Among such external factors, human-induced increases in greenhouse gases and aerosols have been considered as key drivers of global and continental-scale climate changes. El Niño-Southern Oscillation (ENSO), Arctic Oscillations, intraseasonal oscillations, and monsoons have been suggested as internal factors influencing extreme events over East Asia.

This study provides an overview of recent studies on extreme events over East Asia, particularly focusing on changes and variability of extremes over the Korean Peninsula.

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Observational and modeling studies are reviewed with some updated analyses based on recently available observations. Possible mechanisms are synthesized and near-future research directions are suggested for further investigations. This paper is structured as follows. Section 2 describes observed changes in temperature and precipitation extremes over the Korean Peninsula. Influence of global warming on long-term trends in extreme events over East Asian is discussed in section 3. Impact of intraseasonal variability is reviewed in section 4, followed by discussion on Arctic factors in section 5. In section 6, extreme El Niño and its possible influence on the Korean climate is evaluated. Conclusions and discussion are given in section 7.

2. Observed changes in temperature and precipitation extremes in Korea

a. Temperature

The long-term trend of surface air temperature in the Korean Peninsula has been extensively examined since a pioneering work of Roh (1973). He identified that surface air temperature in Seoul has been increased by 0.18°C dec^{-1} in the period 1931-1970. By extending the analysis period to 1954-1977, Lee (1978) found a stronger trend of 0.28°C dec^{-1} and suggested that surface air temperature trend in Seoul (and other cities in Korea) has been accelerated during the latter half of the 20th century. This result was further confirmed by Kang and Roh (1985). The accelerated warming has been attributed to the local urbanization and global warming with the former being more important than the latter in the cities (Kim et al., 1999; Ha et al., 2004; Kug and Ahn, 2013). In terms of seasonality, it is generally documented that surface warming trend is faster in the winter than in the summer (e.g., Jung et al., 2002; Choi et al., 2008). For example, linear trend of DJF-mean surface air temperature, averaged over 11 KMA (Korea Meteorological Administration) stations, is estimated 0.32°C dec^{-1} in the period 1960-2012, while JJA-mean temperature trend is only 0.09°C dec^{-1} (Table 1). Similar results are also found in daily minimum temperature (Tmin) and maximum temperature (Tmax) trends, indicating that annual-mean temperature trend is mostly due to the wintertime temperature change (Choi et al., 2008).

Table 1. Long-term trends of 11-station mean surface air temperature in the period of 1960-2012. Trends are evaluated in °C dec^{-1} for annual- and seasonal-mean temperatures derived from daily-mean temperature (T_{mean}) for the three time periods. Values that are statistically significant at the 95% confidence level are indicated by asterisk. Stations and significant tests used in this study are identical to those in Kim et al. (2014a).

	1960-2012	1960-1999	2000-2012
Annual T_{mean}	0.23	0.27	0.17
Winter T_{mean}	0.32	0.50*	–0.85
Summer T_{mean}	0.09	0.03	0.65

It is important to note that the above seasonal dependency of temperature trend has dramatically changed in the past decade (Table 1). As summarized in Table 1, DJF-mean temperature trend becomes negative since 2000, whereas JJA-mean trend becomes even stronger than the 20th-century trend. This unexpected cooling in DJF is not local but hemispheric phenomenon, and has been often referred to as the global warming hiatus (Eastering and Wehner, 2009; Kosaka and Xie, 2013). Although not shown, essentially the same results are found in Tmin and Tmax trends. As discussed in Cohen et al. (2012a), surface cooling in the past 10 years has primarily observed in boreal winter. This asymmetric temperature trends, i.e., warming in summer but cooling in winter (third column in Table 1), has been partly attributed to the Arctic sea ice loss, Eurasian snow cover change and negative trend of AO index in the recent past (Cohen et al., 2012b; Mori et al., 2014). The exact causes however still remain to be determined. Regardless of dynamical mechanisms, this nonlinearity in mean temperature change makes the analysis of extreme temperature trends quite challenging.

A significant trend has been also observed in the frequency and intensity of extreme temperature events (e.g., Ryoo et al., 2004; Choi et al., 2008; Choi and Moon, 2008; Choi et al., 2009; Jung et al., 2011; Ha and Yun, 2012). Ryoo et al. (2004) examined Tmin over 1958/1959 to 2000/2001 winters and found that the number of extreme cold days of Tmin < –5.5°C (one standard deviation below from the mean value) is observed to be less after mid-1980s, largely due to the secular increasing trend of the seasonal mean. On the contrary, there is no significant change in the occurrence frequency of cold surges (defined as the temperature fall more than 7.5°C for 2

Table 2. Quantile slopes in °C dec^{-1} for daily minimum temperatures (Tmin) in winter and maximum temperatures (Tmax) in summer in the period of 1960-2012. Values that are statistically significant at the 95% confidence level are indicated by asterisk. A bootstrap significance test, where sampling is performed by considering autocorrelation, is used to test significance as in Franzke (2013) and Kim et al. (2014a). Note that this table essentially updates Tables 2 and 3 of Lee et al. (2013).

	Station	Quantile Regression						
		1P	5P	10P	50P	90P	95P	99P
Winter T_{min}	Seoul	0.50*	0.69*	0.58*	0.46*	0.36	0.25	0.04
	Chupungryong	0.23	0.30	0.24	0.04	–0.05	–0.04	–0.11
Summer T_{max}	Seoul	0.19	0.07	0.10	0.11	0.00	–0.04	0.17
	Chupungryong	0.12	0.05	–0.04	–0.10	–0.07	0.00	0.00

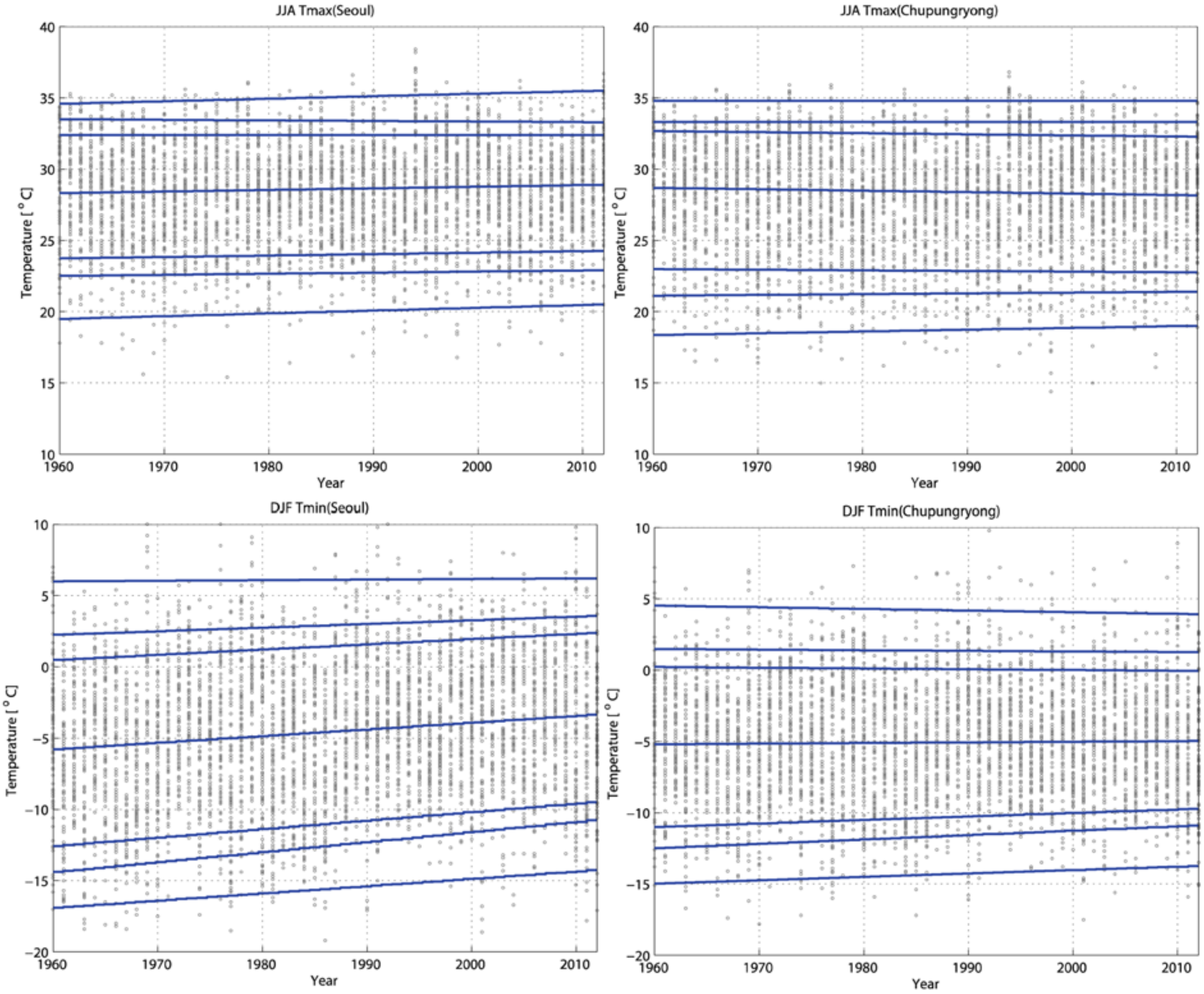

Fig. 1. Time series of daily maximum temperatures in summer (top) and minimum temperatures in winter (bottom) for Seoul (left) and Chupungryong (right) for the period of 1960-2012. Daily observations at a given year are indicated by black dots, and the linear slopes of 1P, 5P, 10P, 50P, 90P, 95P, and 99P temperatures (from bottom to top) are shown by solid lines. Updated from Figs. 2 and 3 of Lee et al. (2013).

days[a]), implying that the frequency of extremely severe cold events occurring once or twice a year has not changed significantly in the 20th century. A similar result, i.e., negative trend in number of cold days but no trend in number of cold surges, was also reported in Park et al. (2011). The trend even can be reversed due to different choice of the definition of cold days (Choi et al., 2009). Choi et al. (2008) further documented a significant negative trend in the frequency of cool nights (TN10p; -9.2 days dec^{-1}) for the period of 1973-2007. Significant negative trends are also observed in the frequency of ice days and frost days. However, the frequencies of warm days (TX90p; 6.8 days dec^{-1}) and warm nights (TN90p; 4.9 days dec^{-1}) were found to increase over 1973-2007. Likewise, strong positive trends are found in the maximum Tmin and the length of the growing season (see their Table 2).

