Changes in Temperature-based Extremes Indices Due to Global Warming Projected by a Global 20-km-mesh Atmospheric Model

Takao Uchiyama¹, Ryo Mizuta², Kenji Kamiguchi¹, Akio Kitoh¹ and Akira Noda¹
¹Meteorological Research Institute, Tsukuba, Japan
²Advanced Earth Science and Technology Organization, MRI, Tsukuba, Japan

Abstract

Changes in temperature-based extremes over land due to global warming estimated by a global 20-km-mesh atmospheric model are analyzed using Frich's five extremes indices. At the end of the 21st Century, under the Intergovernmental Panel on Climate Change (IPCC) SRES A1B scenario, the model projects that the total number of frost days (Fd) decreases by more than 20 days per year and the length of the growing season (GSL) increases by about 14-15 days in northern mid- and high latitudes. The heat wave duration index (HWDI) and the percentage of heat wave days (HWD) increase by more than 3 days and 0.1%, respectively. The intra-annual extreme temperature range (ETR) decreases in northern high latitudes, east Asia, and eastern North America by 1.3-1.9°C, but it increases by 1.0°C in the Amazon. The high-resolution simulation reveals that changes in these indices are influenced by regional properties, such as the altitude and distance from the coast.

1. Introduction

Global warming is an important issue, with a variety of influences on water, the economy, health, and agriculture. It is now recognized that changes in climate variability and extreme events affect society more than changes in the mean climate (IPCC 2001). Various extremes indices have been proposed, but ten indices (five temperature-based and five precipitation-based indices) proposed by Frich et al. (2002) have been selected by the JSC/CLIVAR Working Group on Coupled Modeling (WGCM) to monitor and reproduce past climate changes and to assess future projections. Some results are emerging from such multi-model analyses, but the horizontal resolution of those models is still limited (at most 100 km) and is not enough to investigate the increasing risk of intense events. Having conducted a global warming time-slice experiment with a very high-resolution atmospheric model (20-km-mesh), which is considerably finer than any other global-scale models for studies of extremes, we show the extremes indices with this model because some of indices are better simulated with the high-resolution model. For example, Hosaka et al. (2005) shows that both snow coverage and snow water equivalent generally decrease in the Northern Hemisphere in the model, but, in some of the coldest and highest-elevations, the snow water equivalent actually increases because of the increase in the amount of precipitation in a warmer climate. In this paper, we first evaluate temperature-based extremes indices in the present climate simulated by the model against observations, and then describe changes of these indices at the end of the 21st Century. A companion paper, Kamiguchi et al. (2006), discusses precipitation-based extremes indices while Mizuta et al. (2005) shows changes in extremes indices over Japan both for temperature and precipitation.

2. Model and extremes indices

The model used is an atmospheric general circulation model (AGCM) with a horizontal resolution of about 20 km (TL959 linear Gaussian grid). The model has 60 vertical levels with the top at 0.1 hPa. Details of the model are given in Mizuta et al. (2006).

We have conducted two “time-slice” 10-year simulations. One is a present-day simulation that uses the observed seasonally varying climatological sea surface temperature (SST) averaged from November 1981 to December 1993 (Reynolds and Smith 1994). The other is a global warming simulation in which the SST anomalies from the present (the last 20-year mean from the 20th Century climate simulation) to the future (20-year mean at the end of the 21st Century) obtained from the MRI-CGCM2.3 (Yukimoto et al. 2006) were added to the observed SSTs for the present-day simulation. The AGCM experiment also uses the same concentration of greenhouse gases and aerosols based on the IPCC SRES A1B scenario used in the MRI-CGCM experiment.

We use five temperature-based extremes indices proposed by Frich et al. (2002). All these indices are derived from the daily maximum, minimum, and mean temperatures. The definition of these indices is shown in Table 1. The annual mean surface air temperature (Tav) is not an extremes index, but it is used for analysis because it is a basic variable to diagnose climate change. All the indices are calculated over land for each year, and the average over the whole period is used. For the evaluation of the model present-day climatology, we use data for the period 1961-1990 from the Global Daily Climate Network V 1.0 (GDCN) produced by the National Climatic Data Center (NCDC).

3. Results

The geographical distribution of six indices defined in Table 1 over land is shown in Fig. 1. The area averages for 23 regions are shown in Table 2, following the classification of Giorgi and Francisco (2000). The statistical signifi-

Table 1. Extremes indices and a basic index on temperature.

