Assessment of the changes in extreme vulnerability over East Asia due to global warming

Min-Hee Lee · Chang-Hoi Ho · Jinwon Kim ·
Chang-Keun Song

Received: 19 March 2010 / Accepted: 2 October 2011 / Published online: 23 November 2011
© The Author(s) 2011. This article is published with open access at Springerlink.com

Abstract A number of indices have been employed to describe weather extremes on the basis of climate regimes and public concerns. In this study, we combined these traditional indices into four groups according to whether they relate to warm (T_{warm}), cold (T_{cold}), wet (P_{wet}), or dry (P_{dry}) extremes. Analysis of the combined indices calculated for the daily temperatures and precipitation at 750 meteorological stations in Korea, China, and Japan for 1960s–2000s shows increasing trends in T_{warm} and P_{dry} events and decreasing trends in T_{cold} events in recent decades, particularly in the northern part of East Asia. A notable regional variation is an increase in the P_{wet} events in the Korean Peninsula. We applied the same analysis to a 200-year global climate model simulation for 1900–2099 using the National Center for Atmospheric Research-Community Climate System Model 3. During the 20th century, the changes in T_{warm} and T_{cold} calculated from the model data are largely consistent with those calculated from the observations, especially in northern East Asia. The model projections for the 21st century indicate statistically significant increasing T_{warm} and decreasing T_{cold} trends in extreme events over the region. Results obtained from historical archives and model simulations using our combined weather extreme indices suggest that northern East Asia will be subject to increased warm and dry extremes and the Korea Peninsula will experience more wet extremes.

M.-H. Lee · C.-H. Ho
Computational Science and Technology, Seoul National University, Seoul, South Korea

C.-H. Ho (✉)
Climate Physics Laboratory, School of Earth and Environmental Sciences, Seoul National University,
Seoul 151-742, South Korea
e-mail: hoch@cpl.snu.ac.kr

J. Kim
Department of Atmospheric and Oceanic Sciences, UCLA, Los Angeles, CA, USA

C.-K. Song
Climate Research Division, National Institute of Environmental Research, Incheon, South Korea

1 Introduction

Extreme weather events take a heavy toll on human lives, crops, water supply, industries, and ecosystems. Weather extremes, rather than changes in the mean climate, are the most consequential impact of global climate change (Kim 2005; Trenberth et al. 2007), though these extreme events may significantly respond to small changes in the mean climate (Katz and Brown 1992). Assessing the changes in extremes associated with recent climate change is thus one of the most important concerns of climate research.

The impact of climate change on a variety of weather extremes has been examined in a number of studies for North America (e.g., Karl et al. 1996; DeGaetano 1996), Europe (e.g., Heino et al. 1999; Osborn and Jones 2000), and East Asia (e.g., Iwasima and Yamamoto 1993; Zhai and Pan 2003, Park et al. 2011). In particular, East Asia has experienced intense natural disasters accompanied by extreme weather episodes in recent decades. As examples, record-breaking rainfall from typhoon ‘Rusa’ in 2002 resulted in a number of human casualties and economic losses of over 5 billion US dollars in Korea (c.f., Kim et al. 2006; Park and Lee 2007), and in September 2006, a heat wave occurred over an extended period across most of China with daily maximum temperatures well over 35°C (Ding et al. 2009). Such weather extremes cause substantial damages to the heavily concentrated industries and densely populated areas in East Asia. Reducing the damages inflicted by weather-related natural disasters is a priority in the region, and current disaster prevention plans include monitoring weather extremes and investigating the detailed mechanisms that produce such extremes.

Most previous studies have examined the characteristics of a single extreme weather event such as a typhoon, heavy rainfall, or warm/cold incident (Kim et al. 2005; Peterson and Manton 2008; Alexander and et al. 2006; Park et al. 2011). Single-event study is essential, because each event has some unique distribution or other characteristic. However, it is human nature for people to think that these extreme events happen only “elsewhere” and will not occur where they live even though global warming is changing weather worldwide. To provide perspective on the potential for extreme weather events, we here introduce a set of new indices created by integrating the existing various extreme-weather indices. Our new indices may help individuals to see the larger impact of various weather extremes and even the particular vulnerability of their own residential area to weather extremes.

We also investigated historical changes in extreme vulnerability, and modeled projected weather extremes expressed in the new indices, using observations and General Circulation Model (GCM, also known as Global Climate Model) simulations. The gridded values of our new group indices provide geographic visualization of regional and local vulnerabilities to extreme weather, information potentially very useful to both residents and policy makers.

This paper is organized as follows. Section 2 describes the dataset and methodology used for grouping indices to integrate various impacts of extremes. Sections 3 and 4 discuss changes in the extreme vulnerability over East Asia using these newly suggested indices, from observation and climate model projection, respectively. A summary is given in Section 5.