Ha and Yun (2012) examined long-term changes of summertime Tmin and the frequency of tropical night (TN: Tmin > 25°C) in Seoul since the weather station data are available in 1908. The increasing rate of the TN frequency is estimated at approximately 13 days per century for the period of 1964 - 2008. They indicated that the TN episode in Seoul is mostly accompanied by high specific humidity as well as high nighttime temperature, which they attribute to the change in the low level southwesterly flow with warm and humid air. As they mentioned, however, rapid urbanization of Seoul is one of complicating factors to make it difficult to attribute the TN frequency change solely to the human-induced global warming. Here it is important to note that these results may not hold at other stations. Park and Suh (2011) indicated that TN frequency change is highly inhomogeneous in space and not

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[a] This definition is somewhat relaxed than the definition of the KMA operation. The KMA uses a 1 day temperature fall more than 10°C for the definition of cold surge.

statistically significant if averaged over multiple KMA stations.

The above studies have primarily focused on the linear trends of extreme temperature events in the 20th century although a few studies have extended such trends up to 2007. None of them have taken into account the recent cooling in wintertime temperature (Table 1). It is known that, because of this cooling, extreme temperature events have changed since late 1990's. For example, Cohen et al. (2014) showed that number of icing days over the Northern Hemisphere continents has increased since late 1990's. A similar change in trend has also been observed in KMA stations. Although not discussed in detail, Choi et al. (2008) showed that the number of cool nights does not change much since late 1990's (see their Fig. 3a). Yoo et al. (2015) documented that the number of cold days have rapidly increased in 2010-2012 as hinted in the bottom row of Fig. 1. These results clearly indicate that nonlinearity needs to be considered when long-term trends of extreme temperature events are examined.

Regardless of the methods, a fast decreasing trend of winter cold extremes but a slow increasing trend of summer warm extremes in the 20th century, which are consistent with seasonal dependency of long-term temperature trends, are robustly documented in the literature (Choi, 2004; Heo and Lee, 2006; Choi et al., 2008). These results are all based on the predefined extreme indices. The predefined indices, however, do not account for the long-term trend of the probability distribution function (PDF). For example, cool nights (or TN10p) are typically computed from the 10th percentile of Tmin over the whole analysis period although the temperature corresponding to the 10th percentile has changed in time. To quantify this change, Lee et al. (2013) and Kim et al. (2014a) applied a quantile regression method to the long-term Tmax and Tmin records in Korea. Briefly, the quantile regression estimates the extreme values corresponding to each quantile by minimizing a weighted average of absolute errors [see Yu et al. (2003) for more details]. This contrasts to the least square fit which minimizes the sum of squared errors.

Figure 1 and Table 2 show a quantile regression of the 1st to 99th percentiles of JJA Tmax and DJF Tmin (1P, 5P, 10P, 50P, 90P, 95P, and 99P) and their linear trends over 1960-2012. As reference stations, Seoul and Chupungryong, which represent the urbanized city and the rural places, respectively, are considered as in Lee (1978) and Lee et al. (2013). The results for other KMA stations (and seasons) can be found in Lee et al. (2013) and Kim et al. (2014a). The 50P temperature trends, which are quantitatively similar to the seasonal-mean temperature trends based on the least square fit, exhibit stronger trends in winter than in summer; i.e., 0.46^{o}C dec^{-1} for DJF Tmin versus 0.13^{o}C dec^{-1} for JJA Tmin in Seoul (not shown). In addition, the temperature trend in the city is stronger than that in the rural place; i.e., 0.46^{o}C dec^{-1} for DJF Tmin in Seoul versus 0.04^{o}C dec^{-1} for DJF Tmin in Chupungryong (not shown). These are consistent with the above-described results. Although not shown, a quantile regression is also performed with a second-order polynomial fit (Kim et al., 2014a). It is found that extreme cold temperature exhibit negative trends since late 1990's. This decadal change is absent in extreme warm temperature trends. This result is again consistent with the global warming hiatus shown in Table 1.

A key feature of Fig. 1 and Table 2 is that Tmax and Tmin trends are not fixed but vary with the percentile even in the linear limit. This is particularly true in DJF Tmin (bottom panels). For both Seoul and Chupungryon, extreme cold temperatures (e.g., 1P, 5P, and 10P) show much stronger positive trends than extreme warm temperatures (e.g., 99P, 95P, and 90P). This is qualitatively consistent with the previous studies that have shown a rapid decline of the frequency of winter cold nights in the 20th century (e.g., Choi et al., 2008). However, it contrasts with the long-term trends of extreme warm temperatures. No systematic trends are observed in the 99P, 95P, and 90P temperatures especially in those of JJA Tmax (Table 2). This indicates that winter cold extreme and summer warm extreme trends are asymmetric. Note that most values shown in Table 2 are statistically insignificant, indicating that 53 years of temperature records are not sufficient to identify extreme temperature trends. This result is different from Lee et al. (2013; see their Tables 2 and 3) who showed more significant trends. This difference is due to the consideration of autocorrelation in the bootstrap significance test (Franzke, 2013; Kim et al., 2014a), which is not taken into account in Lee et al. (2013).

The quantile regression analysis, however, does not answer a question how frequently climate extremes above a certain threshold occur. Likewise, it is unable to quantify the other characteristics of extreme other than the frequency. Taking this aspect into account, Mieruch et al. (2010) introduced a systematic method based on Markov chain to quantify multilateral characteristics of the extremes: frequency, persistence, and entropy. They defined the temperature threshold and counted individual events above or below the predefined threshold. The frequency was then obtained by counting the occurrence number (or the reciprocal of recurrence time) in a unit of day; the persistence was calculated by the averaged period of consecutive events in a unit of day; the entropy (a measure of the unpredictability of the given events) was taken from the conditional Shannon entropy (Mieruch et al., 2010). These variables together are referred to as "climate descriptors". The recent study by Kim et al. (2014b) slightly modified the method to be suitable for the study of the extremes from long-term climatic data. For instance, the frequency was defined as the number of groups (one group is composed of consecutive extreme days) instead of the days because one group generally results from the same dynamical reason. They also treated all consecutive cold days in that group including at least one rare extreme as the rare extreme event with the certain persistence and entropy (i.e., 5P and 95P). The present study has applied the methodology used in Kim et al. (2014b) to long-term (19602012) records of Tmax and Tmin in Seoul and Chupungryong (Fig. 2). In this approach, the thresholds of the winter cold extremes and summer warm extremes are