<table>
<thead>
<tr>
<th>Index</th>
<th>Unit</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tav</td>
<td>°C</td>
<td>Annual mean surface air temperature (This is not an extremes index)</td>
</tr>
<tr>
<td>Fd</td>
<td>days</td>
<td>Total number of frost days (days with a minimum temperature &lt; 0.0°C)</td>
</tr>
<tr>
<td>ETR</td>
<td>°C</td>
<td>Intra-annual extreme temperature range: Difference between the highest temperature of any given calendar year (Tmax) and the lowest temperature of the same calendar year (Tmin)</td>
</tr>
<tr>
<td>GSL</td>
<td>days</td>
<td>Growing season length: Period between times with a daily mean temperature (Tmean) &gt; 5.0°C for &gt; 5 days and Tmin &lt; 5.0°C for &gt; 5 days</td>
</tr>
<tr>
<td>HWDI</td>
<td>days</td>
<td>Heat wave duration index: Maximum period &gt; 5 consecutive days with a daily maximum temperature (Tmax) &gt; 5.0°C above the long-term daily Tmax normal</td>
</tr>
<tr>
<td>Tn90</td>
<td>%</td>
<td>Percent of time with a daily minimum temperature (Tmin) &gt; the long-term 90th percentile of daily Tmin</td>
</tr>
</tbody>
</table>

corresponding author: Takao Uchiyama. Meteorological Research Institute, 1-1 Nagamine, Tsukuba 305-0052, Japan. E-mail: tuchiyam@mrj-mia.go.jp. ©2006, the Meteorological Society of Japan.
cance of change is calculated using the t-test. Table 2 indicates that most indices change significantly due to global warming, but changes in ETR are significant only in the high latitudes, the east coast of continents in the mid-latitudes (east Asia and eastern North America), and the Amazon.

3.1 Mean temperature

The annual mean temperature (Tav) in the present-day simulation (Fig. 1–1b) is, for example, about 30°C in the subtropical arid region and about 0°C in the Arctic region. Compared with GDCN (Fig. 1–1a), the model simulates both the magnitude and distribution very well. Tav increases worldwide due to global warming (Fig. 1–1c). A great increase is seen in the Arctic region, arid regions (except for western China), and mountainous regions. Greater warming (>4°C) is noted over the western Tibetan Plateau. A relatively smaller (but statistically significant) increase is seen in Patagonia, western Europe, western China, and eastern Siberia.

3.2 Frost days

The annual number of frost days (Fd) in the present-day simulation (Fig. 1–2b) is comparable to GDCN (Fig. 1–2a).
Fd is large in the high latitudes and the high mountain regions. It exceeds over 300 days per year in both polar regions.

Fd decreases worldwide due to global warming (Fig. 1c). Larger decreases by more than 30 days are seen in central and northern USA, southern Canada, the Andes, northern and eastern Europe, Tibet, eastern China, Korea, and Japan. It is noteworthy that the decrease in Fd is smaller in the high latitudes, such as Siberia, Alaska, and Canada, because of low temperature even in a warming world. Changes in Fd in the low latitudes are naturally small where present-day Fd is already small.

### 3.3 Intra-annual extreme temperature range

The intra-annual extreme temperature range (ETR) in the present-day simulation (Fig. 1–3b), which compared well with GDCN (Fig. 1–3a), is large in the inlands in high latitudes, where there is a clear and large seasonal cycle. It exceeds 80°C in those regions. ETR is not very large in Europe when compared with that of other regions in the same latitude. Antarctica and Greenland do not have a particularly large ETR either. ETR is generally small in the tropics.

ETR generally decreases in the high latitudes and increases in the low-latitude arid regions as a result of global warming (Fig. 1–3c). A significant decrease is seen in northern Europe, north Asia, and eastern North America, with an area mean decrease by more than 2.5°C. East Asia also exhibits a significant decrease by 1.3°C. On the other hand, a significant increase by 1.0°C is seen in the Amazon. These different responses can be interpreted from different changes in warming between the warm and cold seasons. Figure 2 compares the changes in the annual maximum temperature and the annual minimum temperature. Those regions with decreased ETR are high-latitude cold areas where changes in the annual minimum temperature are larger than those in the annual maximum temperature. On the other hand, the Amazon is a region with a relatively large increase in the annual maximum temperature. Kamiguchi et al. (2006) show that the annual maximum number of consecutive dry days significantly increases due to a severer dry season in the Amazon. A heat budget analysis (not shown) indicates that the latent heat flux decreases in dry season, while the sensible heat flux and net upward longwave flux increase, which causes more increase in annual maximum temperature than in annual minimum temperature.

### 3.4 Growing season length

The length of the thermal growing season (GSL) in the present-day simulation (Fig. 1–4b), which compared very well with GDCN (Fig. 1–4a), can be defined only in the mid-latitudes to high latitudes except for over ice sheets (Antarctica and Greenland) and is generally small in the high latitudes and the high-mountain areas. GSL generally increases worldwide due to global warming (Fig. 1–4c). A large increase is seen in northern Europe and eastern North America, where a lengthening by more than 30 days is projected.