2 Data and method

2.1 Data

We analyzed the observed daily precipitation (PRCP), maximum temperature (TX), and minimum temperature (TN) over East Asia to assess the characteristics of historical extreme

events. The daily datasets analyzed were obtained from meteorological stations operated by the governmental meteorological administrations of Korea, China, and Japan. The analysis period covers the recent five decades (1960s–2000s); the beginning and ending years of individual records vary according to stations and variables, but all selected stations included the records for 1970–1999. For data quality control, stations that had missing data for more than seven consecutive days or for a total of 30 days during the five decades were excluded. Although we could not check the individual accuracy of each station used, the data did show a spatially coherent pattern in the variation of each dataset, which we believe confirms the reliability of data used in this study (figure not shown). After filtering out stations that did not meet our quality control criteria, we collected the data from 607 Chinese, 118 Japanese, and 25 Korean stations, for a total of 750 meteorological datasets. The final list of stations included in the analysis is presented in Table 1.

To project the changes in future extreme weather, we performed a future climate simulation using a coupled GCM (CGCM), the National Center for Atmospheric Research (NCAR) Community Climate System Model 3 (CCSM3; Collins et al. 2006), in conjunction with the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A2, A1B, and B1 (Nakicenovic et al. 2000) for projecting the climate in the 21st century (i.e., 2000–2099). The CCSM3 has been configured with T85 (approximately $1.4^\circ \times 1.4^\circ$) in the horizontal and 26 layers in the vertical. These scenarios assume that the carbon dioxide (CO₂) emission in the end of the 21st century will range from 5 gigatons of elemental carbon per year (GtC yr⁻¹) for B1, to 6 GtC yr⁻¹ for A1B, and up to 28 GtC yr⁻¹ for A2. The corresponding atmospheric CO₂ concentration is expected to range from 500 to 900 parts per million by volume (ppmv). In addition, a 20th century experiment (20C3M) for the period 1900–1999 was also performed for comparison with observations; forcing agents in this experiment were the historical records of greenhouse gases.

To confirm the reliability of the projected changes in this study, we additionally analyzed several coupled GCMs that participated in IPCC AR4. Among the 25 IPCC AR4 models, six included the required daily maximum and minimum temperature: BCCR-BCM2.0, CCCMA-CGCM3.1 (T42), CNRM-CM3, CSIRO-MK3.0, CSIRO-MK3.5, GFDL-CM2.0. More detailed descriptions of these six models are found in Table 2.

2.2 Indices for extreme vulnerability

To evaluate the integrated impact of several weather extremes, we designed four simplified new indices by combining various indices previously used. Table 3 compiles the definitions of the single, previously defined, indices which were adapted from the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) and have been widely used as tools to estimate and monitor changes in extremes (Peterson and Manton 2008; Alexander et al. 2006). Because combining indices of contrasting characteristics (e.g., warm extreme variables versus cold extreme variables) is likely to result in the loss of

Table 1 Numbers of Chinese, Korean, Japanese, and total meteorological stations used for calculating daily maximum temperature (TX), daily minimum temperature (TN), and daily precipitation (PRCP)

	TX	TN	PRCP
China	539	549	607
Korea	25	24	25
Japan	118	118	118
Total	682	691	750

Table 2 Description of the coupled global circulation models (CGCMs) used in this study

Model	Originating Group	Country of origin	Atmospheric resolution
BCCR-BCM2.0	BCCR	Norway	T63L31
CCCMA-CGCM3.1 (T47)	CCCMA	Canada	T47L31
CNRM-CM3	CNRM	France	T63L45
CSIRO-MK3.0	CSIRO	Australia	T63L18
CSIRO-MK3.5	CSIRO	Australia	T63L18
GFDL-CM2.0	GFDL	USA	2.5°×2°L24
CCSM3	NCAR	USA	T85L26

inherent characteristics of individual indices, we grouped a total of 24 indices into 4 categories according to their distinctiveness such as warm, cold, wet, and dry, as shown in Table 3. The warm extreme group (T_{warm}) contains the annual maximum of daily maximum/minimum temperatures (TX_x/TN_x), summer days (SU25), tropical nights (TR20), the occurrence of warm days/nights ($TX90p/TN90p$), and the warm spell duration

