

## Different characteristics of cold day and cold surge frequency over East Asia in a global warming situation

Tae-Won Park,<sup>1,2</sup> Chang-Hoi Ho,<sup>1</sup> Su-Jong Jeong,<sup>3</sup> Yong-Sang Choi,<sup>4</sup> Seon Ki Park,<sup>4</sup> and Chang-Keun Song<sup>5</sup>

Received 21 November 2010; revised 3 April 2011; accepted 12 April 2011; published 30 June 2011.

[1] This study investigates the changes in winter cold extreme events over East Asia in the present and future climates. Two distinct terms to indicate cold extreme events are analyzed: “cold day,” which describes a temperature below a certain threshold value (e.g., simply cold weather), and “cold surge,” which describes an abrupt temperature drop (e.g., relatively colder weather than a previous day). We analyze both observations and long-term climate simulations from 13 atmospheric and oceanic coupled global climate models (CGCMs). The geographical distribution of sea level pressure corresponding to a cold day (cold surge) is represented by a dipole (wave train) feature. Although cold day and cold surge show similar patterns of surface air temperature, they are induced by the out-of-phase sea level pressures. From the results of our analysis of a series of future projections for the mid and late twenty-first century using the 13 CGCMs, cold day occurrences clearly decrease with an increasing mean temperature (a correlation coefficient of  $-0.49$ ), but the correlation between cold surge occurrences and the mean temperature is insignificant (a correlation coefficient of  $0.08$ ), which is supported by the same results in recent observation periods (1980–2006). Thus, it is anticipated that cold surge occurrences will remain frequent even in future warmer climate. This deduction is based on the future projections in which the change in the day-to-day temperature variability is insignificant, although the mean temperature shows significant increase. The present results suggest that living things in the future, having acclimatized to a warmer climate, would suffer the strong impact of cold surges, and hence the issue of vulnerability to cold surges should be treated seriously in the future.

**Citation:** Park, T.-W., C.-H. Ho, S.-J. Jeong, Y.-S. Choi, S. K. Park, and C.-K. Song (2011), Different characteristics of cold day and cold surge frequency over East Asia in a global warming situation, *J. Geophys. Res.*, *116*, D12118, doi:10.1029/2010JD015369.

### 1. Introduction

[2] Cold extreme events bring a high-latitude cold air into midlatitude and subtropical regions. Because of the vulnerability of living things to extreme weather conditions corresponding to recent climate change, cold extreme events inflict enormous sufferings on human societal activities [Kunkel *et al.*, 1999]. It is important to understand and assess the behavior of cold extreme events, especially in relation to the recent notable global warming and the future climate. Generally, cold extreme events are defined as an extremely low

daily temperature anomaly termed “cold day” [Trenberth *et al.*, 2007] and/or an abrupt temperature drop from one day to the next called “cold surge” [Boyle and Chen, 1987].

[3] Over the last few decades, surface temperature has globally risen, with large regional variations and considerable warming trends in East Asian countries [Trenberth *et al.*, 2007]. Considering the positive shift of the normal temperature distribution induced by an increase in the mean, it is natural that cold day occurrences would decrease with the shrinking of the cold tail. The majority of global land areas have suffered less severe cold days since the 1970s [Alexander *et al.*, 2006]; in particular, a reduction in cold day occurrences is more apparent over East Asia [Zhai and Pan, 2003; Gong and Ho, 2004; Choi *et al.*, 2009]. On the basis of numerous models, ranging from simple climate models to atmospheric and oceanic coupled global climate models (CGCMs), Meehl *et al.* [2007] have summarized that, almost everywhere, cold days are projected to significantly decrease in the warmer climate projected in the future. The most dominant signal of such a trend is found over East Asia [Gao *et al.*, 2002; Mizuta *et al.*, 2005; Boo *et al.*, 2006].

[4] By contrast, cold surge, a term distinct from cold day, is associated with the daily variability of temperature, rather

<sup>1</sup>Climate Physics Laboratory, School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea.

<sup>2</sup>Now at School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA.

<sup>3</sup>Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey, USA.

<sup>4</sup>Environmental Science and Engineering, Ewha Womans University, Seoul, Korea.

<sup>5</sup>Climate Research Division, National Institute of Environmental Research, Incheon, South Korea.

than the mean temperature. Since the mean (e.g., daily average) and the variability (e.g., day-to-day changes) are separate properties of nature, the decrease in cold surges may not be able to be simply induced by a general warming. *Walsh et al.* [2001] claimed that despite recent global warming, there is no long-term trend toward fewer cold surge occurrences in Europe and the United States in historical observations. However, so far, no study has documented the influence of global warming on changes in cold surge occurrences over East Asia, while some previous studies have focused on the characteristics of cold surges [*Takaya and Nakamura*, 2005; *Jeong et al.*, 2006] and their relation to large-scale circulations [*Jeong and Ho*, 2005; *Park et al.*, 2011]. Though the cold surge-related temperature variability strongly influences human activity and a living thing adjusted to recent or future warming climates, changes in the variability of daily temperature under global warming seem to be neglected somewhat, compared with the changes in the mean temperature.

[5] In general, the cold surges are regarded as the only temperature decrease. In a case over East Asia, however, the definition of cold surges includes an amplification of the Siberian High (i.e., a sudden surface pressure change) as well as an abrupt temperature drop [e.g., *Zhang et al.*, 1997a; *Jeong and Ho*, 2005; *Park et al.*, 2011]. Because the surface pressure change is an essential factor in the cold surge definition, the cold surges are called ‘East Asian pressure surges’ [*Compo et al.*, 1999]. During cold surge occurrences, the increase in surface pressure leads to a strengthening northerly wind related to cold advection along the eastern edge of the Siberian High. When the dominant northerly wind brings a cold air from the continent into East Asia, a wind chill/sensory temperature becomes colder, while a real temperature is constant regardless of the northerly wind. Namely, the dominant northerly wind can greatly drop the wind chill temperature during cold surge occurrences. Thus, the cold surges induce the lower wind chill temperature though the real temperature during cold surges may be higher than that during cold days. Undoubtedly, if the cold surges overlap with cold days the combined impacts of both the lower wind chill and real temperatures can cause the severe societal damage on human activity. Recently, we have experienced abrupt temperature drops and low temperatures over East Asia during the 2005/2006 and 2009/2010 winters, and the frequent occurrences of cold surges and cold days led to severe damage in the social and economic sectors [*Park et al.*, 2008, 2010]. These events highlight the importance of studies of changes in cold surges and cold days related to global warming.

[6] In addition, in terms of a consideration on temperature adaptation and its vulnerability for a living thing, to get suddenly colder day by day in relatively warmer days (i.e., cold surge) may be more influenceable, compared to be just cold day (i.e., cold day). *Cannell and Smith* [1986] and *Inouye* [2000] have reported a seemingly paradoxical hypothesis in which a warming climate may actually increase the risk of plant frost damage. The underlying hypothesis is that mild and warm winters, which are expected to occur as the climate warms, induce premature plant development, resulting in exposure of vulnerable plant tissues to subsequent abrupt temperature drop. *Gu et al.* [2008] have confirmed the hypothesis that a sudden temperature drop in a warming situation has a harmful influence on an ecosystem through a

case study about the severe freeze damage to plants induced by the dramatic temperature decrease under unusually warm conditions over the eastern United States in 2007. Thus, they have emphasized that an abruptly getting colder day can become a real threat to terrestrial ecosystem in a warming climate, compared to a simply lasting cold day.

[7] In the present study, we examine the changes in cold days and cold surge occurrences over East Asia in the present and future climates on the basis of both observations and climate change projected simulations of models anticipated in the Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (AR4). Subsequently, as a possible reason for the changes in cold day and cold surge occurrences, we investigate the links between cold day, cold surge, mean temperature, and temperature variability.

[8] The paper is organized as follows. Section 2 describes the CGCMs data used and the definitions adopted to identify cold days and cold surges. Section 3 presents the general features of cold days and cold surges in the present climate and their future projected changes, followed by the responsible causes for these changes. Finally, the findings of the present study are summarized and discussed in section 4.

## 2. Data and Methodology

### 2.1. Data

[9] To verify the performance of the model for simulating changes in cold days and cold surges and to gain confidence for future projections, the spatial features and changes in the present climate derived from the model simulations are compared with those from observations. For this, we use daily surface air temperature (SAT) data from 103 stations in China and 13 stations in Korea obtained from the China Meteorological Administration and the Korea Meteorological Administration, respectively. In addition, daily SAT and sea level pressure (SLP) from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis [*Kalnay et al.*, 1996] is used in order to capture the cold anomaly and the amplification of the Siberian High, respectively, related to the cold surges. Observation analyses are carried out for the 26 winters from 1980/1981 to 2005/2006.