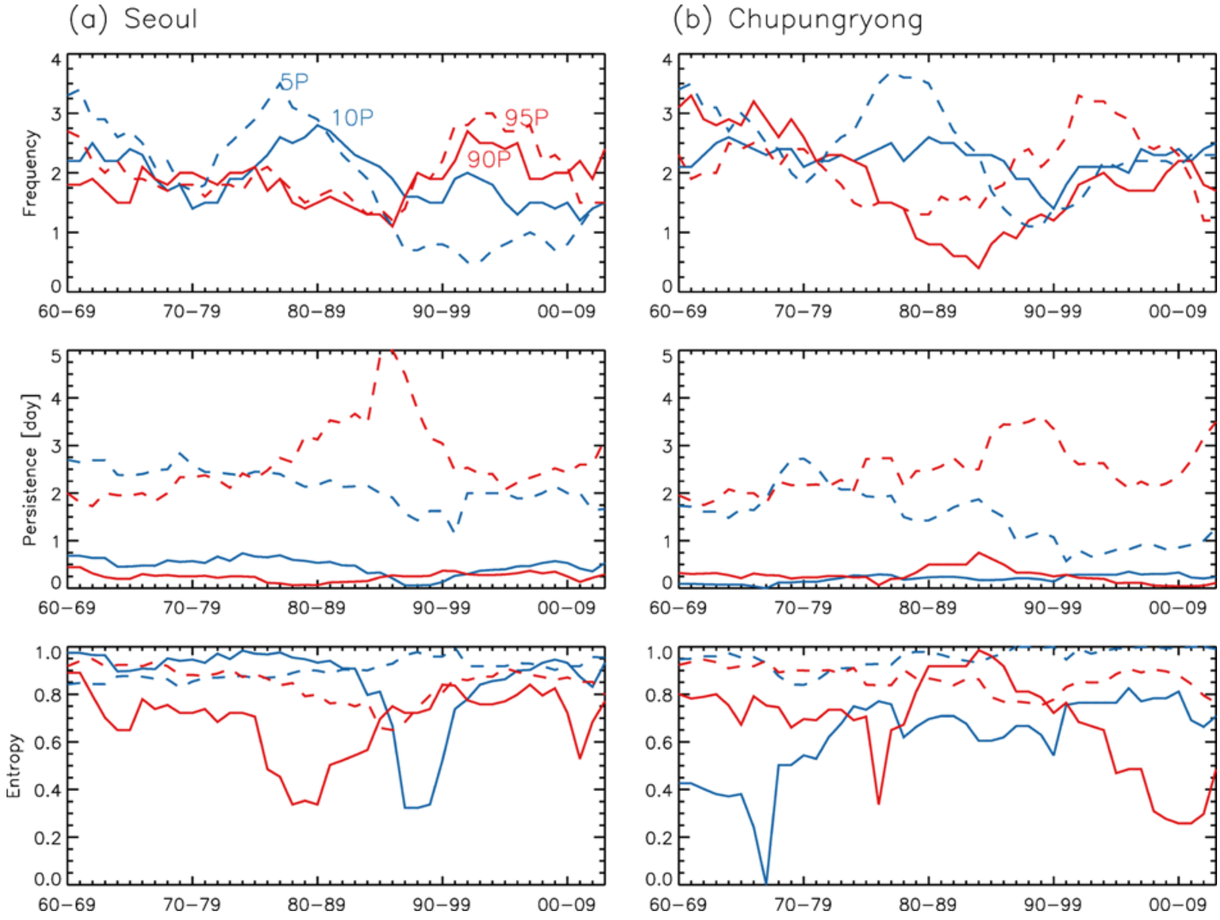

Fig. 2. 10-year running averages of the climate descriptors (frequency, persistence, and entropy) of the extreme temperature events for Seoul (left) and Chupungryong (right); The climate descriptors are estimated for 90P and 95P of daily maximum temperatures in summer (red), and for 5P and 10P of daily minimum temperatures in winter (blue).

determined based on the 5P, 10P, 90P, and 95P of DJF Tmin and JJA Tmax PDFs over the whole analysis period.

Figure 2 shows the time-dependent changes of the three climate descriptors. In the case of Seoul (Fig. 2a), the frequency of the summertime warm extremes (red) is maximized particularly around 2000. However, independently, the persistence and entropy of the 95P extremes are maximized and minimized around 1990, respectively. The persistence of 90P extremes is rather very short, and their entropy is minimal in the 1980s. This is intriguing since this result implies that higher frequency of the extreme does not result in longer persistence and higher predictability. On the other hand, the wintertime cold extremes (blue) in Seoul had large decadal variability (large in the 1960s and 1980s, and small in the 1970s and 1990s) in the frequency, but gradually decreased during the last half century (5P > 10P in magnitude). Furthermore, it is shown that the persistence (entropy) of the 5P extremes gradually decreases (increases). The trend in the persistence and entropy of the 10P extremes are not so clear, but the minimum value was detected around 1990 in Seoul. Note that the persistence and entropy could not be calculated for 99P and 1P due to lack of samples. Compared to Seoul, the time-varying pattern of the climate descriptors of the extremes in Chupungryong is similar in general (Fig. 2b). This means that the scale of atmospheric circulation causing the temperature extremes is large enough to cover both stations. Nevertheless, we note that different magnitudes of the descriptors between two stations may reflect the extremes amplified or weakened by topographical effects or any other regional characteristics. The more distinguished features at Chupungryong station are the decreasing (increasing) trend in the persistence of the 5P (95P) extremes, and the increasing (decreasing) trend in the entropy of 10P (90P) cold extremes.

It is worth to discuss the difference between Fig. 1 and Fig. 2. Although the same terminology is used, quantiles in Fig. 1 are determined over a given season, but they are derived over the whole analysis period in Fig. 2. More importantly, the formers are allowed to vary in time, while the latters are fixed in time. Due to these differences, different type of information could be obtained. For example, it is clear from Fig. 1 that extreme cold temperatures in DJF have been significantly warmed over the last few decades. When the temperature of the cold extremes is predefined, it is found that extreme cold events in DJF have generally become less frequent, less persistent, but more predictable during the last half century. It is also shown that extreme cold events in the recent few years remain frequent in Chupungryong. Since there is no standard approach in the analysis of climate extremes, it would be better to combine such diverse approaches, i.e., time-varying and fixed thresholds, to better quantify long-term trends and variability of climate extremes.

b. Precipitation

According to an annual report of National Emergency Management Agency, about 90% of natural disasters in South Korea are associated with precipitation. In South Korea, summer rainfall amounts are more than half of the annual precipitation in most regions, and their temporal distribution can be divided by two rainy periods, i.e., June to July and August to September (Kwon et al., 1998), though the detailed peaks of the two periods appeared differently before and after the late 1970s (Ho et al., 2003). Between the two periods, the long-term increase in precipitation is statistically significant in the 2nd period over the last 80 years (Kwon et al., 1998). A series of studies have reported that long-term increases in precipitation intensity, amount and consecutive dry (non-precipitation) days are characteristically found for most cities in Korea since 1959 (Choi, 2004; Chung et al., 2004; Chang and Kwon, 2007; Choi et al., 2008). Here the precipitation intensity is defined as the annual total amount of precipitation divided by the number of precipitation days over 1.0 mm day^{-1}. During the past 25 years (1959-1983) and the recent 25 years (1984-2008), the average precipitation intensity is 14.2 mm day^{-1} and 15.9 mm day^{-1}, respectively; the average consecutive dry days are 28.0 and 31.1 days, respectively. It remains as an open question whether these changes are partly from interdecadal variability. However, confining the period to the last 50 years when the observations are available in many cities, precipitation in South Korea has been concentrated on fewer days, possibly increasing vulnerability to both flood and drought.

Precipitation extremes have been investigated by relatively few studies. Jung et al. (2011) analyzed the daily precipitation data obtained from 183 surface rain gauge sites for 1973-2005, and found that the annual precipitation amount shows a positive trend. They pointed out that the increase of annual precipitation is mainly associated with the increase of frequency and intensity of heavy precipitation in summer. On the other hand, precipitation during spring and winter shows a decreasing trend, implying more risk of flood and drought in the recent climate. This result is mostly consistent with the study by Choi and Moon (2008) who examined the daily precipitation records for the past 56 years of 1951-2006. They further investigated the changes in yearly maximum values of daily precipitation to find the secular positive trends. They attributed this trend to the intensification of typhoon activity in the vicinity of Korean peninsula, possibly induced by global warming and the increase of local sea surface temperature in the area. As in temperature analysis (e.g., Kim et al., 2014a), quantile regression has also been applied to precipitation data. However, So et al. (2012) found that the long-term trend from the quantile regression is too sensitive to precipitation extremes, so the methodology needs caution.

3. Influence of global warming

a. Extreme events in Korea

Although observational studies more or less support the idea that the frequency and intensity of extreme events have changed in Korea, it is still unclear whether such changes are the direct consequences of global warming due to insufficient observation records and larger internal variability on local scales to obtain robust statistical significance. Feasible mechanisms would help explain the causal relationship, but our scientific understanding for the extreme events is yet poor how the global warming would affect the extreme events in the local region of Korea. In this regard, the modeling studies with different greenhouse gas concentration can provide a posteriori clue on the attribution.

As the current climate models have relatively low horizontal resolution, which seems too coarse to depict the change in the extreme events in Korea, two different approaches have been adopted in previous studies. One is the downscaling approach by projecting coarse- resolution global or regional model output from greenhouse gas experiments to the fine-scale output over the domain of Korea, either statistically or dynamically (Boo et al., 2004, 2006; Oh et al., 2004; Im and Kwon, 2007; Lee et al., 2012a; Oh et al., 2014; etc.). Due to a large internal variability, those studies compared current climate simulations with future simulations with enhanced greenhouse gas forcing. Another is the upscaling approach where large-scale patterns associated with the specific extreme event in local region are identified from the analysis using local station data and large-scale reanalysis (or model), and then the observed changes in those large-scale patterns are compared with model simulations with different greenhouse gas forcings (Min et al., 2014).

Boo et al. (2006)'s study can be regarded as an example of dynamical downscaling for the attribution study. Using MM5 downscaling simulations, they attempted to predict the future changes in frequency and intensity of the daily mean temperature and precipitation in Korea for 1971-2100. With the continuous increase of mean temperature by 5.5°C between 1971-2000 and 2071-2100, model results showed that hot events in Korea would become more frequent, and strengthened, whereas the frequency of cold events would decrease with less intensity. The model projection also showed the increase in the number of days of heavy precipitation in future: a result suggesting that the global warming may locally change the precipitation distribution over the Korean peninsula. In a similar study using a different model, Im and Kwon (2007) obtained a consistent result. They further detailed the analysis