Table 3 Indices for daily climate extremes based on ETCCDMI

Extreme	ID	Definition
Warm (T_{warm})	SU25	Number of days with $TX > 25^{\circ}\text{C}$
	TR20	Number of days with $TN > 20^{\circ}\text{C}$
	TX_x	Maximum value of TX
	TN_x	Maximum value of TN
	$TN90p$	Number of days with $TN > 90\text{th percentile}$
	$TX90p$	Number of days with $TX > 90\text{th percentile}$
	WSDI	Number of days with at least 6 consecutive days with $TX > 90\text{th percentile}$
Cold (T_{cold})	FD0	Number of days with $TN < 0^{\circ}\text{C}$
	ID0	Number of days with $TX > 0^{\circ}\text{C}$
	TX_n	Minimum value of TX
	TN_n	Minimum value of TN
	$TN10p$	Number of days with $TN < 10\text{th percentile}$
	$TX10p$	Number of days with $TX < 10\text{th percentile}$
	CSDI	Number of days with at least 6 consecutive days with $TN < 10\text{th percentile}$
Wet (P_{wet})	RX1d	The largest 1 day rainfall total
	RX5d	The largest 5 day rainfall total
	SDII	Simple daily intensity index
	R10	Number of days with $PRCP > 10 \text{ mm day}^{-1}$
	R20	Number of days with $PRCP > 20 \text{ mm day}^{-1}$
	R50	Number of days with $PRCP > 50 \text{ mm day}^{-1}$
	R95p	Total amount of $PRCP > 95\text{th percentile}$
	R99p	Total amount of $PRCP > 99\text{th percentile}$
	PRCPTOT	Total amount of $PRCP > 1 \text{ mm day}^{-1}$
Dry (P_{dry})	CDD	Maximum number of consecutive dry days with $PRCP < 1 \text{ mm day}^{-1}$

indicators (WSDI). The cold extreme group (T_{cold}) consists of seven single indices including the minimum of daily maximum/minimum temperatures (TX_n/TN_n), the occurrence of cold days/nights ($TX10p/TN10p$), frost days ($FD0$), ice days ($ID0$), and the cold spell duration indicator (CSDI). In the wet category (P_{wet}), 10 single indices were grouped including: the maximum 1-day/5-day precipitation amounts ($RX1\text{day}/RX5\text{day}$), the annual precipitation total (PRCPTOT), simple daily intensity index (SDII) that shows precipitation rate, the number of very wet days ($R95p$), extremely wet days ($R99p$), heavy precipitation days ($>10 \text{ mm day}^{-1}$; $R10$), very heavy precipitation days ($>20 \text{ mm day}^{-1}$; $R20$), and extreme precipitation days ($>50 \text{ mm day}^{-1}$; $R50$). The category of dry extreme (P_{dry}) is represented by only one index: the consecutive dry days (CDD).

All indices above were calculated at each of the 750 meteorological stations. The station values were then converted into gridded values by averaging over the stations within a rectangular area of $5^\circ \times 5^\circ$ centered at the grid point. After gridding all single indices, the individual indices were divided by the spatial and temporal means of the corresponding variables, because taking an average of all indices in their original values can exaggerate the impact of certain indices due to their different units and magnitudes. This standardization by the spatiotemporal mean also allows the resultant gridded indices to represent the relative strength of the extreme in a region at a given day compared to other regions and/or other days. That is, a grid point value exceeding 1 means that the type of extreme event gridded is more frequent (or stronger) at the grid point than the climatological value over the entire analysis domain (i.e., East Asia), implying that the grid point is more vulnerable to the extreme.

After the individual indices were gridded, they were combined in the groups detailed above, with the seven warm indices grouped as index T_{warm} , seven cold indices grouped as index T_{cold} , nine wet indices grouped as index P_{wet} , and the single dry extreme index noted as index P_{dry} . These group index grids visually show the change in the vulnerability of geographic residential regions to the corresponding extremes due to global warming. This visualization could be of significant use to policy makers, who can now easily compare the vulnerability of their region at present to the past vulnerability in the whole of East Asia, and can plan accordingly.

3 Extreme vulnerability in the historical archive

To examine the historical variations in the vulnerability to extreme weather, we have investigated the climatology for the entire period (i.e., 1960s–2000s) and the anomalies of our four new group indices for each decade. The value of T_{warm} varies from 0.2 to 1.8 with the maximum value in the southern China coastal region (Fig. 1a). In the zonal band along 30°N and 40°N , T_{warm} is generally larger in the eastern region with maxima over eastern China, Korea, and Japan, perhaps caused by the influence of the subtropical North Pacific high that covers the area during summer. Anomalies for each decade (Fig. 1b–f) show robust negative values in most of the region until the 1980s, and then they become positive in the 1990s and 2000s with a 95% confidence level (see gray dots). This pattern clearly indicates that warm temperature extremes represented by T_{warm} have been increasing during recent decades. In particular, as shown in the area marked by a rectangle in Fig. 1f, the increase in T_{warm} is especially large over northern China and Korea with the values ranging from 0.05 to 0.3 in the 2000s, 25% higher than the climatological averages for the region; compared to the 1960s, the increment in this area is 82% higher than the climatological average for the region.

