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

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Abstract

Future changes in extremes indices on precipitation were projected with a 20-km horizontal grid atmospheric general circulation model. At the end of the 21st Century, heavy precipitation was shown to increase enormously in South Asia, the Amazon, and West Africa, while a dry spell was shown to increase in South Africa, south Australia, and the Amazon, suggesting that the risk of water-related disasters will be higher in these regions. In the Asian monsoon region, heavy precipitation increases notably in Bangladesh and in the Yangtze River basin due to the intensified convergence of water vapor flux in summer. In the Amazon, a dry spell greatly increases due to a reduction in the Walker circulation caused by an El Niño-like change in SST prescribed as boundary condition.

1. Introduction

It is feared that the frequency and intensity of extreme precipitation events, such as heavy rain or severe drought, will increase in certain areas in the near future due to changes in the strength or patterns of hydrological cycles as global warming progresses. These extreme events may threaten human life and economic growth. Changes in the frequency and intensity of extreme events are more likely to affect society than changes in the mean climate (e.g., Katz and Brown 1992). Therefore, reliable future projections using climate models are in high demand. However, extreme events are difficult to express with low-resolution models because phenomena such as those for heavy precipitation are local and their values are smoothed in a coarse grid.

We conducted a global warming experiment using a 20-km-mesh atmospheric general circulation model (AGCM) and analyzed future changes in precipitation-based “extremes indices” proposed by Frich et al. (2002). This very high-resolution model is expected to be superior to low-resolution models because the topography is more realistic, so that topographically constrained precipitation can be well resolved.

2. Model and extremes indices

2.1 Model and experiment

The model used in this study is an MRI-JMA (Meteorological Research Institute and Japan Meteorological Agency) AGCM. The triangular truncation wave number is 959, with a linear Gaussian grid (TL959) which corresponds to a horizontal 20-km grid resolution. This is currently the highest resolution of AGCM used in global warming experiments. The number of vertical levels is 60, with a model top at 0.1 hPa. Further details of the model are described in Mizuta et al. (2006).

Two 10-year runs, referred to as AJ and AK, were conducted by the “time-slice” method. AJ is a present climate simulation using the observed climatological sea surface temperature (SST) as the boundary conditions. The monthly mean climatological SST and sea ice concentration are those obtained by Reynolds and Smith (1994), averaged from November 1981 to December 1993. AK is a global warming simulation forced by the climatological SST plus anomalies. The SST anomalies are the difference between the average from 1979 to 1998 in the 20th Century climate simulation and that from 2080 to 2099 in a scenario simulation using the MRI-CGCM2.3 (Yukimoto et al. 2006). The concentrations of greenhouse gases (CO2, CH4, N2O) and aerosols in the scenario simulation with MRI-CGCM2.3 and in the AJ-run are based on the IPCC Special Report on Emission Scenario (SRES) A1B, which assumes CO2 increases about twice in concentration between the periods. The atmospheric part of the CGCM has a horizontal spectral truncation of T42 corresponding to a horizontal grid spacing of about 270 km and has 30 vertical levels.

2.2 Extremes Indices

In the future projection of extreme events using a climate model, the intercomparison of different models is very important to estimate the uncertainty of the results on a common basis. Among several statistical methods to diagnose extreme events on precipitation, we focused on “extremes indices” proposed by Frich et al. (2002), as they are widely used in recent studies and adopted as IPCC standard output data for the upcoming AR4 (IPCC 4th Assessment Report). The name, definition, and unit of the indices are listed in Table 1, and more detailed information is found in the Stardex website (http://www.cru.uea.ac.uk/cru/projects/stardex/).