[10] We analyze long-term model simulations obtained from 13 CGCMs, which are parts of the models that participated in the IPCC AR4. For this study we select the following 13 models: CCCMA-CGCM3.1\_T63, CCCMA-CGCM3.1\_T47, CNRM-CM3, CSIRO-MK3.0, CSIRO-MK 3.5, GFDL-CM2.0, GFDL-CM2.1, GISS-AOM, GISS-ER, MIROC3.2\_hires, ECHAM5/MIP-OM, MRI-CGCM2.3.2, and CCSM3. Detailed descriptions of the CGCMs used are summarized in Table 1. Among the IPCC AR4 CGCMs, some models are excluded because of the absence of required daily variables and inconsistency of the time calendar.

[11] Three time periods spanning 20 years each are used for the analysis of the present and future climate. The present climate is represented by model simulations with anthropogenic and natural forcing for the late twentieth century (1980–1999), which is a part of the 20C3M simulation. To represent the future climate, we adopt the CGCMs output for the mid twenty-first century (2046–2065) and the late twenty-first century (2081–2100) corresponding to the Special Report for Emission Scenario (SRES) A1B climate change projection

**Table 1.** Description of the Coupled Global Climate Models Used in This Study

Model	Originating Group	Country of Origin	Atmospheric Resolution
CCMA-CGCM3.1 (T63)	CCMA	Canada	T63L31
CCMA-CGCM3.1 (T47)	CCMA	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
GFDL-CM2.1	GFDL	USA	2.5° × 2°L24
GISS-AOM	NASS/GISS	USA	4° × 3°L12
GISS-ER	NASS/GISS	USA	5° × 4°L20
MIROC3.2_hires	CCSR/NIER/FRCGC	Japan	T106L56
ECHAM5/MPI-OM	MPI	Germany	T63L31
MRI-CGCM2.3.2	MRI	Japan	T42L30
CCSM3	NCAR	USA	T85L26

run. For these three time periods, daily SLP and SAT data are analyzed during the period of November through March when affects of cold days and cold surges are dominant.

## 2.2. Definitions of Cold Day and Cold Surge

[12] The cold days and cold surges in observation are defined using the SAT at stations. To exclude small-scale cold extremes caused by local effects such as radiative cooling, which can affect a single station, and for a reliable comparison between the observation and model simulations, we divide the 116 stations into  $5^\circ \times 5^\circ$  grid boxes and then apply the SAT values averaged over each grid box.

[13] A cold day is defined in basis on the SAT anomaly relative to the mean for 1980–2006 at  $5^\circ \times 5^\circ$  grid boxes over the East Asian region (105°E–130°E, 20°N–50°N), as depicted in Figure 1. When the SAT anomalies in one grid point and its surrounding grid points (i.e., five grid points) are less than  $-1.5\sigma$  ( $\sigma$  is the standard deviation of daily SAT during the 26 winters of 1980–2006 and 151 days for each winter) at a specific grid point, the day is determined as a cold day occurrence. For example, if  $1\sigma$  at a specific grid point is  $2^\circ\text{C}$ , the day when all SAT anomalies in the grid point and its four surrounding grid points are less than  $-3^\circ\text{C}$  is selected as cold day occurrence.

[14] A cold surge is identified by both a strong Siberian High and an abrupt SAT drop. First, the day of the strong Siberian High is determined as the day when the magnitude of SLP in the center of the surface anticyclone over southern Siberia (90°E–115°E, 35°N–55°N, Figure 1) exceeds 1035 hPa [Zhang *et al.*, 1997a]. The center of the surface anticyclone is defined as the grid point where the SLP is larger than the values of the eight surrounding grid points [Zhang and Wang, 1997]. Next, among the days of the strong Siberian High, the cold surge is defined as the day when the SAT in both the grid box and its four surrounding grid boxes over East Asia decreases abruptly by  $1.5\sigma$  over one or two days. The procedure of the cold surge definition is analogous to the methods of Park *et al.* [2011].

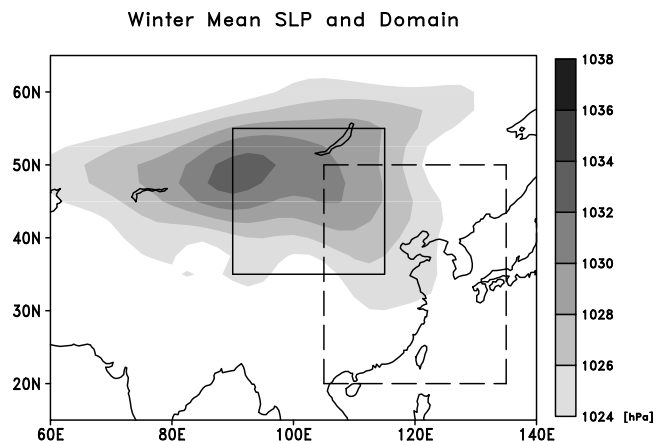
[15] In model simulations, the cold days and cold surges are defined using the model-based gridded SAT instead of the SAT of  $5^\circ \times 5^\circ$  grid boxes calculated from the values at the stations. We apply the same definitions as those used for the observation data. Cold days are identified from the daily SAT anomaly and  $\sigma$  at the grid points over East Asia in the models (Figure 1), which are based on a value relative to the mean for 1980–1999 at each grid point and its standard

deviation, respectively. This cold day definition is a slightly modified one on that of Vavrus *et al.* [2006]. The days of strong Siberian High and abrupt SAT drop at the grid points are also used for the definition of cold surge in the models [Zhang *et al.*, 1997b]. Because of the difference in the number of grid points over southern Siberia and East Asia, corresponding to the horizontal resolutions, it is noted that the numbers of cold days and cold surges in the models detected by the above definitions depend on the horizontal resolutions of the climate models. Thus, a model of higher resolution is apt to simulate more occurrences of cold days and cold surge. As we will see, this intermodel discrepancy does not affect our major conclusion, which is associated with the time dependency of cold extremes.

## 3. Results

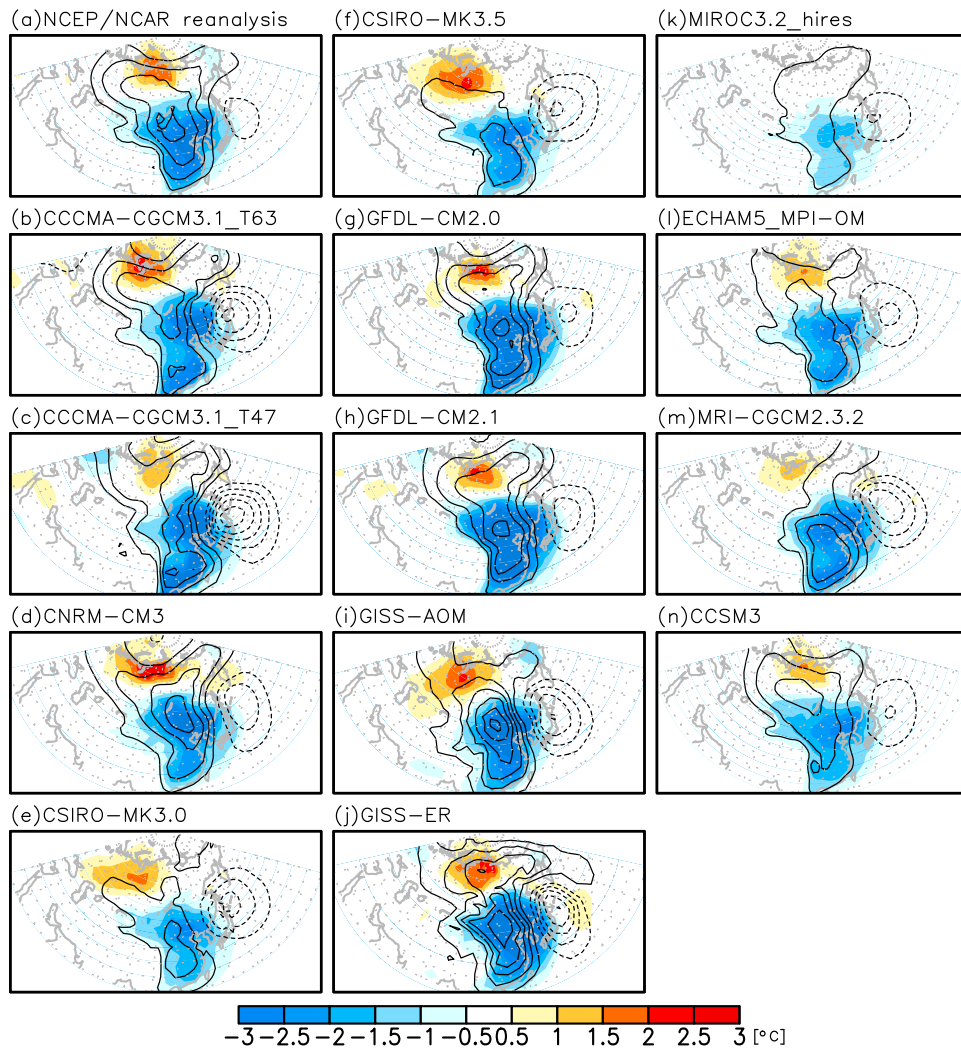
### 3.1. General Features of Large-Scale Environments During Cold Days and Cold Surges