Fig. 1 Climatology (a) and anomalies of warm temperature extremes (T_{warm}) for the 1960s (b), 1970s (c), 1980s (d), 1990s (e), and 2000s (f). Regions significant at the 95% level are indicated by gray dots

Figure 2 shows both the mean and decadal anomalies of group index T_{cold} , which is characterized by larger values in the northern inland region and smaller values in the southern regions, especially along the coastline (Fig. 2a). In the decadal anomalies, positive anomalies are largely distributed in the inland region for the 1960s (Fig. 2b), then become weak and scattered in the 1970s and the 1980s (Fig. 2c and d). In the recent two decades of the 1990s and the 2000s, negative anomalies are dominant (Fig. 2e and f). This pattern clearly indicates that the cold extremes represented by T_{cold} have been decreasing over East Asia, particularly over the northern regions marked by a rectangle in Fig. 2f. This decreasing trend of T_{cold} seems to correspond to the increase of T_{warm} in the boxed region. Although warming due to urbanization over northeastern China would be one of the important factors contributing to the increase in T_{warm} and decrease in T_{cold} (Ren et al.

Fig. 2 Same as Fig. 1 except for cold temperature extremes (T_{cold})

2008), the significant changes are consistently found in the rural region in the western China. We believe this indicates that changes in vulnerabilities to warm/cold extremes during recent decades can be interpreted as signals related to global warming (Zhai and Pan 2003; Gong and Ho 2004; Alexander et al. 2006; Meehl et al. 2007).

Climatological vulnerability to wet extremes is generally large in the coastal regions in China, Korea, and Japan, which are strongly affected by the East Asian monsoon system and tropical storms (Fig. 3a). Unlike the two temperature extreme indices (T_{warm} and T_{cold}), P_{wet} anomalies are not spatially and/or temporally organized (Fig. 3b–f), which implies that wet extremes vary in a more complex manner spatially and temporally than do temperature extremes. Nevertheless, the increase in P_{wet} from the 1960s to 2000s in the vicinity of the Korean peninsula (the box area in Fig. 3f) is clearly defined in temporal variations of the index, increasing by about 50% during the period. This increase in precipitation extremes

over Korea adds to a consensus of previous studies (e.g., Ho et al. 2003; Wang et al. 2006; Kim et al. 2006) which conclude that Korea has become more vulnerable to wet extremes in recent decades.

The climatology and anomalies of P_{dry} are plotted in Fig. 4. Note that, unlike the other three indices, P_{dry} is composed of a single index, CDD. Climatologically, the largest value appears over the desert in northern China, which is nearly three times as large as values over the eastern region including eastern China, Korea, and Japan that are strongly affected by monsoon rainfall (Fig. 4a). Dry extremes are influenced mostly by large-scale circulations rather than regional convections, so the anomalies of P_{dry} show more coherent spatial patterns than P_{wet} (Fig. 4b–f). In northern inland China, which is affected by large variations in temperature extremes (the box area in Fig. 4f), the vulnerability to dry

Fig. 3 Same as Fig. 1 except for wet precipitation extremes (P_{wet})

extremes intensified from the 1960s to 2000s, consistent with the documented recent desertification of northern China (Yang et al. 2007; Wang et al. 2008).

Having analyzed the spatial distributions and decadal variations of the four indices from the climatology and the anomalies of each index per decade, we were able to recognize the locations of the core variability region of each index. However, the anomalies cannot show how much the core variability regions are vulnerable to these extremes compared to other regions, because the anomalies are simply the departures from the climatological averages. To approach this problem, we examined the annual time series of the four group indices averaged over the core variability region for each index. We also investigated the time series of the original individual indices that were grouped into the new indices, to examine whether the signal of change is exaggerated by combining several similar indices.

Fig. 4 Same as Fig. 1 except for dry precipitation extremes (P_{dry})

The black solid line in Fig. 5a shows the T_{warm} time series averaged over the core variability region, a rectangular region of 80°E – 150°E and 35°N – 45°N . T_{warm} values were about 0.8 in the 1960s, exceeded 1 after the 1990s, and since the 1990s have continuously increased with a statistical significance of 95%, implying that the impact of warm extremes in the region has become stronger as compared to the climatological mean for the entire

Fig. 5 Time series of domain averaged indices and individual components for T_{warm} (a), T_{cold} (b), P_{wet} (c), and P_{dry} (d). The lower part of the panel (d) shows what the individual indices used in the construction of the integrated index indicate and a color bar for the time series of the individual indices in (a)–(c)

East Asia region. As seen in the lower panel of the figure, this change is consistently found in the time series of the individual indices used in the construction of the integrated index. All indices show the increase in the corresponding warm extremes in the region, especially after the 1990s. In particular, the frequency indices (i.e., WSDI, TX90p, TN90p) have increased more than the intensity indices (i.e., TXx, TNx). Figure 5b presents the time series of T_{cold} and the individual components averaged over the same area with T_{warm} . Even though T_{cold} has gradually decreased until the 2000s with a statistical significance of 95%, the values remain greater than unity. This implies that T_{cold} responds more gradually to the global warming than T_{warm} does. For each index, an obvious decreasing trend is found in CSDI, TX10p, and TN10p.