### 3.5 Heat wave duration index

The heat wave duration index (HWDI), which indicates maximum consecutive days with a daily maximum temperature (Tmax) over 5.0°C higher than the present-day long-term Tmax normal, in the present-day simulation (Fig. 1–5b) is generally large in the high latitudes, the arid regions, and the high mountains. Compared with GDCN (Fig. 1–5a), but the normal is for the 1961–1990 base period of the GDCN, the model yields a very good simulation, except for an overestimation in Tibet and Australia and an underestimation in the eastern half of China and southeast USA.

HWDI increases due to global warming (Fig. 1–5c), and regionally averaged changes are statistically significant everywhere. A great increase is seen in the high latitudes, the arid regions, and the high mountains, as in the mean temperature changes (Fig. 1–1c). These regions agree well with the regions that originally have a large HWDI in the present climate.

### 3.6 Percent of time Tmin > 90th percentile

The percentage of time with a daily minimum temperature (Tmin) above the present-day long-term 90th percentile of Tmin (Tn90) has a constant value of 10% in the present-day climate by definition; therefore, only the changes due to global warming are shown. Tn90 increases worldwide due to global temperature increases (Fig. 1–6c). It increases more in the low latitudes and less in the high latitudes and high mountains.

---

**Table 2. Extremes indices and a basic index in the present (upper) climate and changes due to global warming (lower) in each area.**

<table>
<thead>
<tr>
<th>Index</th>
<th>NAS</th>
<th>ALA</th>
<th>GRL</th>
<th>NEU</th>
<th>MED</th>
<th>CAS</th>
<th>TIB</th>
<th>EAS</th>
<th>WNA</th>
<th>CNA</th>
<th>ENA</th>
<th>SAH</th>
<th>WAF</th>
<th>EAF</th>
<th>SAF</th>
<th>SAS</th>
<th>SEA</th>
<th>SEA</th>
<th>NAU</th>
<th>SAU</th>
<th>CAM</th>
<th>AMZ</th>
<th>SSA</th>
<th>ANT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tav</td>
<td>-4.5</td>
<td>-8.1</td>
<td>-11.4</td>
<td>4.7</td>
<td>13.9</td>
<td>11.9</td>
<td>0.2</td>
<td>8.5</td>
<td>5.6</td>
<td>11.2</td>
<td>7.8</td>
<td>25.4</td>
<td>25.1</td>
<td>23.3</td>
<td>21.1</td>
<td>21.3</td>
<td>23.3</td>
<td>23.8</td>
<td>16.7</td>
<td>16.0</td>
<td>22.6</td>
<td>15.5</td>
<td>-30.4</td>
<td></td>
</tr>
<tr>
<td>Fd</td>
<td>239</td>
<td>260</td>
<td>291</td>
<td>155</td>
<td>83</td>
<td>107</td>
<td>129</td>
<td>228</td>
<td>124</td>
<td>150</td>
<td>102</td>
<td>135</td>
<td>2.0</td>
<td>0.0</td>
<td>2.0</td>
<td>2.4</td>
<td>0.0</td>
<td>2.2</td>
<td>0.7</td>
<td>3.0</td>
<td>3.4</td>
<td>365</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETR</td>
<td>67.1</td>
<td>67.5</td>
<td>57.9</td>
<td>49.8</td>
<td>45.1</td>
<td>55.7</td>
<td>53.8</td>
<td>53.1</td>
<td>58.9</td>
<td>54.9</td>
<td>56.9</td>
<td>41.7</td>
<td>28.4</td>
<td>25.8</td>
<td>33.9</td>
<td>36.1</td>
<td>17.1</td>
<td>37.8</td>
<td>40.0</td>
<td>31.7</td>
<td>20.7</td>
<td>35.0</td>
<td>39.7</td>
<td></td>
</tr>
<tr>
<td>GSL</td>
<td>125</td>
<td>105</td>
<td>-164</td>
<td>-164</td>
<td>-208</td>
<td>181</td>
<td>191</td>
<td>176</td>
<td>-186</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>HWDI</td>
<td>27</td>
<td>20</td>
<td>21</td>
<td>18</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>7</td>
<td>4</td>
<td>14</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>6</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Present</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWDI</td>
<td>+7</td>
</tr>
<tr>
<td>Tav</td>
<td>-3.1</td>
</tr>
<tr>
<td>Fd</td>
<td>-21</td>
</tr>
<tr>
<td>ETR</td>
<td>-2.6</td>
</tr>
<tr>
<td>GSL</td>
<td>+16</td>
</tr>
<tr>
<td>HWDI</td>
<td>+57</td>
</tr>
</tbody>
</table>