[16] The primary aim of this study is to assess changes in cold day and cold surge occurrences under global warming using observation and model simulations. First, it is necessary to examine the characteristics of large-scale environments related to the observed cold days and cold surges in the present climate and further compare them with those simulated



**Figure 1.** Domain of East Asia (dashed lines) and Siberian High (solid lines). Shading indicates the climatological sea level pressure during the period of November to March.

## SAT and SLP anomalies during Cold days



**Figure 2.** Composite anomalies of sea level pressure (contour: intervals of 1 hPa; zero line is omitted) and surface air temperature (shading) for occurrence dates of all cold days obtained from observations and 13 models.

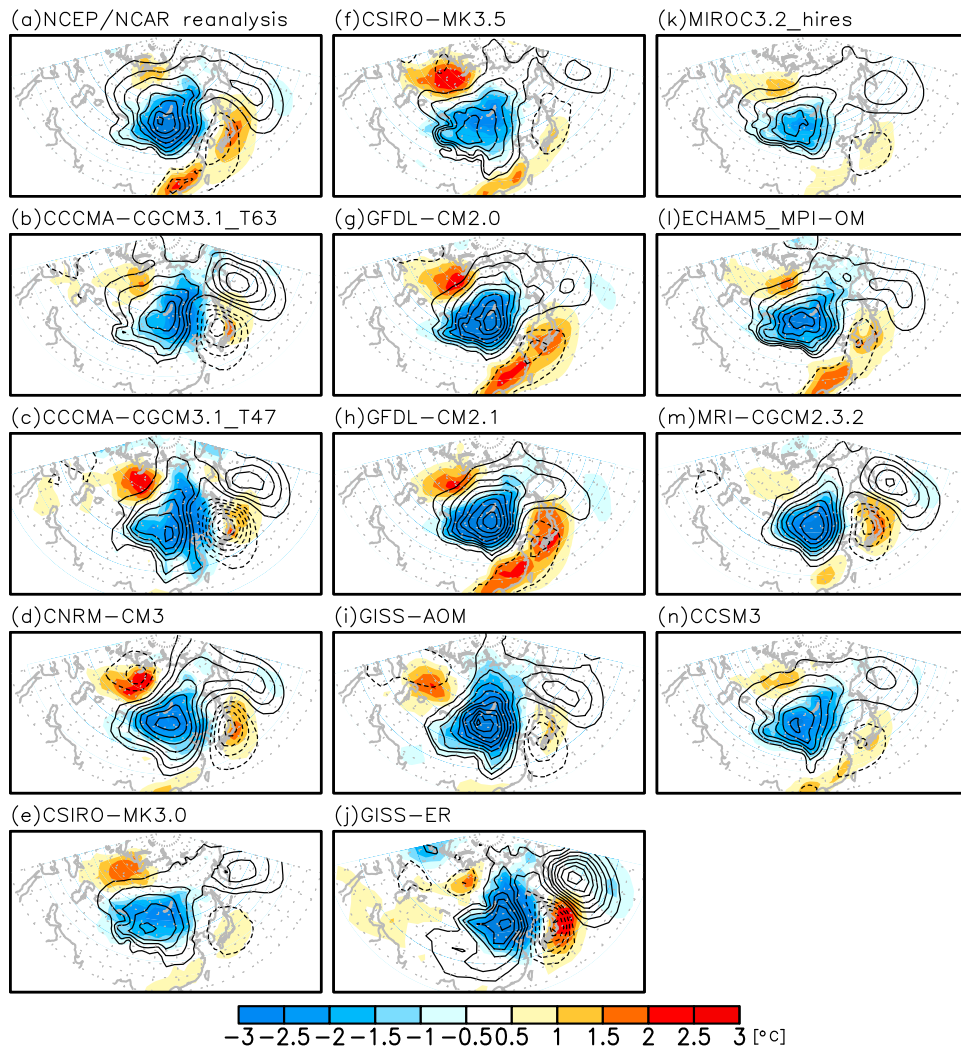
in the CGCMs. The analysis results would help validate our assessment of changes in the future climate.

[17] The observed distributions of SLP and SAT during the dates of cold day occurrences are displayed in Figure 2a. Dipole features of high pressure over the East Asian continent and low pressure over the northwestern Pacific are found. The high pressure seems to have originated from the Siberian High and expands to the Far East, while the low pressure is weak relative to the high pressure. Because of a southerly flow along the western edge of the high pressure and a northerly flow between the high and low pressures, warm and cold anomalies are located around the Arctic and over East Asia, respectively (figure not shown), which is out of phase with the SLP pattern. Cold days influence the whole of East Asia through a widespread cold anomaly. Figures 2b–2n show the spatial pattern of SLP and SAT for the cold days simulated in the 13 CGCMs. In general, the dipole features have a slight difference in amplitude with respect to the models; e.g., weaker in MIROC3.2\_hires (Figure 2k) and

stronger in GISS-AOM (Figure 2i) and GISS-ER (Figure 2j) relative to other models. All the models produce nearly the same dipole features on cold days corresponding to the observations, although some models (e.g., GISS-ER and CCCMA-CGCM3.1\_T63/T47) show very weak wave train features with weak high pressures over the North Pacific.

[18] Unlike cold days, the observed SLP anomalies on the dates of the cold surge occurrence are characterized by a wave train feature (Figure 3a): two high-pressure systems over the Lake Baikal area and the North Pacific and a low-pressure system over the Korea–Japan region. The related warm–cold–warm anomalies are found in the regions between the high–low–high pressures. Southerly and northerly flows along the edges of these pressure patterns seem to lead to out-of-phase features of SLP and SAT, which are in accord with the geographical features of typical cold surges as shown by *Park et al.* [2011]. The cold anomaly associated with the cold surges tends to concentrate around a smaller region, compared with the cold anomaly during cold days. Interestingly,

## SAT and SLP anomalies during Cold surges



**Figure 3.** Same as Figure 2 but for cold surges.

a widespread warm anomaly ranging from south China to Japan is observed ahead of the cold anomaly, which means an outbreak of warm weather before the cold surge occurrence. In the model simulations of the cold surge, CNRM-CM3 (Figure 3d), GFDL-CM2.0 (Figure 3g), and GFDL-CM2.1 (Figure 3h) simulate a relatively weak wave train feature in which incomplete high pressure forms over the North Pacific. Moreover, the wave train feature in CCCMA-CGCM3.1\_T63 and T47, GISS-AOM and ER, and MRI-CGCM2.3.2 is more evident than that in the observations and the other models. In general, most models reproduce the observed wave train features of SLP and SAT for cold surges well.