For all five extremes indices, higher values indicate more extreme events on precipitation. CDD means the length of dry spell, whereas R5d, R10, SDII, and R95T express the intensity of heavy precipitation. In Frich’s original definition, R95T uses the 95th percentile of daily precipitation among the wet days (≥ 1 mm/day) from 1961 to 1990. However, the 10-year data

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

<table>
<thead>
<tr>
<th>Index</th>
<th>Unit</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pav</td>
<td>mm/day</td>
<td>Annual mean of daily precipitation (this is not an extremes index)</td>
</tr>
<tr>
<td>CDD</td>
<td>days</td>
<td>Consecutive dry days: The annual maximum number of consecutive dry days with &lt; 1 mm/day</td>
</tr>
<tr>
<td>R5d</td>
<td>mm</td>
<td>Maximum 5-day precipitation total: The annual maximum consecutive 5-day precipitation total</td>
</tr>
<tr>
<td>R10</td>
<td>days</td>
<td>The number of days in a year with precipitation &gt; 10 mm/day</td>
</tr>
<tr>
<td>SDII</td>
<td>mm/day</td>
<td>Simple daily intensity index: Total annual precipitation divided by the number of days with ≥ 1 mm/day</td>
</tr>
<tr>
<td>R95T</td>
<td>%</td>
<td>Fraction of annual total precipitation due to extreme wet days exceeding the 95th percentile of the present-day simulation</td>
</tr>
</tbody>
</table>

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of AJ is used here as a base period representing the present climate. All indices are derived in each year, and the 10-year averages are compared between the present and future climate simulations. The results over the land grids are presented here.

3. Results

3.1 Model evaluation

The model performance on reproducing the present climate was evaluated by comparing the model (AJ; red lines) and the model (AF; blue lines). The solid lines and the dashed lines denote the tropical/subtropical (30°S–30°N) and the extratropics (40°S–70°S, 40°N–70°N), respectively.

Fig. 1. Probability distribution functions (PDFs) of daily precipitation computed from the observation (GPCP-1DD, blue lines) and the model (AJ; red lines). The solid lines and the dashed lines denote the tropical/subtropical (30°S–30°N) and the extratropics (40°S–70°S, 40°N–70°N), respectively.

The model precipitation data of AJ is used here as a base period representing the present climate. All indices are derived in each year, and the 10-year averages are compared between the present and future climate simulations. The results over the land grids are presented here.

3. Results

3.1 Model evaluation

The model performance on reproducing the present climate was evaluated by comparing the model (AJ) and the observed climatology based on GPCP-1DD (Huffman et al., 2001) for the 7-year data from 1997 to 2003. GPCP-1DD, which is a daily precipitation data with 1°×1° degree for horizontal resolution, is considered as the best data available to compare global daily precipitation at the present moment. However, the quality should be evaluated further because it is based mainly on satellite observations.

The probability distribution functions (PDFs) of daily precipitation both in the tropics/subtropics (30°S–30°N) and in the extratropics (40°S–70°S, 40°N–70°N) are shown in Fig. 1. The model precipitation data is regridded to the same grid as GPCP-1DD. The simulated PDF agrees well with the observation in the extratropics, though it somewhat overestimates the frequency of heavy rain larger than 20 mm/day. Meanwhile, in the tropics/subtropics, the PDF of the model overestimates the frequency of weak rain between 5 and 15 mm/day and underestimates the frequency of heavy rain larger than 15 mm/day.

The distribution maps of the six indices defined in Table 1 in the observation and AJ are shown in the left and middle panels of Fig. 2, respectively. All six indices simulated by the model are generally in good agreement with those from the observation. However, the simulated R5d, R10, and SDII are somewhat less than the observed ones in the tropics/subtropics, as reflected in the result of Fig. 1. CDD in the model is slightly larger in number than those from the observation in Antarctica, Brazilian plateau, and Mongolia. R95T is the least well simulated with respect to its spatial patterns among six indices; the model R95T is larger in eastern North America and smaller in the Indian Peninsula than the observed one.

3.2 Future changes

Figure 3 shows a future changes in R5d and in the water vapor flux at 925 hPa in the Amazon monsoon region in June-August (JJA). A large increase in R5d is found in Bangladesh and China's Yangtze River basin, where the convergence of the water vapor flux is intensified due to moisture build-up by global warming. The water vapor flux increases from the Bay of Bengal to the Bangladesh delta (Ashrit et al., 2005). Moreover, an intensified subtropical anticyclone in the western Pacific and an increased atmospheric moisture result in an enhanced water vapor flux which strengthens Meiyu/Baiu rainband from the Yangtze River basin toward Japan (Kitoh et al., 2005).