Figures 5c and d represent the averaged time series of P_{wet} and P_{dry} , respectively. Since P_{wet} is significant only in one grid that includes Korea, the index is averaged only for the region 125°E–130°E and 35°N–45°N. From 1961 to 2008, P_{wet} has steadily increased by 50%, with more rapid increases after the 1990s. All the individual indices are greater than 1, indicating that Korea is strongly affected by precipitation extremes in general. In particular, the heavy extremes such as R99p and R50 show much greater values than the moderate extremes such as R95p and R10 over the region. The time series in Fig. 5d shows that P_{dry} values averaged over the same area as the temperature indices, including selected regions of inland China that are climatologically dry, have increased in recent decades. In particular, the time series of P_{dry} shows a large shift after the late 1970s with a statistical significance of 95%, which means that the number of consecutive zero precipitation days has increased after the late 1970s (Ho et al. 2005).

4 Future extreme vulnerability projected in the model simulations

In order to assess the impact of global climate change on the weather extremes in East Asia, the new grouped indices have been calculated from the outputs of CCSM3 simulations (Section 2.1). Model-projections of changes in extremes suffer from large uncertainties, in particular, on the regional scale; however, at present, a climate model approach appears to be the best way to estimate the tendency of the changes in extremes.

We analyzed the output of a 20C3M scenario run covering 1900 to 1999 to evaluate the CGCM under the present-day climate condition. Figures 6 and 7 show the climatology and anomalies of T_{warm} and T_{cold} , respectively; the spatiotemporal variations of model output are shown in 20-year increments from 1900 to 1999. Compared to the observed climatology of T_{warm} , the value from the 20C3M run is shown to be greater in general, especially in southern China and Japan (Fig. 6a). The core of the variability occurs over these regions in the model simulation, though the observations locate the variability core in the inland area of China; this discrepancy shows the limitations of the CCSM3. As a whole, the pattern of enhancement of T_{warm} over East Asia in recent years is nearly the same as that of the observations (Fig. 6b–f). In the case of T_{cold} (Fig. 7), except for the overestimation in the southern region, the climatological values are similar to observed values in distribution and range, and the core of variability is also shown in the northern part of China, although it tends to be shifted slightly to the east. The pattern of variation is also consistent with that of the observations, showing that using the model results for projection of T_{warm} and T_{cold} is reasonable despite some uncertainty in projection of detailed features.

Figures 8 and 9 present the results of P_{wet} and P_{dry} , respectively. It is well known that the simulation of precipitation is one of the most difficult problems in GCM study, especially on the local and quantitative approaches, so it is not surprising that though the model

Fig. 6 Climatology (a) and anomalies of T_{warm} from 20C3M output for 1900–1919 (b), 1920–1939 (c), 1940–1959 (d), 1960–1979 (e), and 1980–1999 (f)

climatology of P_{wet} shows similar features as the observations over the southern coastal region it overestimates over the inland China region (Fig. 8a). In the anomalies (Fig. 8b–f), the spatial distribution is scattered, similar to the observations. Considering only the changes from 1960 to 1999, P_{wet} seems to increase in the vicinity of Korean Peninsula, however, the significant increase over Korea found in the observations does not appear in the model data. Compared to the observations, P_{dry} is underestimated in the 20C3M simulation, and the high observed values over the northwestern part of the region cannot be found in the model shown in Fig. 9a. Particularly, the model does not show the signal of desertification over China in the anomalies of P_{dry} (Fig. 9b–f). The spatial distribution of anomalies in the model shows a dispersive pattern unlike the homogeneous pattern in the analysis of the observation. Given these results, we now know that obtaining reliable

Fig. 7 Same as Fig. 6 except for T_{cold}

precipitation estimates from GCM simulation is difficult not only for mean climate modeling but also for modeling extremes, and we have excluded the modeling results of precipitation extremes from further consideration..

The primary goal of our efforts to project the changes in extremes is to estimate the future climate state. For this work, we used three SRES emissions scenarios including A2, A1B, and B1, for simulating the 21st-century climate. To easily compare the changes in the 21st century to those in the 20th century, we used the same value as the 20C3M (i.e., the averaged value over whole region during 1900–1999 in 20C3M) for the normalization of individual indices. Although the degree of changes varies between the three scenarios, the spatial patterns are similar among them (figure not shown). In further discussion, we will only explain the spatial variation of extreme vulnerability in the climate with the A2 scenario, in which the highest rate of carbon emission is assumed.

Fig. 8 Same as Fig. 6 except for P_{wet}

Figures 10a–f show the mean of T_{warm} during the last 20 years in the 20C3M simulation and the deviation of the projected T_{warm} into the 21st century from the 20-year mean, respectively. As expected, the amplitudes of changes in the projected index are very large; for instance, the mean of T_{warm} during the last 20 years of 20th century has a range between 0 and 2, but its increment during the 100 years of the 21st century is more than 1.8 in the region of maximum anomaly. Figure 11 shows the same calculations for T_{cold} ; although the amplitude of changes in T_{cold} is not as much as that in T_{warm} , the decreasing trend is apparent over the whole region.