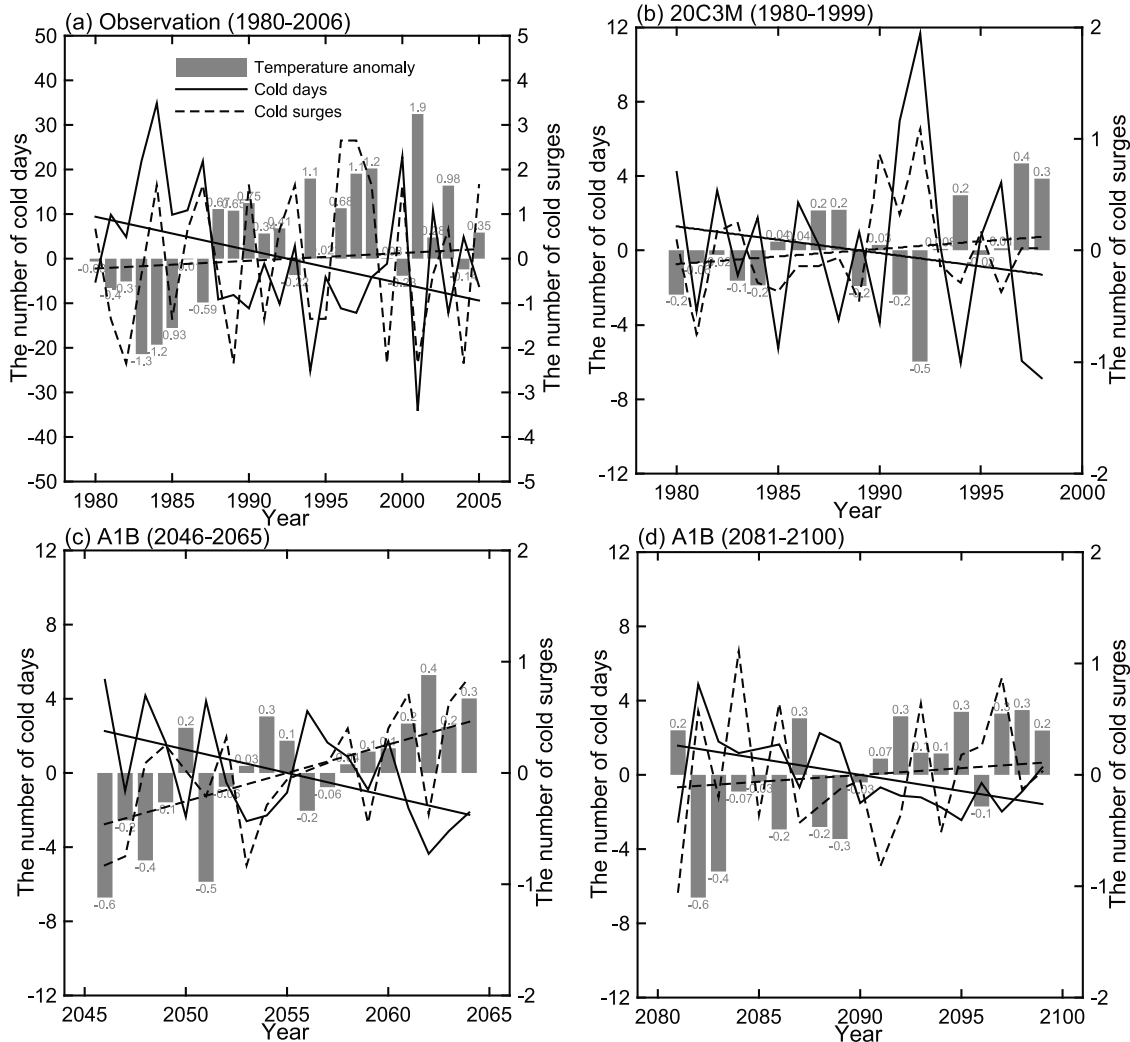
### 3.2. Changes in Cold Day and Cold Surge Occurrences in the Present and Future Climates

[19] Prior to analyzing changes in cold day and cold surge occurrences from the CGCM simulations, we examine the observed features in the present climate situation. During the last 26 winters (1980–2006), a considerable decrease in cold days, a slight increase in cold surges, and a strong warming

trend are observed over East Asia (Figure 4a). The decrease trend of cold days and the warming trend are significant at the 99% confidence level (Table 2). However, the number of cold surge occurrences hardly change for the period from 1980 to 2006, corresponding to an insignificant change of 0.174 per 10 years in Table 2.

[20] Next, we look at the changes in the present climate simulated by CGCMs, depicted in Figure 4b. The analyzed three variables have less interannual variability compared to that in the observations, because we take the ensemble mean of the 13 models that have various interannual variabilities. That is, the huge differences of the analyzed three variables between observation and ensemble mean are caused by averaging each model which has a different interannual variability. In addition, as stated in the section of cold event definitions, the number of cold event occurrences shows a dramatic difference with respect to model resolutions. For example, while the most frequent occurrences of cold events are found in the highest-resolution model (i.e., MIROC3.2\_hires), the lowest-resolution model (i.e., GISS-ER) simulates





**Figure 4.** Time series of (a) observed and (b–d) simulated winter mean temperature anomaly (bar), the number of cold days (solid line), and the number of cold surges (dashed line). Observed values are obtained from surface observations and NCEP/NCAR reanalysis for 1980–2005. The simulated values are the ensemble mean of 13 CGCMs for the late twentieth century (Figure 4b), the mid twenty-first century (Figure 4c), and the late twenty-first century (Figure 4d). All values are denoted as anomalies relative to the mean values in each period. Thick solid and dashed lines indicate the linear trend of the number of cold days and cold surges, respectively.

the smallest number of cold event occurrences (Figure 5). Thus, the model resolution bias is also a significant contributor to the huge discrepancy in the number of cold events between the observations and the model ensemble mean. In spite of the fact that there are discrepancies of variabilities among the CGCMs, it is noteworthy that in the ensemble

mean, the number of cold days and cold surges significantly decrease and slightly increase, respectively, under the strong warming trend, which coincides with the observations. The results are supported by statistical values of trends in 20C3M, as shown in Table 2. Thus, the model performances simulating the changes in the present climate give us further

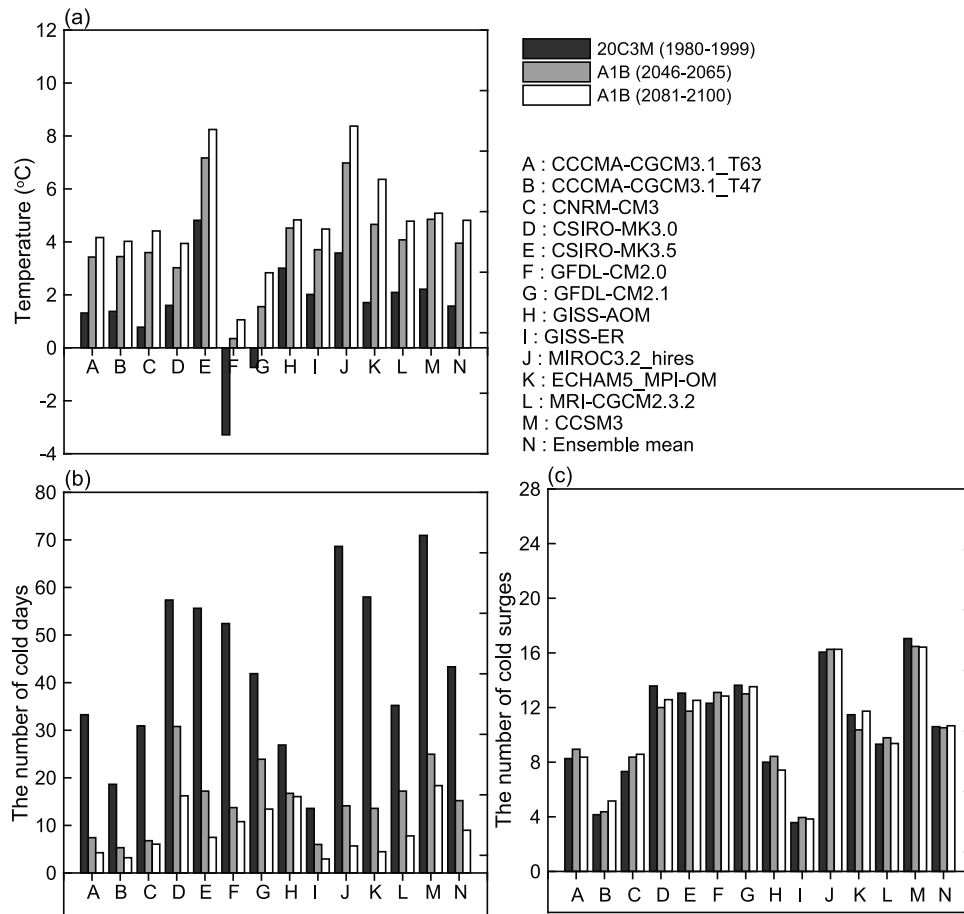
**Table 2.** The Slope of the Trend for Changes of Winter Mean Temperature, the Number of Cold Days, and the Number of Cold Surges in the Observations and Simulations of the Late Twentieth Century, the Mid Twenty-First Century, and the Late Twenty-First Century

	Observation (1980–2006)	20C3M (1980–1999)	A1B (2046–2065)	A1B (2081–2100)
Winter mean temperature (°C/10 years)	0.54 <sup>a</sup>	0.15 <sup>b</sup>	0.37 <sup>a</sup>	0.27 <sup>a</sup>
Cold days (number/10 years)	−7.52 <sup>a</sup>	−1.43 <sup>b</sup>	−2.51 <sup>b</sup>	−1.75 <sup>b</sup>
Cold surges (number/10 years)	0.17	0.14	0.51 <sup>c</sup>	0.12

<sup>a</sup>Significant values at the 99% confidence level.