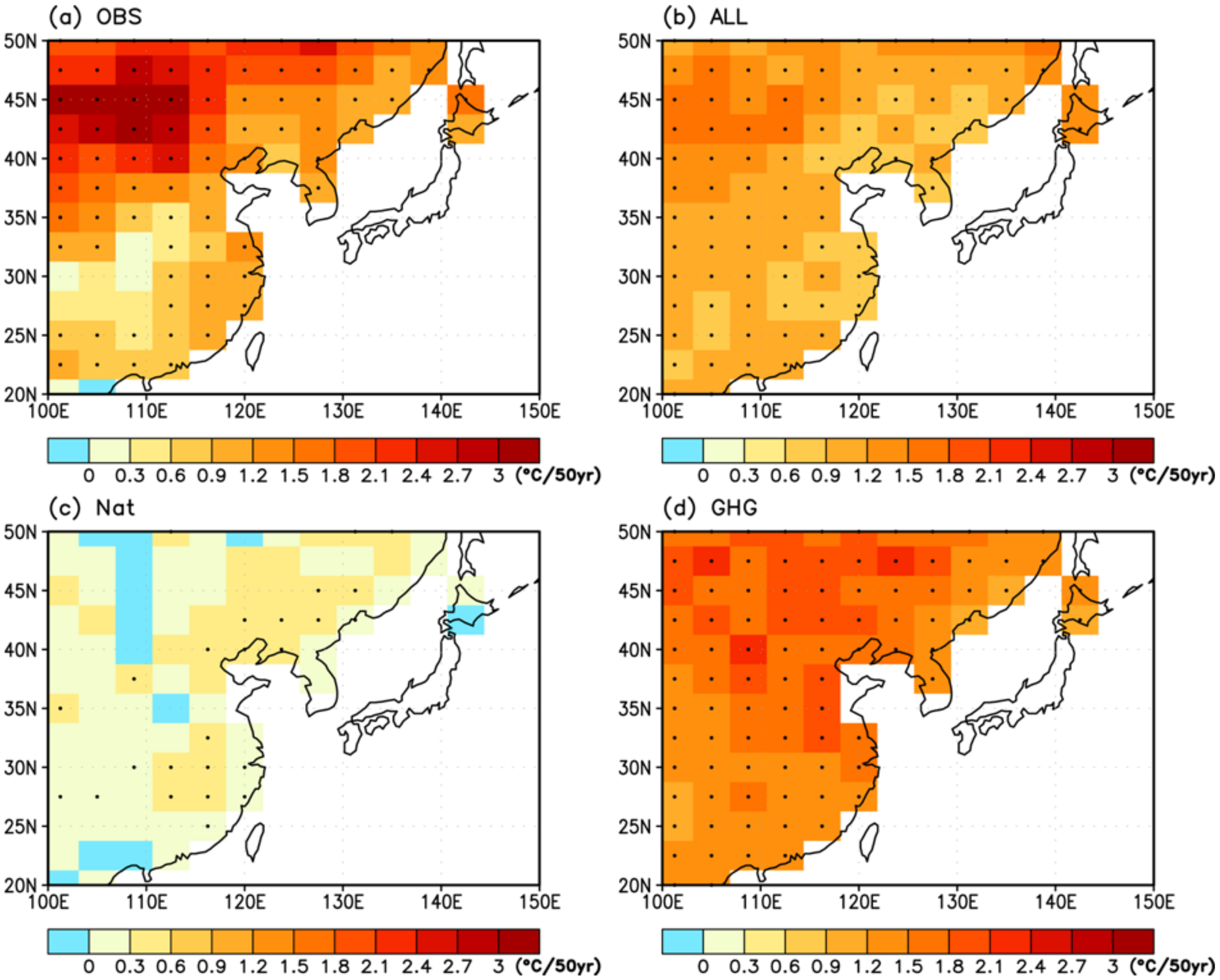

Fig. 3. Observed and simulated trends in annual maximum of daily minimum temperature (TNx) during 1961-2010 over East Asia. Updated from Min et al. (2013) using HadEX2 observations (Donat et al., 2013) and 8 CMIP5 models (ALL - natural plus anthropogenic forcing, NAT - natural forcing only, and GHG - greenhouse gas forcing only) and drawn for East Asian domain. Dots represent statistically significant trends at 5% level.

to the projected changes in extreme events between the present (1971-2000) and future (2021-2050) climate, by separating categories of extreme evens according to their duration. Their model results show different sign of changes between the short-term spells and long-term spells, which need verification using different models.

Using RCP scenario simulations, Lee et al. (2012a) downscaled data into 10-km horizontal resolution over Korea. The study again highlighted that the anthropogenic greenhouse gas forcing might induce the changes in extreme events in the region, with more summer days and tropical nights, and with less ice days and frost days. Their results also showed strong locality in the change of individual extreme events. Another modeling study using the RCP scenarios by Oh et al. (2014) showed the increase of heavy precipitation events under hotter and more humid summer climate in future in response to the increase of anthropogenic greenhouse gas concentration.

As one of the well-documented upscaling approach, Min et al. (2014) analyzed the Korean station data and the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model outputs, and identified the large-scale SST pattern connected with the occurrence of Korean heat waves. By comparing the historical experiments integrated with natural forcing (due to changes in solar and volcanic activities) and the experiments with the anthropogenic forcings (due mainly to increases in greenhouse gases and aerosols), they demonstrated that the extreme hot event such as one in 2013 would become 10 times more frequent due to human-induced global warming, consistent with similar analyses of heat waves over Japan and China (Herring et al., 2014).

It should be noted, however, that the attribution of extreme events based on the model results are still quite challenging and the conclusions from the previous studies pertain to many limitations and deficiencies in the current models. For example, the model projections are still based on imperfect summer monsoon simulation in Korea (e.g., Oh et al., 2014), and with limited ability of resolving extreme weather events explicitly such as typhoons and severe winter storms.

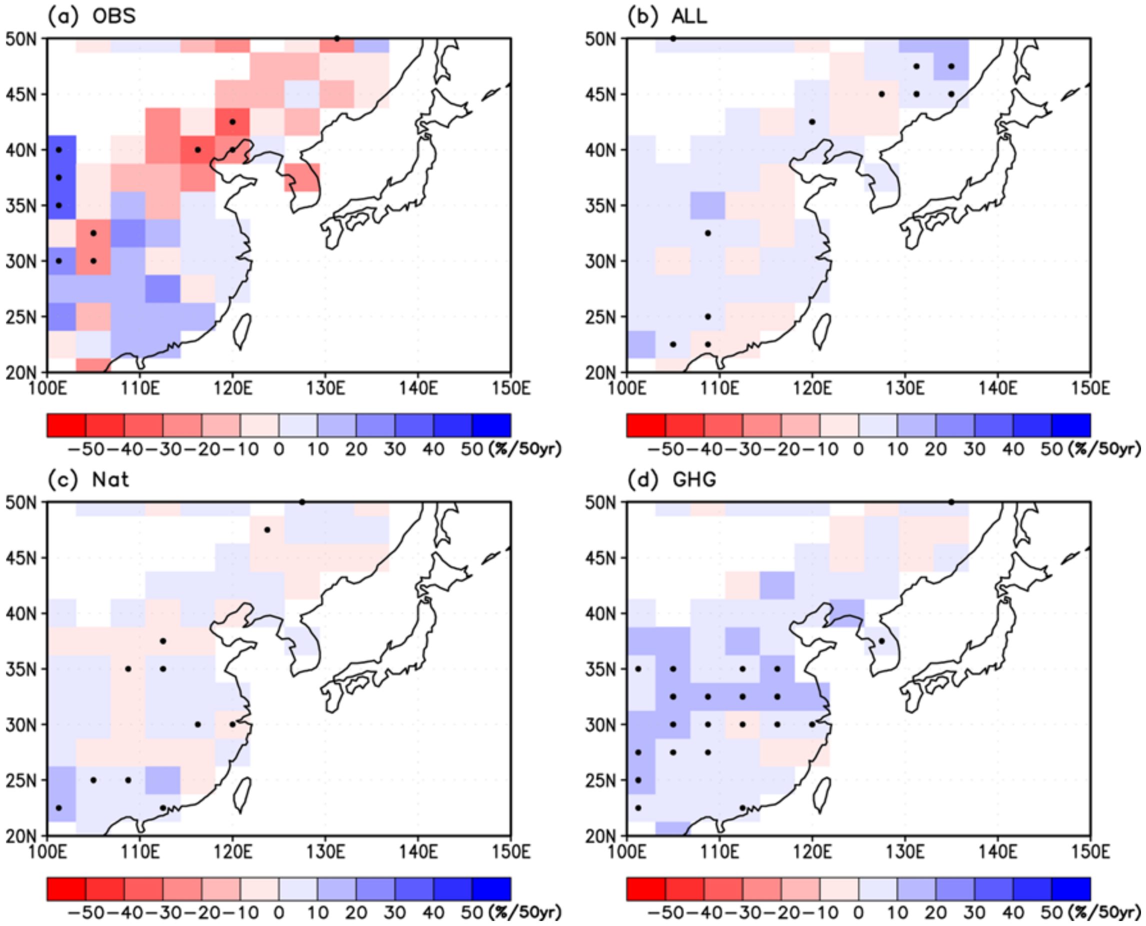

Fig. 4. Same for Fig. 3 except for trends in annual maximum of daily precipitation (RX1day) using HadEX2 observations and 8 CMIP5 models. Probability-based index ranging 0%-100% has been obtained prior to analysis by converting RX1day series into cumulative density function values based on the fitted generalized extreme value distribution on each grid point following Min et al. (2011). Dots represent statistically significant trends at 5% level.

b. Extreme events over East Asia

This section extends the domain of interest to the East Asia and beyond. The IPCC has recently concluded that "warming of the climate system is unequivocal" and also that "it is extremely likely (95% confidence) that human influence has been the dominant cause of the observed warming since the mid-20th century" (IPCC, 2013). This strong conclusion could be reached from growing body of evidence for human influence on climate since the fourth assessment report of the IPCC published in 2007. Human influence on the observed changes is typically identified through rigorous statistical comparisons between observations and climate model simulations integrated under external forcing factors such as increases in greenhouse gases and aerosols. Studies have detected human influence on many of the observed changes in the climate system listed above at the global and continental scales and usually on long-term trends longer than 50 years (Bindoff et al., 2013).