It is noteworthy that the negative trend in T_{cold} exists even in the southernmost region where the value in the last 20 years of 20C3M is nearly zero. This means that T_{cold} over the region during the 21st century is the negative value itself, which could be induced by the fact that T_{cold} includes the index using the absolute value of daily minimum temperature,

Fig. 9 Same as Fig. 6 except for P_{dry}

TNn. In other words, when the value used for normalization (i.e., averaged value over the temporal and spatial domain) is negative and the original TNn is positive in a certain grid, the normalized TNn can have a negative value in the grid. Then, if this normalized TNn contributes more to T_{cold} than the other six individual indices, T_{cold} may have a negative value. We could not find the negative value of T_{cold} in the observations or 20C3M simulation, suggesting that the influence of TNn may not be very large, but, in the A2 scenario for the 21st century, TNn over the southern region rapidly increases to a large positive value, while the value used for normalization shows a small negative value. In that interval, the influence of TNn is apparently sufficient to make T_{cold} negative.

Following the analysis of the observed data, we examined the temporal variation of domain-average indices using model outputs. As noted in Figs. 6 and 7, the selected domain is confined to 80°E–145°E, 30°N–45°N, which is an extensive region including a

Fig. 10 Mean of T_{warm} during the last 20 years in the 20C3M simulation (a) and the deviation of the projected T_{warm} into the A2 simulation from the 20-year mean during 2000–2019 (b), 2020–2039 (c), 2040–2059 (d), 2060–2079 (e), and 2080–2099 (f)

large variability compared to that of the observation analysis. To compare the changes in the different climate conditions, we also analyzed B1 and A1B scenarios in which the lowest and intermediate rates of carbon emission are assumed, respectively. In Fig. 12, red, green, and blue solid lines display the changes in extreme vulnerability for A2, A1B, and B1 scenario simulations, respectively. To show historical change, the result of the 20C3M scenarios is also plotted together as a black line. Consistent with the anomalies for each two-decade interval, T_{warm} shows increasing trends, and T_{cold} shows decreasing trends in all scenarios. The amplitude of changes is largest in A2 and lowest in B1 scenario, meaning that the further global warming progresses, the more T_{warm} and T_{cold} will change.

Fig. 11 Same as Fig. 10 except for T_{cold}

Additional detailed assessment of changes in extreme vulnerability with various climate scenarios is summarized in Table 4. For T_{warm} , values have risen 37% from 1900 to 1999 in the 20C3M simulation and risen 95% from 2000 to 2099 in the result of A2 scenario. Although the increment in the B1 scenario is small compared to the others, it is still 29%. T_{cold} has dropped by 14% during 100 years of 20th century observations, and by 70% during 100 years of 21st century in the A2 scenario. In the future climate simulated by B1 scenario, the total decrement in T_{cold} is about 31%, however, this change mainly occurs in the first 50 years of the 21st century and the tendency of decline has disappeared after the 2040s.

To evaluate the projected changes in CCSM3 simulation, we additionally analyzed the output of six IPCC AR4 models for T_{warm} and T_{cold} . Figure 13 shows the mean of T_{warm}

Fig. 12 Time series of domain averaged values for T_{warm} indices (a) and T_{cold} indices (b) from various model scenario run. Black, red, green, and blue solid lines indicate the results from 20C3M, A2, A1B, and B1 scenarios, respectively

Table 4 Changes (%) in T_{warm} and T_{cold} averaged over 80°E–145°E, 30°N–50°N for 20C3M (1900–1999), A2, A1B, and B1 (2000–2099) outputs

	T_{warm}	T_{cold}
20C3M (1900→1999)	+37%	−14%
A2 (2000→2099)	+95%	−70%
A1B (2000→2099)	+46%	−45%
B1 (2000→2099)	+29%	−31%

and T_{cold} averaged over the region of 80°E–145°E, 30°N–45°N during 1980–1999 and 2081–2100 from seven IPCC AR4 models including CCSM3. Although T_{warm} shows the largest changes and T_{cold} in 20C3M only shows values less than 1 in the CCSM3 result, the differences across models are not very large. All models including CCSM3 consistently show the increase in T_{warm} and the decrease in T_{cold} in the 21st century compared to the present day. Especially, the maximum and minimum changes are consistently modeled in all A2 and B1 scenarios. Therefore, we can conclude that the projected changes in T_{warm} and T_{cold} in CCSM3 in this study are reliable.