<sup>b</sup>Significant values at the 95% confidence level.

<sup>c</sup>Significant values at the 90% confidence level.



**Figure 5.** (a) Winter mean temperature, (b) the number of cold days, and (c) the number of cold surges averaged for 20 years in the late twentieth century (black bar), the mid twenty-first century (gray bar), and the late twenty-first century (white bar).

confidence for projection of future events. For the mid and late twenty-first century, the ensemble mean of the 13 CGCMs simulates long-term trends of decrease and increase in cold day and cold surge occurrences under ongoing warming throughout the analysis periods (Figures 4c and 4d). Interestingly, as shown in Table 2, while the mid twenty-first century under a steep warming trend ( $0.37^{\circ}\text{C}$  per decade) shows larger changes in cold day and cold surge occurrences ( $-2.51^{\circ}\text{C}$  and  $+0.51^{\circ}\text{C}$  per decade, respectively), the CGCMs at the end of the twenty-first century predict little changes ( $-1.75^{\circ}\text{C}$  and  $+0.12^{\circ}\text{C}$  per decade, respectively) with a relatively weak warming trend of  $0.27^{\circ}\text{C}$  per decade. It might well be caused by the nature of the A1B scenario, which assumes fossil fuel emissions will decrease after a peak around 2050.

[21] Figure 5 shows the values of the winter mean temperature, the number of cold days, and the number of cold surges over East Asia averaged over 20 years, for the three time periods in the 13 models and their ensemble mean. A large variation, ranging from  $-3.5^{\circ}\text{C}$  in GFDL-CM2.0 to  $5^{\circ}\text{C}$  in CSIRO-MK3.5, across models is found in the simulation of winter mean temperature in the present climate (1980–1999). The temperature biases are also shown in two future climate simulations (2046–2065 and 2081–2100). In general, while GFDL-CM2.0 and GFDL-CM2.1 have

cold biases relative to other models, CSIRO-MK3.5 and MIROC3.2\_hires tend to simulate higher temperatures over East Asia. Differences of cold day and cold surge occurrences among models are also apparent. In the late twentieth century, both cold day and cold surge occurrences reach a minimum value in GISS-ER (e.g., about 13 and 3, respectively) and a maximum value in MIROC3.2\_hires (e.g., about 70 and 16, respectively). The differences in the mid twenty-first century and late twenty-first century are analogous to those in the late twentieth century. The intermodel wide-range discrepancy of cold day and cold surge occurrences is caused by the horizontal resolution of each model. The higher-resolution model has more grid points in East Asia, resulting in more numerous detections of cold extreme events of a smaller scale as well as a larger scale, while the lower model can capture only large-scale cold events because of fewer grid points and coarser resolution.

[22] Despite the large variation across models, all models consistently show the continuously increasing winter mean temperature from the late twentieth century to the late twenty-first century, in accordance with the results shown in previous studies [Meehl *et al.*, 2007]. All models show a significant decline of cold day occurrences for the mid twenty-first century relative to the late twentieth century, from 35% to 80% according to the model. By the late twenty-first century,

the significant decrease reaches 40% to 90%. This indicates that a rise of winter mean temperature induced by global warming drives the warmer SAT anomalies than those in the present climate (i.e., used in definition of cold days); thus the fixed criteria for cold days has become relatively stricter in the future climate [Vavrus *et al.*, 2006].

[23] Comparing the mid and late twenty-first century with the late twentieth century, eight of the 13 models show a slight increase in cold surge occurrences and the remaining five show a slight decrease. Though there are some discrepancies among the models, the increase and decrease are located within the limits of  $\pm 12\%$  change in which the maximum change is simulated in CSIRO-MK3.0. In addition, the percentage change of cold surge occurrences in the ensemble mean are at most  $-0.75\%$  for the mid twenty-first century and  $+0.66\%$  for the late twenty-first century, relative to the late twentieth century. In contrast, those of the cold day occurrences are found to be 65% and 80% for the same two periods. Thus, the changes in the number of cold surges under global warming are insignificant and the occurrences are projected to remain frequent in the future warm climate.

[24] As shown in Figure 5, there are the huge differences of the number of cold event occurrences with respect to the model resolution, though the considerable decrease of cold day occurrences and the insignificant change of cold surge occurrences are found regardless of the model resolutions. The five grid point definitions of cold events applied in this study inherently induce that the higher-resolution models can detect the smaller-scale cold events that are missed by the lower-resolution models because of the different areal coverage. The model resolution dependency of the frequency of the cold events may make the interpretation of main results in this study complicated. Thus, to remove the impact of the model resolution, we subdivide the East Asian region into four regions, which have the same areal coverage, and then the cold events are defined using the values averaged at the individual grid points over each region. Four regions are north China ( $105^{\circ}\text{E}$ – $125^{\circ}\text{E}$ ,  $30^{\circ}\text{N}$ – $40^{\circ}\text{N}$ ), middle China ( $105^{\circ}\text{E}$ – $125^{\circ}\text{E}$ ,  $40^{\circ}\text{N}$ – $50^{\circ}\text{N}$ ), south China ( $105^{\circ}\text{E}$ – $125^{\circ}\text{E}$ ,  $20^{\circ}\text{N}$ – $30^{\circ}\text{N}$ ), and Korea ( $125^{\circ}\text{E}$ – $135^{\circ}\text{E}$ ,  $30^{\circ}\text{N}$ – $50^{\circ}\text{N}$ ). Figure 6 shows the number of cold days and cold surge occurrences averaged over each region in late twentieth century, the mid twenty-first century, and the late twenty-first century simulations. When the same areal coverage regardless of the model resolution (i.e., a regional approach) is applied to the cold event definition instead of the five grid point approach, the model resolution dependency of the frequency of the cold events is eliminated. As seen in Figure 6, a clear decrease of cold days and an insignificant change of cold surges are also found, which coincides with the results in Figure 5.

[25] By comparison with the noteworthy changes of the number of cold days, changes in the number of cold surge occurrences are very insignificant. The model indicates that the increasing mean temperature caused by the enhanced greenhouse gas concentration has almost no effect on the cold surge occurrences, in contrast to the robust diminishing influence on cold day occurrences.

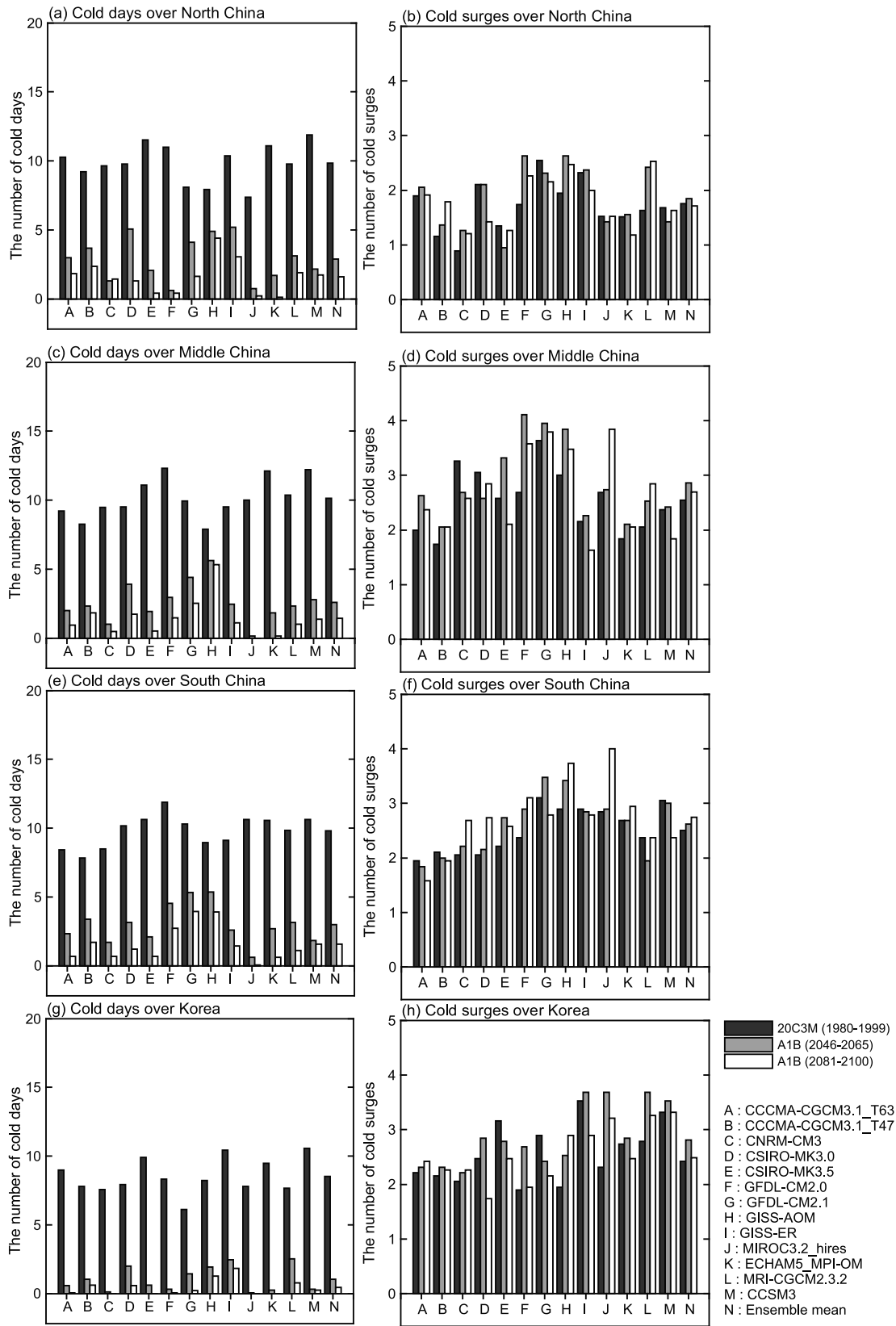
### 3.3. Relation of Cold Day and Cold Surge Occurrences to the Mean and Variability of the Temperature