Recently, increasing number of studies have also reported observed increases in frequency and intensity of extreme events such as heat waves and heavy precipitations over the large part of the global land area (IPCC, 2012, 2013; Donat et al., 2013). In general, it is more difficult to detect significant changes in extremes than those in means due to larger uncertainties associated with relatively shorter time and smaller spatial scales of those events and the sparse availability of daily long-term observations. Nonetheless, human-induced warming of temperature extremes has been detected on global and regional scales (Bindoff et al., 2013). In case of precipitation extremes, only large-scale intensification of heavy precipitation has been attributed to human activities, which is consistent with IPCC's conclusion that "it is likely that anthropogenic influences have affected the global water cycle with medium confidence" (IPCC, 2013). Here we review detection studies of extreme temperature and precipitation for East Asia.

Global warming can manifest itself in regional-scale temperature and its extremes although confounding factors like urbanization effect, land use change, and internal climate variability can affect more strongly on smaller scales (Bindoff et al., 2013). Based on the optimal detection method (Allen

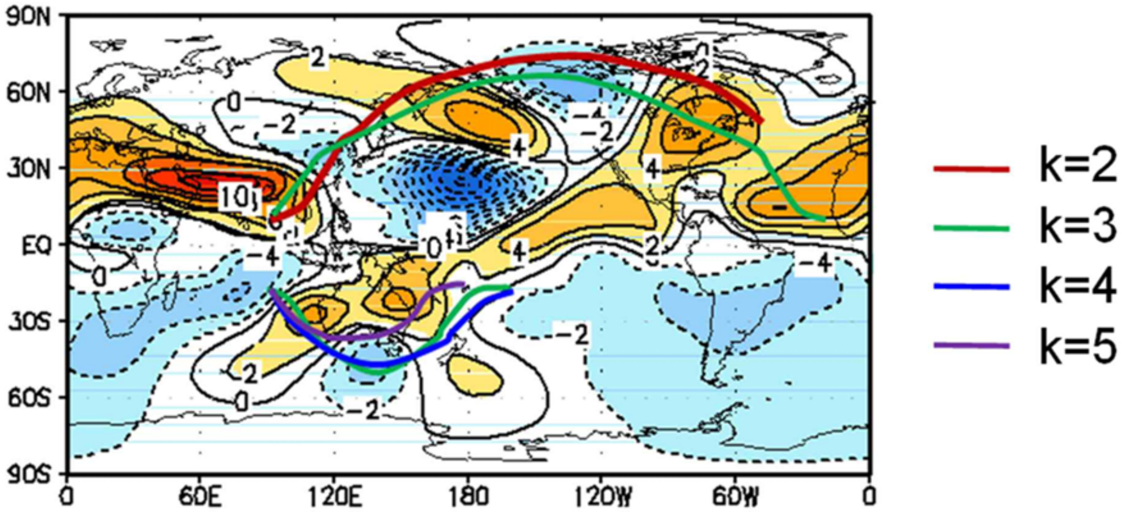

Fig. 5. Rossby ray path computed from the nondivergent barotropic Rossby wave theory for phase-3 forcing. *k* is zonal wavenumber. Only the wave train starting from the Indian Ocean is shown for day 15 of model integration. The zonal wavenumbers not shown in the figure are either very short or trapped in the vicinity of the starting point or critical latitude (adapted from Seo and Son, 2012).

and Stott, 2003) which quantifies observation-model comparisons with systematic consideration of internal variability, all previous studies consistently found human influence due to increase in greenhouse gases on the observed warming of extreme temperatures over large land areas including Asia or East Asia (Zwiers et al., 2011; Min et al., 2013; Morak et al., 2013; Wen et al., 2013; Seo et al. 2014). Morak et al. (2013) utilized percentile-based frequency indices of extreme temperatures while the other studies examined changes in intensity-based indices. Min et al. (2013) and Wen et al. (2013) further found that the detected human influence is also separable from influence of natural forcings due to changes in solar and volcanic activities over Northern Hemisphere continents and some sub-continental regions including East Asia and China, more strongly in night-time hot temperatures. For example, Fig. 3 shows the spatial patterns of the observed and simulated trend in annual maximum of daily minimum temperature (TNx) over East Asia during 1961-2010. Observations show an overall warming trend with larger amplitude over northern inland area than southern China and the Korean Peninsula, consistent with station-based results of Lee et al. (2012a). Multi-model simulations with natural and anthropogenic forcing can capture the observed trend reasonably well, whereas natural forcing only simulations cannot reproduce it. This clearly suggests that the observed intensification of warmest night temperature for the past 50 years cannot be explained by natural forcing only and that model simulations incorporating greenhouse gas forcing can reproduce the observed changes.

Extreme precipitation is expected to get stronger under the greenhouse warming due to increased moisture content in the atmosphere (Allen and Ingram, 2002; Trenberth et al., 2003). However, detecting external influence on extreme precipitation is much more difficult than that on temperature extremes since it has local nature of occurrence and hence increased noise level. In addition, long-term observations are more limited for daily precipitation and larger uncertainty exists in climate modeling of physical processes associated with precipitation extremes (O'Gorman and Schneider, 2009). Min et al. (2011) and Zhang et al. (2013) are the only detection studies that identified anthropogenic signal from extreme precipitation changes beyond the range of internal variability noise by comparing observed and simulated changes with an optimal detection technique. Human influence was found to be detectable, however, on hemispheric and continental scales only mainly over Northern Hemisphere land areas where sufficient observations are available. East Asia including Korea has been experiencing an increasing number of heavy precipitation events, which have been linked with multi-decadal variability of the East Asian summer monsoon (e.g., Zhou et al., 2009), as well as anthropogenic increase in greenhouse gases and aerosols (Lei et al., 2011; Song et al., 2014). However, as shown in Fig. 4, the observed long-term trends in extreme precipitation do not suggest spatially coherent increases over East Asia. Model simulations with different forcing factors do not show distinct pattern of increasing or decreasing trends either, indicating larger uncertainties. Trends in frequency of heavy precipitation exhibit very similar patterns (figure not shown). Therefore, it is imperative to understand the causes of the changes in East Asian monsoon circulation and quantify contribution of natural and anthropogenic origin in order to predict future changes in extreme precipitations with higher confidence.

4. Influence of tropical intraseasonal variability

The two major components of the tropical intraseasonal oscillation (ISO), which affect climate extremes in Korea and East Asia, are the Madden-Julian Oscillation (MJO) and the boreal summer ISO (BSISO). The former is characterized by a cycle of 30-60 days and predominant eastward propagation along the equator mainly during boreal winter (e.g., Madden and Julian, 1972) and the latter is by the periods of 10-20 and 30-60 days and prominent northward propagation over the Indian summer monsoon (ISM) and Western North Pacific (WNP)-East Asian region during boreal summer (e.g., Yasunari, 1980; Kemball-Cook and Wang, 2001). It has been noted that the tropical ISO with 30-60 days represents an important and as yet unexploited source of predictability over the globe on the subseasonal time scale (e.g., Waliser, 2006; Zhang, 2013; Lee et al., 2015a). The tropical-origin ISOs have significant impacts on extreme weather and climate over the extratropics including Korea though upscale/downscale modulations and tropical-extratropical teleconnection in boreal winter (e.g., Jeong et al., 2005, 2008; Kim et al., 2006; Han and Seo 2009; Park et al., 2010; Moon et al., 2011; Seo and Son, 2012) and boreal summer (e.g., Kang et al., 1999; Ding and Wang, 2007; Moon et al., 2013a, b; Lee et al., 2013). This section reviews on the modulation of climate variabilities and extremes over Korea and East Asia by the MJO and BSISO.

a. MJO teleconnection

The MJO convective anomalies are initiated over equatorial Africa and the western equatorial Indian Ocean, and the associated circulation systems propagate eastward as a Kelvin-Rossby wave couplet, and excite Rossby wave propagation to the higher latitudes. Kim et al. (2006) demonstrated that the divergent (convergent) circulation driven by the enhanced (suppressed) convection of the MJO interacts with the vertical wind shear of the wintertime Asian-Pacific jet, resulting in a prominent MJO-midlatitude teleconnection feature in the Northern Hemisphere. Seo and Son (2012) suggested that a large fraction of MJO-related circulation anomalies are direct responses to tropical heating in both the tropics and extratropics, and can be largely explained by linear dynamics. A ray tracing method using a theory of linearized barotropic vorticity equation demonstrates that teleconnection by the Rossby wave train and extreme events arise from the initial northeastward and ensuing southeastward propagation of the zonal wavenumbers 2 and 3 in the Northern Hemisphere during boreal winter season (Seo and Son, 2012) (see Fig. 5).

The MJO also plays an important role on extreme temperature and precipitation events in East Asia including Korea (Jeong et al., 2005, 2008; Han and Seo 2009; Park et al., 2010; Moon et al., 2011). Jeong et al. (2005), revealed that the spatial pattern and magnitude of surface air temperature over East Asia significantly change with respect to MJO phase and most extreme cold surges tend to occur when the MJO convective center is located over the Indian Ocean (the MJO phases 2-3). By analyzing four major cold surges including a record-breaking event occurred on 4 January 2010 for the winter of 2009-2010, Park et al. (2010) suggested that an MJO-induced circulation corresponding to strong tropical convection over the tropical Indian Ocean may reinforce the cold surges and snowfalls over East Asia by modulating the active local Hadley circulation and enhancing midlatitude synoptic disturbances. They further emphasized that the effects of the MJO and Arctic Oscillation (AO, see also section 5) along with the existing low-level moisture supply contributed to heavy snowfalls associated with strong cold surges over Korea during the winter.