5 Summary and discussion

Given climate changes as represented by global (and/or regional) warming, the attendant changes in extremes have generated major concern in the scientific and public society. It is especially necessary for answering questions of public and decision makers related to the extreme vulnerability to know overall influence of various extremes as well as changes in individual extreme events. To satisfy these curiosities, we have developed new indices that integrate the influences of various existing extreme indices based on ETCCDMI. Our four indices are characterized by warm (T_{warm}), cold (T_{cold}), wet (P_{wet}), and dry (P_{dry}) extremes. The changes in these four indices have been examined using meteorological station observations for the period from the 1960s to the 2000s and model simulations using CCSM3 for 1900–2099.

In the observed data, three of the four extreme indices (all except P_{wet}) show significant changes in northern regions of East Asia during the recent five decades. The temporal variations characterized by increase in T_{warm} and P_{dry} and decrease in T_{cold} may be

Fig. 13 T_{warm} indices (a) and T_{cold} indices (b) averaged over the region of 80°E–145°E, 30°N–45°N during 1970–1999 and 2081–2100 from various IPCC AR4 model runs. Black, light gray, dark gray, and white bars indicate the results from 20C3M, A2, A1B, and B1 scenarios

considered as consistent warming signals due to an anthropogenic climate changes. In particular, the results, which show the change in climatological average values of T_{warm} is large in the southern region but the change in anomaly is large in the northern region, are line with previous studies concluding that the response to global warming is more obvious in the extratropics rather than the tropics (Dai et al. 2001). Correspondingly, T_{cold} decreases over the northern region and P_{dry} increases, because over the northern inland region the available moisture is not sufficient despite the increase of temperature. The spatial variation of P_{wet} in the East Asia region presents a very sparse pattern and the temporal variation shows an insignificant pattern. However, in the area of Korea, observed P_{wet} has steadily increased during the past 40 years, consistent with previous studies that have examined the large increase of heavy rainfall over the same region in recent years.

In the model simulation using CCSM3 for 1900–2099, changes consistent with those in the observations are detected in the two temperature extremes (T_{warm} and T_{cold}) of the 20th century simulation, and consistent changes are continuously shown in the projection for the 21st century. In the additional analysis of six IPCC AR4 models, the changes in T_{warm} and

T_{cold} are projected in similar ranges to the CCSM3. From the results of both the historical and the model analyses, we can conclude that planning for increases in the vulnerability of the northern East Asia to the warm and dry extremes and in that of the Korea Peninsula to the wet extreme is strongly urged.

Indeed, many weather extreme events could be mitigated reasonably well by planning responses to the increased vulnerability of the East Asia region. In the absence of planning and proper policy, even a moderate weather event can become a disaster. It is thus important to assess the impact of extremes and establish the proper policy for minimizing the damage from disaster. By using our combined indices, people can easily understand the integrated impact of various extremes on their residential area, not taking care of the detail characteristics. In addition, these indices directly show how vulnerable the region is to extremes compared to other regions, since they are represented by the normalized value using the spatiotemporal mean of extremes over East Asia. Areas in the region shown to be vulnerable to greater dry extremes can for instance establish planning based on proven policies in currently dry areas, and so on. These indices can be helpful in preparing response to extreme weather by showing the vulnerability to the extremes with quantitative values.

Prior to applying these indices to public policy, we should note several limitations of the analysis. First, some indices obtained from ETCCDMI, especially the indices using a fixed threshold such as TR20 and SU25, may be insufficient to fully reflect the characteristics of extremes over East Asia. In addition, CDD is only one index for dry extreme in ETCCDMI. It is possible that we could confirm better-optimized indices for East Asia by applying this method on a sub-regional scale for East Asia. Second, to show the vulnerability more realistically, socio-economic factors such as population density and national economy should be considered as well. Finally, it must be noted that the conclusions of this study are limited to extreme weather events based on the indices represented by absolute variations in temperatures and precipitation. It is, however, dependent upon the perception of people affected by an event whether the event is considered as an extreme or not. For example, although the minimum temperature has increased in recent years, cold events suddenly occurring after consecutive warm days can be still considered as an extreme event by some people. Therefore, in further study, it is necessary to supplement our indices by considering even such a relative concept of the extremes as personal perception, to assess more realistically the extreme vulnerability.

Acknowledgements This research was performed under support of CATER 2006-4204. The first author was also supported by the BK21 project of Korean government.