[26] From the above discussion, it is presumed that the increase in the winter mean temperature is irrelevant to the

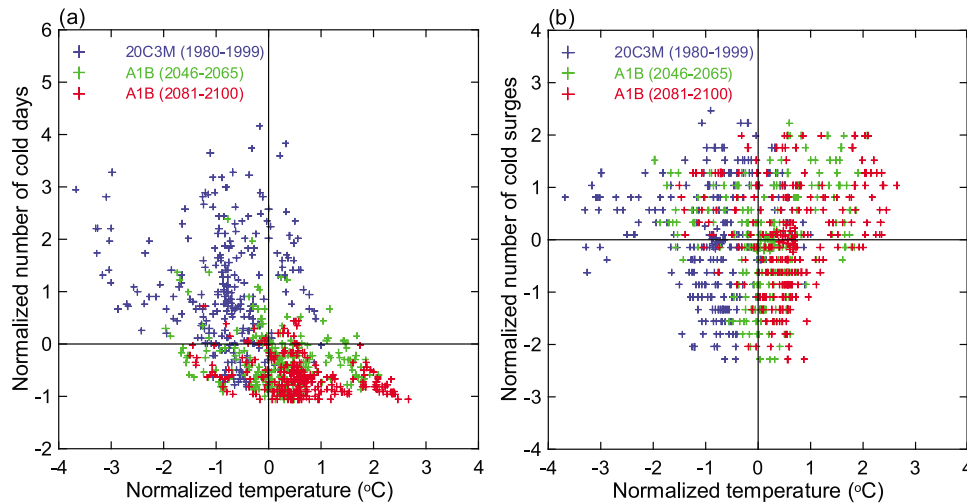
changes in cold surges; however, it contributes to a remarkable decline of cold day occurrences. To further verify the behavior of cold days and cold surges with respect to the winter mean temperature, scatterplots for the relationship between the winter mean temperature and the number of cold days and cold surges are represented in Figure 7. Values for periods of 20 years for the 13 models and their ensemble means in the three time periods are used for the scatterplots. Thus, the number of scattered values is 840, which is computed by a multiplication of the three time periods, 20 years, and 14 models (thirteen models and one ensemble mean). Considering the widespread scattering of the values by the large variations across models (Figure 5), it is difficult to verify the above mentioned relationship. For a convenient and direct comparison among the three time periods regardless of discrepancies among models, we normalize the winter mean temperatures, the number of cold days, and the number of cold surges with respect to all the scattered values (i.e., 840 values) prior to the plotting. Figure 7a shows the relationship between the normalized winter mean temperature and the normalized number of cold days. The blue, green, and red symbols represent the values for the late twentieth century, mid twenty-first century, and late twenty-first century, respectively. It is evident that there is a rise of winter mean temperature and a reduction of cold day occurrences from the late twentieth century through the mid twenty-first century to the late twenty-first century. Almost all the values in the late twentieth century are found above zero for the number of cold days and below zero for the winter mean temperature, while those in the mid twenty-first century tend to concentrate on the zero. However, the projected results for the late twenty-first century display a scatterplot of winter mean temperature and cold day occurrences distributed on positive and negative values, respectively. These results indicate that they are negatively correlated. The correlation coefficient of  $-0.49$  supports the evidence of the negative relationship. Interestingly, the negative relationship does not seem to be linear. The number of cold days in the late twentieth century decreases steeply with increasing winter mean temperature. However, in the mid twenty-first century the gradient of the reduction slope is much smaller and in the late twenty-first century the slope almost diminishes. In addition, an interesting feature is that the cold days do not decrease any lower than  $-1$  with further warming, though the statistically normalized values generally range from  $-4$  to  $+4$ . This indicates that the behavior of cold days is sensitive under warming below a specific threshold, but above the threshold, even a consistent increase in winter mean temperature under serious global warming cannot reduce the occurrence of cold days.

[27] The scatterplot showing the distribution of the number of cold surges with respect to the winter mean temperature is shown in Figure 7b. The three time periods are separated into three groups, which are negative, neutral, and positive normalized temperatures, according to the winter mean temperature, indicating an increase in the winter mean temperature under global warming. However, the differences in the number of cold surges among the three time periods are insignificant. That is, the number of cold surges is spread with a distribution that is irrelevant to the winter mean temperature, resulting in a very low correlation coefficient of 0.08 between them. In addition, Figure 7b shows that only the positive normalized numbers of cold surges reach values





**Figure 6.** (a, c, e, g) The number of cold days and (b, d, f, h) cold surges over north China (105°–125°E, 30°–40°N) (Figures 6a and 6b), middle China (105°–125°E, 40°–50°N) (Figures 6c and 6d), south China (105°–125°E, 20°–30°N) (Figures 6e and 6f), and Korea (125°–135°E, 30°–50°N) (Figures 6g and 6h) averaged for twenty years in the late twentieth century (black bar), the mid twenty-first century (gray bar), and the late twenty-first century (white bar).



**Figure 7.** Scatterplot of normalized values for temperature versus the number of (a) cold days and (b) cold surges. Blue, green, and red dots indicate values in the late twentieth century, the mid twenty-first century, and the late twenty-first century, respectively.

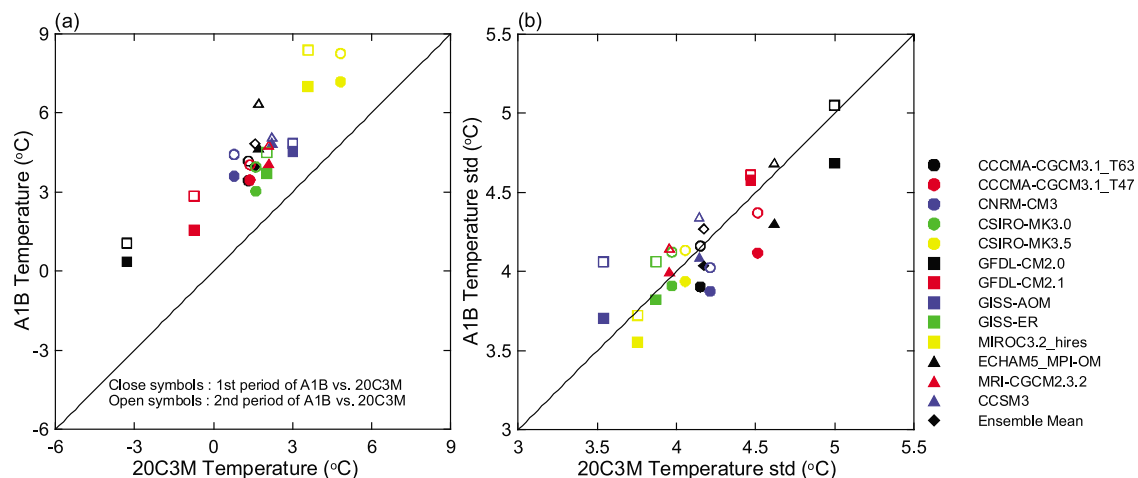
beyond the winter mean temperature of  $\pm 1^{\circ}\text{C}$ , while most of the negative numbers are concentrated within a winter mean temperature of  $\pm 1^{\circ}\text{C}$ . More than the average number of cold surges seems to occur under a whole range of winter mean temperature, and it means that frequent cold surge occurrences are not influenced by an increasing temperature under global warming.