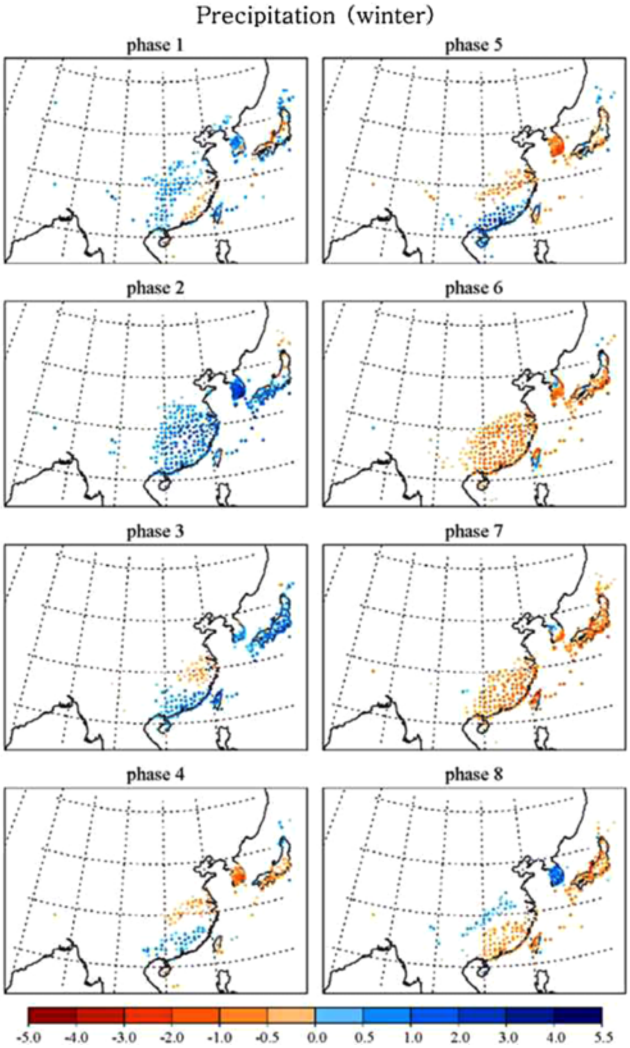

Fig. 6. December-January-February composite precipitation for MJO amplitude greater than 1 standard deviation in Korea, China, Japan, and Taiwan. Colored regions represent the stations where the composite values are significant at the 95% confidence level (from Han and Seo, 2009).

Jeong et al. (2008) found that the MJO significantly modulates the distribution of the wintertime precipitation over East Asia. For example, precipitation and upward motion tend to increase (decrease) when the MJO phases are at 2-3 (6-7) with the convective center over the Indian Ocean (the Western Pacific, respectively) during boreal winter (Fig. 6). They

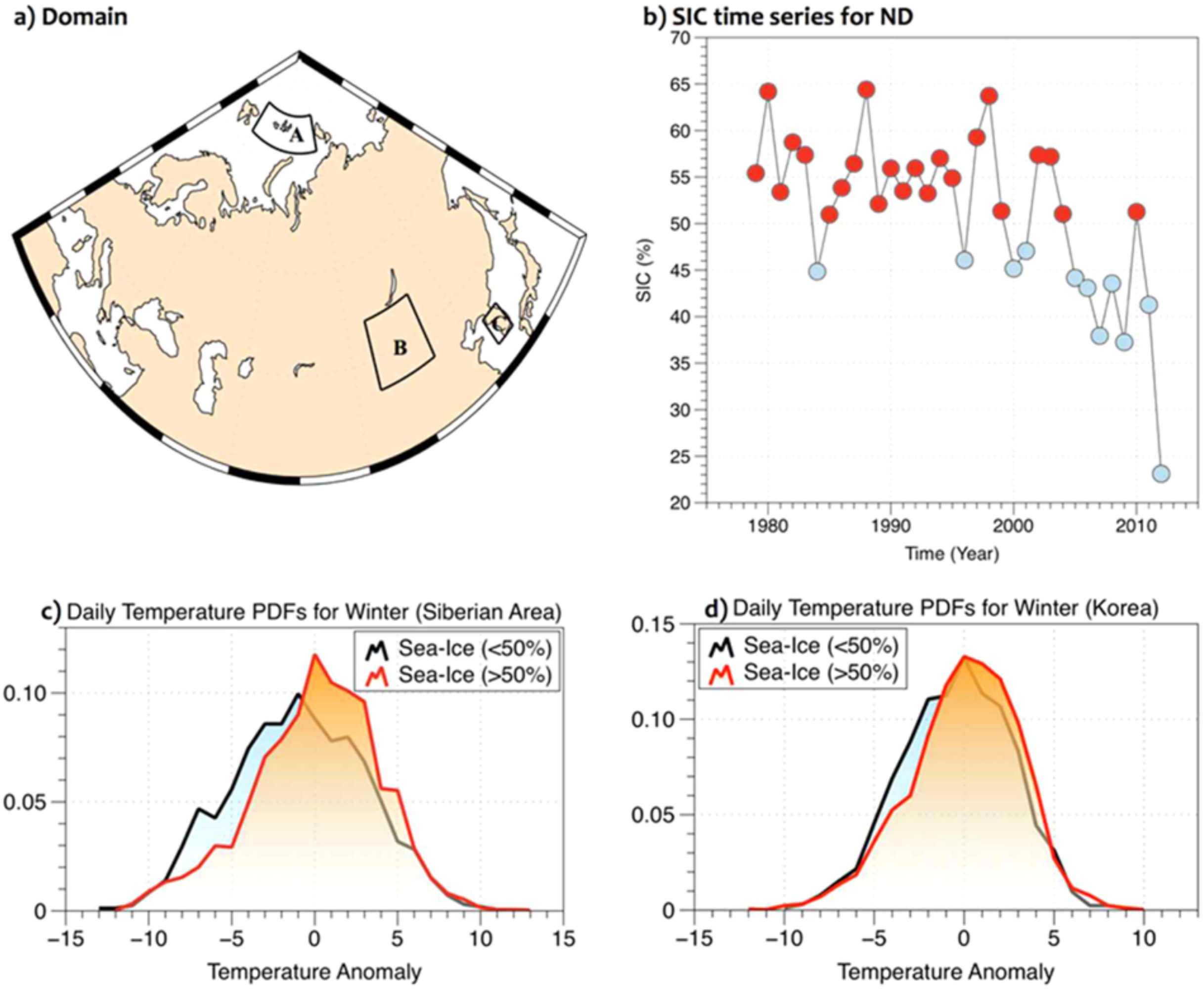

Fig. 7. (a) Three box regions (box A, B, and C) are indicated in the Eurasian continent domain. Arctic sea-ice concentration averaged over Box A for early winter (November-December) is shown in (b). (c) Daily temperature probability distribution function averaged over Box B (Siberian region) for winter (November-March) with years of sea-ice less than 50% (blue) and with years of sea-ice more than 50% (red). (d) Same as (c) except averaged over Box C (Korean Peninsula). Sea-ice data in this study is obtained from Hadley Centre Sea-Ice and SST data (Rayner et al., 2003).

showed that the MJO-precipitation relation is mostly explained by the strong vertical motion anomalies near an entrance region of the East Asia upper-tropospheric jet and moisture supply in the lower troposphere. However, they further demonstrated that the anomalous positive precipitation anomalies develop over the Korean Peninsula during the phase 8 as well as the phases 2-3. The enhanced precipitation for the phases 3 is attributed to the wavenumber-1 circulation response to MJO convection over the Indian Ocean with a cyclonic (anticyclonic) circulation anomaly developed to the west (east, respectively) of the Korean Peninsula and resulting northward moisture advection. Phase 8 has the similar positive moisture advection by southerlies but from a local circulation anomaly over Korea.

Moon et al. (2011) noted that the teleconnection induced by the same phase of MJO may generate different anomalies over East Asia and North America according to the phase of the ENSO. At the MJO phase 3, a barotropic North Pacific anticyclonic anomaly is stronger during La Niña than El Niño and thus much warmer and wetter condition over coastal northeast Asia are developed during La Niña years. On the contrary, at the phase 7, a barotropic cyclonic anomaly forms over the northwest Pacific during La Niña, causing bitter winter monsoon condition over Japan that is not occurred during El Niño.

b. BSISO teleconnection

The MJO is known to persist throughout the year, albeit with a generally weaker strength in boreal summer (e.g., Wheeler and Hendon, 2004), whereas the BSISO can be regarded as a specific mode of the tropical ISO that prevails in boreal summer (e.g., Seo et al., 2007). As discussed in Oh and Ha (2014) in detail, BSISO is related with the onset of East Asian summer monsoon, including Changma, and its active/break phases (e.g., Yun et al., 2008). It is also a possible source of subseasonal to seasonal climate predictability for precipitation and extratropical atmospheric circulation. The potential predictability of ISO estimated by a nonlinear Lyapunov exponent method amounts to 32 days (Ding et al., 2010; 2011a) and that by multi-model estimation reaches up to 35~45 days (Mani et al., 2014; Lee et al., 2015b) for both winter and summer seasons.