Among all the regions, the Amazon shows the most drastic changes. As shown in Fig. 4, CDD increases remarkably in the south of 5°S and R5d increases in the north of 5°S. The following two points can be considered as reasons for the increases in CDD. 1: The onset of the monsoon delays the pentad number of the timing of the monsoon onset shifts from 46.5 to 48.2 at 10°S, 63°W (cross mark in the left panel in Fig. 4); the monsoon onset is defined as the first pentad after pentad 44, in which rainfall is larger than 5 mm/pentad). 2: Even weak rainfall (smaller than 5 mm/pentad), which is sometimes observed in the dry season in the present, almost vanishes in the future. In the present simulation, in many cases when rain takes place in the dry season, equatorial easterly low-level wind from ITCZ hits the Andes and deviates to the south, bringing scattered clouds to the middle of the Amazon from ITCZ. In the future climate, the Walker circulation is weak in comparison with the El Niño-like SST change prescribed as boundary condition. Moreover, the anticyclone over the
southwest Atlantic is also weak. These two changes contribute to the weakening of the equatorial easterly wind and the suppression of rainfall in the middle of the Amazon. On the other hand, the primary reason for increase in $R_{5d}$ is not peculiar to this region. Each rainfall amount simply increases mainly due to an enhancement in water vapor content in the air.

4. Concluding remarks

Future changes in precipitation-based extremes indices were projected using a 20-km-mesh global model. $R_{5d}$, a heavy precipitation index, increases in almost all regions, especially in the area where the present value is large. CDD, a dry spell index, also generally increases in the area in which the present value is large. However, CDD decreases in areas with extremely small amount of annual precipitation, such as Antarctica, Sahara, and Tibet. These results imply that although there are some arid areas in which the length of the dry spell decreases, heavy precipitation and dryness generally become more severe in regions in which these phenomena are severe at present.
Table 2. Extremes indices and a basic index in the present (upper) and future changes (lower) in each region. The underlined value is not statistically significant at the 90% confidence level. The name and location of regions are shown in Supplement-1.

<table>
<thead>
<tr>
<th>Region</th>
<th>Index</th>
<th>Present (AI)</th>
<th>Change (AK-AJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pav</td>
<td>1.5</td>
<td>1.6</td>
<td>0.1</td>
</tr>
<tr>
<td>CDD</td>
<td>32.9</td>
<td>33.0</td>
<td>0.1</td>
</tr>
<tr>
<td>R5d</td>
<td>51.9</td>
<td>52.0</td>
<td>0.1</td>
</tr>
<tr>
<td>R10</td>
<td>10.9</td>
<td>11.0</td>
<td>0.1</td>
</tr>
<tr>
<td>SDII</td>
<td>4.6</td>
<td>4.7</td>
<td>0.1</td>
</tr>
<tr>
<td>R9ST</td>
<td>18.5</td>
<td>18.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Pav</td>
<td>0.2</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>CDD</td>
<td>-4.9</td>
<td>-4.8</td>
<td>0.1</td>
</tr>
<tr>
<td>R5d</td>
<td>6.6</td>
<td>6.7</td>
<td>0.1</td>
</tr>
<tr>
<td>R10</td>
<td>2.7</td>
<td>2.8</td>
<td>0.1</td>
</tr>
<tr>
<td>SDII</td>
<td>0.3</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>R9ST</td>
<td>3.5</td>
<td>3.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Fig. 3. Future change (AK-AJ) in R5d and in the water vapor flux (kg/m/sec) at 925 hPa in JJA around Asia. The areas showing a significant change in R5d at the 90% confidence level are colored.

Fig. 4. Future change (AK-AJ) in CDD and in R5d in Amazon. Areas showing significant changes at the 90% confidence level are colored. See the text about the cross mark.

In this study, annual extremes indices were calculated, and their 10-year averages were used for analysis. However, in order to consider the effect of extreme events on society, it is necessary to consider not only the mean change in extreme indices as discussed in this paper but also changes in their year-to-year variability. Such a topic will be discussed in a separate paper based on another set of the time-slice experiments performed on the Earth Simulator.

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Supplements

1. A map of 23 regions used for analysis is given in the page 1 of Supplement-1. Extremes indices and a basic index of the observation (GPCP-1DD) and the model (AI, AK) are given in the page 2 of Supplement-1.

References


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