[28] The insignificant changes of cold surges under global warming and the irrelevance to the winter mean temperature might be explained by the variability rather than the mean. Thus, it is supposed that the rising temperature related to global warming cannot lead to a change in the winter temperature variability. To confirm the above supposition for the temperature variability, scatterplots for comparison of the mean and standard deviation of the winter temperature in the mid twenty-first century and the late twenty-first century with those of the late twentieth century are constructed for 13 models and their ensemble mean (Figure 8). As shown

in previous studies [Meehl *et al.*, 2007], all the models in Figure 8a simulate a stronger warming associated with the mean temperature in the mid and late twenty-first century than in the late twentieth century, in accord with the results in Figure 5a. For the standard deviation instead of the mean, the scattered values in most of the models are concentrated around the one-to-one reference line, which implies that the difference in standard deviation between the present and future climate runs is small (Figure 8b). As a result, though the magnitudes vary among the models, the temperature variability in the twenty-first century is almost the same as that in the twentieth century, inducing frequent cold surge occurrences in the future warm climate, comparable to the present relatively colder climate.

#### 4. Summary and Discussion

[29] In this study, the behaviors of cold day and cold surge occurrences simulated by 13 CGCMs participating in the



**Figure 8.** Scatterplots of (a) winter mean temperature and (b) standard deviation of temperature for the late twentieth century versus the mid twenty-first century (solid symbols) and the late twenty-first century (open symbols) in the 13 models and their ensemble mean.

**Table 3.** The Number of Strong Siberian High Days, the Magnitude of Centers of Siberian High, and the Values of Domain Mean Siberian High Averaged for 20 Years in the Late Twentieth Century, the Mid Twenty-First Century, and the Late Twenty-First Century in the Ensemble Mean

	20C3M (1980–1999)	A1B (2046–2065)	A1B (2081–2100)
Strong Siberian High days <sup>a</sup> (days)	79.28	79.57	78.52
Centers of Siberian High <sup>b</sup> (hPa)	1034.36	1034.42	1034.31
Domain mean Siberian High <sup>c</sup> (hPa)	1027.68	1027.65	1027.72

<sup>a</sup>The days when the magnitude of SLP in the center of the surface anticyclone over southern Siberia (90°E–130°E, 20°N–50°N) exceeds 1035 hPa.

<sup>b</sup>The magnitude of SLP in the center of the surface anticyclone over southern Siberia.

<sup>c</sup>The values of SLP averaged over southern Siberia.

IPCC AR4 are mainly examined in terms of climate change projections. In the present climate, both observations and the CGCMs show the dipole pattern of cold days and the wave train pattern of cold surges in which SLP and SAT are out of phase with each other. In addition, the changes in cold day and cold surge occurrences under the recent warming found in the observations are well simulated in 20C3M by the CGCMs. This raises our confidence in the projection of the future climate. In agreement with the observation results over the period of 1980–2006, the ensemble mean of simulations for the late twentieth century and mid and late twenty-first century represent a considerable reduction of cold days and a slight increase in cold surges under a strong warming trend. The projected changes in the future climate averaged for years 2046–2065 and 2081–2100 relative to the present climate for years 1980–1999 show a significant decrease in cold days under an increasing mean temperature, which is consistent with the general scientific consensus given in many previous studies. However, no significant change in the number of cold surge occurrences in the mid and late twenty-first century simulations is found, compared to the late twentieth century simulation. Thus, the cold surge occurrences still remain frequent in the future warm climate; that is, they are not correlated with the winter mean temperature. The values of temperature variability in the future warm climate are similar to those in the present colder climate, leading to the frequent cold surge occurrences.

[30] Cold surge events are strongly related to the activity of the Siberian High [Takaya and Nakamura, 2005], so the intensity of the Siberian High is used as one of the main factors in the cold surge definition [Jeong and Ho, 2005; Park et al., 2011]. Thus, it is expected that a recent long-term change in the intensity of the Siberian High is also insignificant, similar to that in cold surge frequency. To examine the change in the Siberian High strength under global warming, we calculate some indices which reveal the strength and then summarize the ensemble mean values averaged for the three time periods in Table 3. The change in the number of strong Siberian High days is about 0.4 at the most. Moreover, the intensities of center and domain mean of Siberian High in the late twentieth century are much the same as those in the twenty-first century. Thus, it indicates that the insignificant change of cold surge frequency can be caused by the lack of changes in a magnitude of the Siberian High. However, there are many controversies concerning the changes in a magnitude of the Siberian High under global warming. Panagiotopoulos et al. [2005] ascertained that a dramatic decreasing trend has been found in the intensity of the Siberian High between 1978 and 2001. In addition, Kim et al. [2005] and Hong et al. [2008] have found that the Siberian

High has grown weak since the 1950s. On the other hand, interestingly, in their studies there is no long-term weakening trend in intensity of the Siberian High after the 1980s under strong global warming, which can support the results of the present study. Thus, the issue of the recent trend of the Siberian High under global warming and its relation to the changes in cold surge occurrences seems to still be under contention. To lead to a general consensus on the matter, more in-depth research based on various observations (e.g., surface stations) or reanalysis data sets (e.g., NCEP/NCAR Reanalysis 1 and 2, European Centre for Medium-Range Weather Forecasts Reanalysis, Japanese 25-year Reanalysis Project, and so on) and model simulations should be conducted.

[31] Several cautionary notes should be mentioned regarding the present study. First, only one ensemble member for each CGCMs is analyzed, which might lead to a reduction in the confidence of the present results because of a chaotic bias by the model-generated atmospheric internal variability. We believe that our findings are not controlled by atmospheric internal variability, but this should be checked in more ensemble members in future studies. Second, we focus only on the changes in occurrence of cold days and cold surges without considering their characteristics. However, global warming seems to induce changes of various properties such as duration and intensity as well as the occurrence numbers reported in this study. The duration and intensity changes of cold days and cold surges are a very important topic in climate change research because of their direct relations to human activities. Finally, cold days and cold surges are strongly linked to external forcing like the Arctic Oscillation (AO) [Jeong and Ho, 2005; Park et al., 2011] and the El Niño–Southern Oscillation (ENSO) [Zhang et al., 1997a; Chen et al., 2004]; however, such changes under global warming have not been discussed in this study. In several studies, changes of the AO [Gillett et al., 2002] and the ENSO [Kug et al., 2010] in response to forced greenhouse gas concentration have been reported. These external forces are responsible for changes in cold days and cold surges under global warming, and the relationship between them and the two extreme cold events will be considered in a future in-depth study.

[32] In spite of the abovementioned limitations, we would like to emphasize the probable frequent occurrences of cold surges, which can be important in the relative concept of the cold extreme events, as being distinct from cold days reported in many previous studies under global warming. For example, there is no doubt that temperature in the climate of the 2000s is higher than that in the climate of the 1950s; however, in spite of similar temperature drops in both decades, humans,

animals and plants in the climate of the 2000s seem to be more aware of the cold surges than in the climate of the 1950s because of being acclimatized to the warmer climate of the 2000s. Thus, the influences of the cold surges on human activities and the surrounding environment, adapted to the future warm climate, might be more severe; therefore, the population's vulnerability associated with cold surges should not be lightly treated regardless of the increasing mean temperature under global warming.

[33] In this study, the projected future cold surges are based on the A1B scenarios in the IPCC AR4 [Meehl et al., 2007]. To mitigate and adapt to future climate changes, most countries in East Asia (China, Japan, and Korea) have adopted their mitigation targets as 2°C global warming above the pre-industrial conditions (i.e., A1B). However, the present study suggests that governments may consider changing their mitigation target policies based on A1B. Our results suggest that the policies that limit greenhouse gases based on A1B cannot prevent the impact of future cold surges over East Asia.

[34] **Acknowledgments.** This research was funded by the Korea Meteorological Administration Research and Development Program under grant CATER 2006-4204 and National Research Foundation of Korea grant 2011-0001281.