Open Access This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

References

- Alexander LV et al (2006) Global observed changes in daily climate extremes of temperature and precipitation. *J Geophys Res* 111:D05109
- Collins WD et al (2006) The Community Climate System Model Version 3 (CCSM3). *J Clim* 19:2122–2143
- Dai A, Wigley TML, Boville BA, Kiehl JT, Buja LE (2001) Climate of the twentieth and twenty-first centuries simulated by the NCAR Climate System Model. *J Clim* 14:485–519

- DeGaetano AT (1996) Recent trends in maximum and minimum temperature threshold exceedences in the northeastern United States. *J Clim* 9:1646–1660
- Ding T, Qian W, Yan Z (2009) Changes in hot days and heat waves in China. *Int J Climatol*. doi:[10.1002/joc.1989](https://doi.org/10.1002/joc.1989)
- Gong DY, Ho CH (2004) Intra-seasonal variability of wintertime temperature over East Asia. *Theor Appl Climatol* 24:131–144
- Heino R, Brazdil R, Forland E, Tuomenvirta H, Alexandersson H, Beniston M, Pfister C, Rebetez M, Rosenhagen R, Rosner S, Wibig J (1999) Progress in the study of climate extremes in northern and central Europe. *Climatic Change* 42:151–181
- Ho CH, Lee JY, Ahn MH, Lee HS (2003) A sudden change in summer rainfall characteristics in Korea during the late-1970s. *Int J Climatol* 24:131–144
- Ho CH, Kim JH, Lau KM, Kim KM, Gong DY, Lee YB (2005) Interdecadal changes in heavy rainfall in China during the northern summer. *Terr Atmos Ocean Sci* 16:1163–1176
- Iwasima T, Yamamoto R (1993) A statistical analysis of the extreme events: Long term trends of heavy precipitation. *J Meteorol Soc Jpn* 71:637–640
- Karl TR, Knight RW, Easterling DR, Quayle RG (1996) Indices of climate change for the United States. *Bull Am Meteorol Soc* 77:279–292
- Katz RW, Brown BG (1992) Extreme events in a changing climate: variability is more important than averages. *Climatic Change* 21:289–302
- Kim J (2005) A projection of the effects of the climate change induced by increased CO₂ on extreme hydrologic events in the western U.S. *Climatic Change* 68:153–168
- Kim JH, Ho CH, Sui CH (2005) Circulation features associated with the record-breaking typhoon landfall on Japan in 2004. *Geophys Res Lett* 32:L14713. doi:[10.1029/2005GL022494](https://doi.org/10.1029/2005GL022494)
- Kim JH, Ho CH, Lee MH, Jeong JH, Chen D (2006) Large increase in heavy rainfall associated with tropical cyclone landfalls in Korea after the late 1970s. *Geophys Res Lett* 33:L18706. doi:[10.1029/2006GL027430](https://doi.org/10.1029/2006GL027430)
- Meehl GA et al (2007) Global climate projections. In: Solomon S et al (eds) *Climate change 2007: the physical science basis*. Cambridge University Press, Cambridge, pp 749–844
- Nakicenovic N et al (2000) Special Report on Emission Scenarios, in A Special Report of Working Group III of the International Governmental Panel on Climate Change. Cambridge University Press, Cambridge, p 570
- Osborn TJ, Jones PD (2000) Airflow influences on local climates: observed United Kingdom climate variations. *Atmos Sci Lett* 1:62–74
- Park SK, Lee E (2007) Synoptic features of orographically enhanced heavy rainfall on the east coast of Korea associated with typhoon Rusa (2002). *Geophys Res Lett* 34:L02803. doi:[10.1029/2006GL027395](https://doi.org/10.1029/2006GL027395)
- Park TW, Ho CH, Yang S, Jeong SJ, Choi YS, Park SK, Song CK (2011) Different characteristics of cold day and cold surge frequency over East Asia in global warming situation. *J Geophys Res* 116:D12118. doi:[10.1029/2011JD015369](https://doi.org/10.1029/2011JD015369)
- Peterson TC, Manton MJ (2008) Monitoring changes in climate extremes: a tale of international collaboration. *Bull Am Meteorol Soc* 89:1266–1271
- Ren G, Zhou Y, Chu Z, Zhou J, Zhang A, Guo J, Liu X (2008) Urbanization effects on observed surface air temperature trends in north China. *J Clim* 21:1333–1347
- Trenberth KE et al (2007) Observations: surface and atmospheric climate change. In: Solomon S et al (eds) *Climate change 2007: the physical science basis*. Cambridge University Press, Cambridge, pp 235–336
- Wang B, Ding Q, Jhun JG (2006) Trends in Seoul (1778–2004) summer precipitation. *Geophys Res Lett* 33:L15803. doi:[10.1029/2006GL026418](https://doi.org/10.1029/2006GL026418)
- Wang X, Chen F, Hasi E, Li J (2008) Desertification in China: assessment. *Earth Sci Rev* 88:188–206
- Yang X, Ding Z, Fan X, Zhou Z, Ma N (2007) Processes and mechanisms of desertification in northern China during the last 30 years, with a special reference to the Hunshandake Sandy Land, eastern Inner Mongolia. *Catena* 71:2–12
- Zhai PM, Pan XH (2003) Trends in temperature extremes during 1951–1999 in China. *Geophys Res Lett* 30:1913. doi:[10.1029/2003GL018004](https://doi.org/10.1029/2003GL018004)