Lee et al. (2013) identified two major modes of BSISO. The first one is the canonical northward propagating mode that often occurs in conjunction with the eastward MJO with quasi-oscillating periods of 30-60 days. The convection associated with this mode first appears over the equatorial Indian Ocean at phase 1 and then propagates northeastward as well as eastward with a Rossby-type circulation cell, reaching Indian Subcontinent in phase3 and the Maritime continent in phases 3-4. Significantly enhanced (suppressed) convection anomaly over the Korean Peninsula is observed during the phases 3-4 (7-8) of the BSISO mode. The second mode is the northward/northwestward propagating mode with periods of 10-30 days during primarily the pre-monsoon and monsoon-onset seasons. The associated convection is located in the equatorial Indian Ocean and the Philippine Sea at phase 1 and then propagates northwestward with an elongated and front-like circulation cell. Phases 4-5 of this mode are favorable for the onset of Changma.

Moon et al. (2013a) showed Northern Hemisphere teleconnection patterns associated with strong ISO convective activities over the ISM and WNP. The active phase over ISM tends to drive extratropical circulation anomalies along the waveguides generated by the North African-Asian jet and North Atlantic-North European jet. The teleconnection pattern has been also noted as the circumglobal teleconnection on both the intraseasonal and seasonal time scales (e.g., Ha et al., 2012; Lee et al. 2014). The negative (positive) phase of circumglobal teleconnection is associated with the depressed convection over the ISM but enhanced (suppressed) convection with cold (hot) condition over East Asia including Korea. During the summer of 2009, the negative phase of circumglobal teleconnection associated with considerable deficit of the ISM rainfall was dominant that excited strong cold wave train along 35^o-40^oN resulting in cold and wet extremes over East Asia including Korea and central North America (Ha et al., 2012).

When the ISO convection strengthens over the WNP sector, a distinct great circle-like Rossby wave train emanates from the WNP across East Asia into the western coast of the United States, which is similar to the Pacific-Japan pattern (Nitta, 1987) and western North Pacific-North America pattern (Yun et al., 2008; Ding et al., 2011b; Lee et al., 2011, 2014) on seasonal timescale. The positive (negative) phase of the western North Pacific-North America pattern is characterized by enhanced (suppressed) convection over the WNP region but depressed (enhanced) convection over East Asia. Moon et al. (2013b) further noted that Korean rainfall anomaly is positively (negatively) correlated with ISO activity over the ISM during June (August) but negatively correlated with ISO in the WNP region.

It has been suggested that the northward propagating ISO affecting climate extremes in Korea may be related to ENSO. Yun et al. (2009) noted that the 30-60-day ISO in East Asia is closely tied with a quasi-biennial type ENSO and suggested that the northward propagating ISO would be a precursor to ENSO. Yun et al. (2010) further noted interdecadal change in the relationship between the ISO in East Asia and ENSO. They found that the winter ENSO influences the ISO activity during following early summer (May to June) before the late 1970s, whereas the strong relationship between ENSO and ISO activity appears during the later summer (July to August) after the late 1970s and this is attributed to the Indian Ocean SST warming that tends to enhance the western WNP subtropical high and Pacific-Japan pattern.

5. Influence of Arctic factors

Arctic region has been warming in an unprecedented rate in recent few decades and the warming trend is mostly salient in winter season (Screen and Simmonds, 2010b; Cohen et al., 2014; Kim et al., 2014c). Along with the unprecedented warming, which is so called as Arctic amplification, a large number of researches are now focusing on the linkage between the Arctic amplification and the changing mid-latitude circulation [See Vihma (2014) and Cohen et al. (2014) for comprehensive reviews on this issue].

In contrast with this abrupt Arctic warming in recent decade, the extratropical Northern continents, particularly including East Asia suffer more frequent occurrences of cold surges and heavy snow events during winter which causes significant socio-economical losses (Honda et al., 2009; Lim et al., 2012; Tang et al., 2013; Kim et al., 2014d; Mori et al., 2014). Among many cold extreme events in the northern mid-latitude in recent decades, a few events are particularly noticeable. In 2009, an extremely strong negative Arctic Oscillation, of which amplitude was highest in historical record since mid-20th century, was developed and brought about the long-sustaining cold extreme events over the northeastern part of US, Canada, Europe and Asia, simultaneously (Cohen et al., 2010). In mid-January of 2012, unusually strong Blocking ridge occurred near the Ural mountain region and the associated meandering of jet stream built up and lasted for more than 1 month, causing long-lasting cold surges over the Eastern Europe, and resulting more than 600 casualties (Peterson et al., 2013).

As a possible explanation on this increasing frequency of cold extremes in recent decades, several studies tried to connect the remote circulation changes with the Arctic sea-ice decline although how Arctic sea-ice decline can regulate atmospheric circulations and weather extremes in remote place is ambiguous in those studies (Honda et al., 2009; Petoukhov and Semenov, 2010; Hopsch et al., 2012; Inoue et al., 2012; Liu et al., 2012). The ambiguity lies on the deficit of Arctic observations of reasonable high quality and on the inaccurate model simulations associated with less developed physical parameterizations.

As a direct impact of the declining Arctic sea-ice, especially in cold season, a significant boundary layer warming can be brought about through the enhanced heat exchange from ocean surface, which is much warmer than near-surface atmosphere (Screen and Simmonds, 2010a). However, how the signal can propagate out of the Arctic to mid-latitudes is still an unresolved issue and might be very sensitive to broad atmospheric conditions. Several possible mechanisms have been proposed in previous studies as summarized in Cohen et al. (2014). First, the decline of Arctic sea-ice can change the storm track path since the ice-ocean boundary can be regarded as a sharp temperature gradient region. Inoue et al. (2012) examined the altered storm track over Eurasian continent when the Arctic sea-ice extent of Eurasian sector, i.e., Barents-Kara seas, is less than a long-term average. They found that Siberian cooling/warming occurred in consonant with the storm activity associated with the sea-ice anomaly. North Atlantic Oscillation (NAO) has been regarded as a large-scale pattern that sensitively depends on the Atlantic storm-track position and strength. The Atlantic sector storm activities are largely influenced by Arctic sea-ice loss and, therefore, actively modulate the NAO. A number of previous studies simulated this NAO dependency to sea-ice anomaly (Alexander et al., 2004; Deser et al., 2010).

The second mechanism is through the changes in the characteristics of the jet stream. A growing number of studies have argued that the Arctic amplification and the associated Arctic sea-ice loss can directly modify the flow pattern of jet stream, i.e. meandering of jet, and the wave phase speed embedded in the jet-stream (Overland and Wang, 2010; Francis and Vavrus, 2012; Jaiser et al., 2012; Tang et al., 2013; Liptak and Strong, 2014).

The third examines the regional changes in the tropospheric circulation induced by sea-ice loss and associates the regional circulation with the triggering of anomalous planetary wave configurations (Honda et al., 2009; Cohen et al., 2012; Kim et al., 2014d). Among these, Kim et al. (2014d) revealed that the tropospheric planetary wave induced by sea-ice loss tends to positively interfere with pre-existing climatological stationary waves. This positive linear interference is a favorable preconditioning for the weakening of the stratospheric polar vortex because the condition largely contributes to the large-scale wave upward propagation into stratosphere.

While some of the above studies documented a significant impact of Arctic sea-ice loss on the Eurasian temperature (i.e., Honda et al., 2009; Inoue et al., 2012; Lim et al., 2012; Liu et al., 2012; Kim et al., 2014d), they marginally discussed the extreme events over East Asian region including Korean Peninsula. Figure 7 provides evidence that the decreased sea-ice over Barents-Kara Seas tends to shift the PDF of the area-averaged daily surface air temperature to the colder direction (Fig. 7c for the Siberian region and 7d for the Korean Peninsula). As indicated in Fig. 7b, in recent decades, the Barents-Kara seas have lost significant amount of sea ice with some inter-annual variability on top of long-term trend. A large amount of air-sea heat exchange is also observed during the years of anomalously low sea-ice concentration over the Barents-Kara Seas partly due to the occurrence of increased Atlantic warm water intrusion in recent years (Screen and Simmonds, 2010a).

It is well conceived that global warming in the 20th century has caused more frequent extreme heat and heavy rainfall events (Min et al., 2011; Coumou and Robinson, 2013). Especially, Coumou et al. (2014) noted that on a global scale, the magnitude of this gradual increase can be to a large extent explained by a slowly warming atmosphere. The increasing number of heat extremes can largely be explained by a shift in the mean to warmer values. Likewise, upward trends in annual maximum daily rainfall are consistent with the increase in atmospheric moisture associated with warmer air. In this regard, the PDF shift toward colder direction in Fig. 7 looks counter-intuitive in a warming climate. However, it should be noted that the linkage between the Arctic sea-ice variability and remote atmospheric circulation revealed by previous studies is inherently dynamical in nature (Honda et al., 2009; Inoue et al., 2012; Liu et al., 2012; Kim et al., 2014d). Therefore, the results in Fig. 7 imply that the thermodynamic consequence of global warming can be hindered by the regional atmospheric circulation change in a particular region. Although the issue of warm Arctic and cold winter is still highly debatable in current literature and inconclusive yet (Barnes, 2013; Screen and Simmonds, 2013; Wallace et al., 2014), we summarize this section by addressing that both consideration of thermodynamic and dynamic factors are needed to better understand regional changes in climate extremes under a global warming.