## References

- Alexander, L. V., et al. (2006), Global observed changes in daily climate extremes of temperature and precipitation, *J. Geophys. Res.*, *111*, D05109, doi:10.1029/2005JD006290
- Boo, K.-O., W.-T. Kwon, and H.-J. Baek (2006), Change of extreme events of temperature and precipitation over Korea using regional projection of future climate change, *Geophys. Res. Lett.*, *33*, L01701, doi:10.1029/2005GL023378.
- Boyle, J. S., and T.-J. Chen (1987), Synoptic aspects of the wintertime East Asian monsoon, in *Monsoon Meteorology*, edited by C.-P. Chang and T. N. Krishnamurti, pp. 125–160, Oxford Univ. Press, Oxford, U. K.
- Cannell, M. G. R., and R. I. Smith (1986), Climatic warming, spring budburst and frost damage on trees, *J. Appl. Ecol.*, *23*, 177–191, doi:10.2307/2403090.
- Chen, T.-C., W.-R. Huang, and J.-H. Yoon (2004), Interannual variation of the East Asian cold surge activity, *J. Clim.*, *34*, 293–305.
- Choi, Y.-S., C.-H. Ho, D.-Y. Gong, J.-H. Jeong, and T.-W. Park (2009), Adaptive change in intra-winter distribution of relatively cold events to East Asian warming, *Terr. Atmos. Oceanic Sci.*, *20*, 807–816, doi:10.3319/TAO.2008.11.20.01(A).
- Compo, G. P., G. N. Kiladis, and P. J. Webster (1999), The horizontal and vertical structure of east Asian winter monsoon pressure surges, *Q. J. R. Meteorol. Soc.*, *125*, 29–54, doi:10.1002/qj.49712555304.
- Gao, X. J., C. Z. Zhao, and F. Giorgi (2002), Changes of extreme events in regional climate simulations over East Asia, *Adv. Atmos. Sci.*, *19*, 927–942, doi:10.1007/s00376-002-0056-2.
- Gillett, N. P., M. R. Allen, R. E. McDonald, C. A. Senior, D. T. Shindell, and G. A. Schmidt (2002), How linear is the Arctic Oscillation response to greenhouse gases?, *J. Geophys. Res.*, *107*(D3), 4022, doi:10.1029/2001JD000589.
- Gong, D.-Y., and C.-H. Ho (2004), Intra-seasonal variability of wintertime temperature over East Asia, *Theor. Appl. Climatol.*, *24*, 131–144.
- Gu, L., P. J. Hanson, W. M. Post, D. P. Kaiser, B. Yang, R. Nemani, S. G. Pallardy, and T. Meyers (2008), The 2007 eastern U.S. spring freezes: Increased cold damage in a warming world?, *BioScience*, *58*, 253–262, doi:10.1641/B580311.
- Hong, C.-C., H.-H. Hsu, H.-H. Chia, and C.-Y. Wu (2008), Decadal relationship between the North Atlantic Oscillation and cold surge frequency in Taiwan, *Geophys. Res. Lett.*, *35*, L24707, doi:10.1029/2008GL034766.
- Inouye, D. W. (2000), The ecological and evolutionary significance of frost in the context of climate change, *Ecol. Lett.*, *3*, 457–463, doi:10.1046/j.1461-0248.2000.00165.x.
- Jeong, J.-H., and C.-H. Ho (2005), Changes in occurrence of cold surges over East Asia in associated with Arctic Oscillation, *Geophys. Res. Lett.*, *32*, L14704, doi:10.1029/2005GL023024.
- Jeong, J.-H., B.-M. Kim, C.-H. Ho, D. Chen, and G.-H. Lim (2006), Stratospheric origin of cold surge occurrence in East Asia, *Geophys. Res. Lett.*, *33*, L14710, doi:10.1029/2006GL026607.
- Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2
- Kim, D.-W., H.-R. Byun, and Y.-I. Lee (2005), The long-term changes of Siberian High and winter climate over the Northern Hemisphere, *J. Korean Meteorol. Soc.*, *41*, 275–283.
- Kug, J.-S., S.-I. An, Y.-G. Ham, and I.-S. Kang (2010), Changes in El Niño and La Niña teleconnections over North Pacific–America in the global warming simulations, *Theor. Appl. Climatol.*, *100*, 275–282, doi:10.1007/s00704-009-0183-0.
- Kunkel, K. E., R. A. Pielke, and S. A. Changnon (1999), Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review, *Bull. Am. Meteorol. Soc.*, *80*, 1077–1098, doi:10.1175/1520-0477(1999)080<1077:TFIWAC>2.0.CO;2.
- Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon et al., pp. 749–844, Cambridge Univ. Press, Cambridge, U. K.
- Mizuta, R., et al. (2005), Changes in extremes indices over Japan due to global warming projected by a global 20-km-mesh atmospheric model, *SOLA*, *1*, 153–156, doi:10.2151/sola.2005-040.
- Panagiotopoulos, F., M. Shahgedanova, A. Hannachi, and D. B. Stephenson (2005), Observed trends and teleconnections of the Siberian High: A recently declining center of action, *J. Clim.*, *18*, 1411–1422, doi:10.1175/JCLI3352.1.
- Park, T.-W., J.-H. Jeong, C.-H. Ho, and S.-J. Kim (2008), Characteristics of atmospheric circulation associated with cold surge occurrences in East Asia: A case study during 2005/06 winter, *Adv. Atmos. Sci.*, *25*, 791–804, doi:10.1007/s00376-008-0791-0.
- Park, T.-W., C.-H. Ho, S. Yang, and J.-H. Jeong (2010), Influences of Arctic Oscillation and Madden-Julian Oscillation on cold surges and heavy snowfalls over Korea: A case study for the winter of 2009–2010, *J. Geophys. Res.*, *115*, D23122, doi:10.1029/2010JD014794.
- Park, T.-W., C.-H. Ho, and S. Yang (2011), The relationship between Arctic Oscillation and cold surges over East Asia, *J. Clim.*, *24*, 68–83, doi:10.1175/2010JCLI3529.1.
- Takaya, K., and H. Nakamura (2005), Mechanisms of intraseasonal amplification of the cold Siberian high, *J. Atmos. Sci.*, *62*, 4423–4440, doi:10.1175/JAS3629.1.
- Trenberth, K. E., et al. (2007), Observations: Surface and atmospheric climate change, in *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon et al., pp. 235–336, Cambridge Univ. Press, Cambridge, U. K.
- Vavrus, S., J. E. Walsh, W. L. Chapman, and D. Portis (2006), The behavior of extreme cold air outbreaks under greenhouse warming, *Int. J. Climatol.*, *26*, 1133–1147, doi:10.1002/joc.1301.
- Walsh, J. E., A. S. Phillips, D. H. Portis, and W. L. Chapman (2001), Extreme cold outbreaks in the United States and Europe, 1948–99, *J. Clim.*, *14*, 2642–2658, doi:10.1175/1520-0442(2001)014<2642:ECOITU>2.0.CO;2.
- Zhai, P., and X. Pan (2003), Trends in temperature extremes during 1951–1999 in China, *Geophys. Res. Lett.*, *30*(17), 1913, doi:10.1029/2003GL018004.
- Zhang, Y., and W.-C. Wang (1997), Model-simulated northern winter cyclone and anticyclone activity under a greenhouse warming scenario, *J. Clim.*, *10*, 1616–1634, doi:10.1175/1520-0442(1997)010<1616:MSNWCA>2.0.CO;2.
- Zhang, Y., K. R. Sperber, and J. S. Boyle (1997a), Climatology and inter-annual variation of East Asian winter monsoon: Result from the 1979–95 NCEP/NCAR reanalysis, *Mon. Weather Rev.*, *125*, 2605–2619, doi:10.1175/1520-0493(1997)125<2605:CAIVOT>2.0.CO;2.
- Zhang, Y., et al. (1997b), East Asian winter monsoon: Results from eight AMIP models, *Clim. Dyn.*, *13*, 797–820, doi:10.1007/s003820050198.

Y.-S. Choi and S. K. Park, Environmental Science and Engineering, Ewha Womans University, Seoul 120-750, South Korea.

C. H. Ho, Climate Physics Laboratory, School of Earth and Environmental Sciences, Seoul National University, Seoul 151-747, South Korea. (hoch@cpl.snu.ac.kr)

S.-J. Jeong, Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ 08544, USA.

T.-W. Park, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332, USA.

C.-K. Song, Climate Research Division, National Institute of Environmental Research, Incheon 404-708, South Korea.