NAS=North America; ALA=Alaska; GRL=Greenland; NEU=Northern Europe; MED=Mediterranean; CAS=Central Asia; TIB=Tibet; EAS=East Asia; WNA-Western North America; CNA-Central North America; ENA-Eastern North America; SAH=Sahara; WAF-Western Africa; EAF=Eastern Africa; SAF-Southern Africa; SAS-South Asia; SEA=South East Asia; NAU=Northern Australia; SAU=Southern Australia; CAM=Central America; AMZ=Amazon; SSA=Southern South America; ANT=Antarctica.
4. Discussion and conclusions

We have analyzed temperature-based extremes indices over land at the present time and at the end of the 21st Century by time-slice experiments with a global 20-km-mesh atmospheric model that has a horizontal resolution considerably finer than that of any other global models applied to studies of extremes. It is reasonable to say that results with such a fine resolution are comparable with those of in situ observations. We have shown here that the global and regional features of all indices for the present time simulation agree well with indices calculated with observational data from GDCN based on in situ observations. This result provides the basis for further studies that discuss extreme events and their future changes focused on specific regions (e.g., Mizuta et al. 2005).

In the global warming simulation, temperature-based extremes indices exhibit changes toward decreases in Fd and increases in GSL, HWDI, and Tn90 because of a global temperature increase. On the other hand, ETR shows both increases and decreases influenced by regional properties. The range of changes in Tav, Fd, and GSL is generally controlled by regional properties, such as latitude, altitude, and distance from the ocean. The change in ETR is associated with the relative warming in the warm season to that in the cold season. The changes in HDWI and Tn90 are related to latitudinal differences in temperature variability. The probability distribution functions of Tav, Fd, and GSL at each grid point for both the present and global warming simulations (illustrative examples at two typical grid points are shown in Supplement 2) suggest that the daily and year-to-year variability is generally large in the high latitudes and small in the low latitudes. By definition, HDWI becomes larger as the number of days in which T<sub>av</sub> is higher than a threshold (5°C above the average of T<sub>av</sub>) increases, so that HDWI has larger values in the high latitudes than in the low latitudes (Frich et al. 2002). The change in the variability of T<sub>av</sub> is not as large as the change in the average of T<sub>av</sub> that is, the probability distribution function of T<sub>av</sub> simply shifts to higher values as a first order approximation. In addition, the positive change in average of T<sub>av</sub> in the high latitudes is almost the same or somewhat larger compared with that in the low latitudes. Consequently, in accordance with the larger frequency above the threshold value in the high latitudes, the change in the frequency is also larger in the high latitudes. The increase in HDWI is therefore larger in the high latitudes than in the high latitudes because of the following reason. Since the variability of T<sub>av</sub> is smaller in the low latitudes than in the high latitudes, the value of the 90th percentile is much closer to the average in the low latitudes. Therefore, even though the change in average of T<sub>av</sub> is smaller in the low latitudes, the increase in frequency above the present-day 90th percentile can be larger in the low latitudes.

We adopted five temperature-based extremes indices widely used in model intercomparison. However, there may be many definitions that can be used. For example, Meehl and Tebaldi (2004) showed changes in the heat waves for North America and Europe using different definitions of heat waves. They found that many of the areas that are most susceptible to heat waves in the present climate experience the greatest increase in heat-wave severity in the future. A similar tendency is found in Figs. 1b and 1c, which shows that the areas with large HDWI in the present climate have large increases in HDWI.

As this global 20-km-mesh AGCM has a horizontal resolution that is considerably finer than that of any other global models applied to studies of extremes, several distinct results in view of the impact of global warming have been obtained. An example can be seen for mountainous regions, such as the Alps, the Rockies, the Tibetan Plateau, and the Andes, where enhanced warming and related changes in extremes are more visible than in the surrounding regions. Since changes in snow cover and snow mass are affected by the elevations of mountains, the high-resolution model resolves cold water resources assessment and tourism. Continuing efforts with a longer integration of this model forced with inter-annually varying SST would provide useful information for climate impact studies.

Acknowledgments

This study was based on the results of time-slice experiments performed on the Earth Simulator by the global modeling group under the framework of the “Kyosei Project 4: Development of Super High Resolution Global and Regional Climate Models” which is a project of the Research Revolution 2002 (RR2002) funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. The figures were drawn by GrADS. We are grateful to Prof. H. Kanzawa. Dr. S. Emori, and an anonymous reviewer for helpful comments.

Supplements

1. A map of 23 regions used for the Table 2 is presented in Supplement 1.
2. Probability distribution functions for daily maximum temperature and daily minimum temperature at selected points are presented in Supplement 2.

References


Hosaka, M., D. Nohara and A. Kitoh, 2005: Changes in snow cover and snow water equivalent due to global warming simulated by a 20km-mesh global atmospheric model. SOLA, 1, 93–96.


Manuscript received 26 September 2005, accepted 9 April 2006

SOLA: http://www.jstage.jst.go.jp/browse/sola/