6. Extreme El Niño and its impacts

The ENSO is referred as an irregular interannual variation of the central-to-eastern equatorial Pacific SST. It causes the climatic and socioeconomic impacts not only on the tropics but also on the extra-tropics through local and remote atmospheric teleconnections, and especially the super-sized El Niño such as 1982-83 and 1997-98 warm events (hereafter extreme El Niño) caused more severe damage on all over the globe. Although there were only two or three extreme El Niño events for the last half-century, we would expect that the number of extreme El Niño will increase as global warming progresses (Cai et al., 2014). Thus, the improvement of the forecast skill of the extreme El Niño is highly demanded, but it is known to be very tricky even in a qualitative manner, in spite of a great effort of climate science community. Here, we introduce the future perspective of extreme El Niño, together with its impact on the Korean Peninsula.

a. Future El Niño associated with global warming

The assessment of IPCC (2013) concluded that the assessment on the changes in the intensity and spatial pattern of El Niño in a warmer climate are on low confidence, by simply comparing ENSO variability from 20th century experiments and that from 21st century scenario experiments of CMIP5. However, Kim et al. (2014e) proposed that ENSO intensity change due to global warming is not monotonic. In other words, the ENSO intensity increases up to the early 21st century and then decreases by the end of 21st century because of warming trend of the Indian Ocean. Ahead of them, An et al. (2008) also argued the non-monotonic change in ENSO intensity due to the global warming, because of the delayed oceanic subsurface warming compared to the relatively fast surface warming, which leads to non-monotonic change of the tropical Pacific oceanic stratification. Therefore, these studies cautioned that a simple assessment like ‘the ENSO will be enhanced or suppressed due to global warming’ may not be meaningful.

Different from moderate El Niño, more confident reports are recently published regarding the future change in extreme El Niño. By analyzing CMIP3 and CMIP5 data sets, Santoso et al. (2013) showed that the frequency of the eastward-moving El Niño events increases in the future scenario simulations compared to the historical simulations, which infers that more frequent emergence of an extreme El Niño event is expected in a future. Cai et al. (2014) also argued that the extreme El Niño events will more frequently occur in a future due to global warming. Firstly, they identified two conditions from the observation (i.e., large tropical eastern Pacific rainfall anomaly and negative tropical Pacific meridional SST gradient), of which values for the observed extreme El Niño events are over thresholds, and then the similar classification applied to the CMIP5 simulations. They concluded that the frequency of extreme El Niño events in 21st century increases more than double compared to 20th century. Therefore, these studies suggest a strong possibility in more frequent occurrence of extreme El Niño in a future.

b. El Niño and extreme climate events over the Korean Peninsula

The El Niño events, particularly the extremely strong events tend to lead conspicuous abnormal climate conditions over the globe (Cai et al., 2014), and the Korean Peninsula could not be an exception. (Ahn et al., 1997; Kang 1998; Cha et al., 1999; Kug et al., 2010; Son et al., 2014; Yeh et al., 2014). As an example, Cha et al. (1999) showed that the variability of rainfall over Korean peninsula during the El Niño/La Niña periods is considerably different from that during the normal years. Recently, it is reported that the El Niño events can be classified into two-types of El Niño (Review of Yeh et al., 2014), unlike La Niña events (Kug and Ham, 2011). Kug Son et al., 2014. (2010) analyzed the climate variation over the Korean Peninsula in association with the two types of El Niño and found that the impact of El Niño on Korean climate depends on their type. For example, most regions in Korea tend to experience cold climate during the developing period of the Cold Tongue El Niño, while these regions experience warm climate during the developing period of the Warm Pool El Niño. In addition, the Cold Tongue El Niño has a significant relation with precipitation in Korea. These results indicates that the climate variation over the Korean Peninsula can be influenced by detailed structures of ENSO.

Recently, Son et al. (2014) pointed out that the Korean winter climate is strongly affected by the circulation changes over the Kuroshio extension region, which is induced by the tropical diabatic heating during El Niño/La Niña period to a large extent. For instance, during La Niña period the tropical diabatic heating leads to cyclonic flow in early winter over the Kuroshio extension regions. This anomalous cyclonic flow accompanies anomalous northerly wind over the Korean Peninsula, which provides a favorable condition for cold extremes.

Based on the relation mentioned above, one may expect the extreme ENSO events will have strong influence on climate variation over the Korean Peninsula. However, it is quite difficult to quantify how much the extreme El Niño affects extreme climate events over the Korean Peninsula, because the samples are extremely small in our historical observation. In particular, the extreme El Niño has been observed only three times: i.e., 1972/73, 1982/83, and 1997/98. In spite of such limitation, we observed abnormally warm winter, and severe heavy rainfall events during summer when the largest 1997/98 El Niño occurred. It has large implication that the occurrence of these extreme events seems to be related to the well-known relationship between ENSO and climate variation over the Korean Peninsula, which were reported from several studies (Wang et al., 2000; Kug et al., 2010; Son et al., 2014; Yeh et al., 2014; Zhou et al., 2014). For example, Wang et al. (2000) pointed out that the circulation responses to the El Niño forcing play a role in transporting warm and moisture air to East Asia from El Niño mature phase to the following summer of El Niño decaying phase, so that the climate over East Asia tends to experience more rainfall and higher temperature, consistent with the climate states in Korea during the 1997/98 El Niño events. Though it is quite difficult to clarify how much the El Niño-related circulation contributed to the extreme evens at that time, it is very likely that the circulation, induced by tropical forcing provides a background condition to be favorable to such extreme events. In this sense, it is now and will be a big challenge in quantifying how and how much the tropical forcing influences on extreme events in the extra-tropical regions.

7. Summary and Conclusions

In this study, recent findings on weather and climate extremes over Korea and East Asia are reviewed, including the observed trends in extreme temperatures and precipitation, influence of global warming, tropical intra-seasonal oscillations, Arctic factors, and extreme El Niño events. Summary for each topic is given below.

- Although winter temperature changes exhibit significant nonlinearity due to recent global warming hiatus, extreme 'cold' temperatures at the reference stations (Seoul and Chupungryong in this study) show statistically significant warming trends. This contrasts with extreme 'warm' temperatures which do not show robust trends. During summer, neither warm nor cold extremes exhibit significant trends over the last few decades. Large decadal variations of cold and warm extremes are also shown. Cold extremes decreased at the reference stations during the last few decades since 1980 with the peak frequency, but remain frequent in recent years especially in Chupungryong. Warm extremes occurred most frequently in the 1960s and 1990s. The significant decreasing (increasing) trend in the persistence of cold (warm) extremes were also detected, while the opposite trend is true in the entropy.
- Influence of greenhouse warming on East Asian climate extremes have been studied very limitedly. However, several detection studies clearly found that the observed intensification of hottest days and nights for the past 50 years is mainly due to human-induced increase in greenhouse gases. On the other hand, long-term changes in extreme precipitations over East Asia remain very uncertain in both observations and models. Further investigations are warranted for better understanding of natural and anthropogenic contributions to the changes in East Asian precipitation extremes in order to produce more reliable future projections and impacts.
- The MJO and BSISO have significant impacts on extreme weather and climate over the Korean Peninsula through upscale/downscale modulations and tropical-extratropical teleconnection. When the wintertime MJO are at phases 2-3 with the convective center located over the Indian Ocean, most extreme cold surges tend to occur along with an increase in precipitation and upward motion over the Korean peninsula. During boreal summer, significantly enhanced (suppressed) convection anomaly is observed in Korea during the phases 3-4 (7-8) of the canonical northward propagating BSISO mode. It has been also noted that ENSO phases significantly modulate the impact of MJO and BSISO on climate over the Korean Peninsula with considerable interdecadal changes.
- The recent rapid Arctic warming and sea-ice decline have received much attention because it has been known that Arctic warming can induce the extratropical cold extremes. Though how the Arctic changes can affect the extratropical climate is still controversial, several possible mechanisms have been proposed to explain the Arctic-to-extratropical connection such as modulation of the storm track path and jet stream, and regional Rossby wave propagation due to the Arctic sea-ice decline. It is also shown that the extreme cold events over the Korean Peninsula are linked to the sea-ice variation over Barents-Kara Seas.
- El Niño is known to reach its influence over the Korean Peninsula, and the impact of its extreme one is supposed to be more severe. However, it is not clear to what extent extreme El Niño influences the local climate change including Korean climate and how different impact of extreme El Niño is from those of moderate El Niño.

We reviewed several external climate factors in affecting the weather and climate extreme events in this study. It is evident that the largely-varying climate conditions due to the global warming, tropical intraseasonal oscillation, El Niño and Arctic warming influence on regional weather extremes, particularly changes in their frequency, duration and intensity. However, it is still unclear how and how much such climate phenomena modulate characteristics of the regional weather extremes. In particular, the quantitative estimation is quite poor in our current stage, despite that it is most important part for predicting weather extreme and minimizing their damage. This uncertainty in the effects of climate phenomena on weather and climate extremes are confronted with several issues.

First, our understanding on the weather and climate extremes themselves is still too poor. In spite of numerous studies, our knowledge is very limited especially on the dynamical and physical processes that play a role in triggering and maintaining individual weather extremes. Without knowing internal processes, it will be impossible to extract a contribution of the external climate factors. Second, the long-term observations are not sufficient to obtain a confident relationship between climate factors and changes in the regional weather and climate extremes. In particular, the high-frequency daily observed data to resolve extreme events are very limited, and spatially-homogenous observations are partly available only since the satellite era. Third, the state-of-the-art climate models are still far behind to be able to resolve realistic weather and climate extremes. As well as the low spatial resolution problem, some physical parameterizations in the climate models tend to be inappropriate to simulating observed weather and climate extremes. These issues are our major obstacles for better understanding extremes and predicting their changes, but are in turn major challenges to be pursued in next step. In particular, the current climate modeling should be designed and developed to resolve the interaction among various spatial and temporal scales. In addition, in order to concretely examine the effects of climate phenomena on weather extremes, the seamless prediction system can be the best strategy to make trustworthy probabilistic prediction of regional climate and weather extremes (Palmer et al., 2008).

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