Changes in the Characteristic Features of Disturbances Appearing in the Baiu Frontal Zone over Western Japan Due to Global Warming

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Abstract

Numerical experiments are performed using a non-hydrostatic regional climate model with a horizontal resolution of 5 km to study changes in the characteristic features of disturbances appearing over the Baiu frontal zones due to global warming. In this study, disturbances are defined as those with precipitation greater than 20 mm/6 hr within a radius of 100 km. An increase in the number of disturbances is found in the Baiu frontal zone over western Japan in the warming climate. The increase is caused by the lengthening of the Baiu duration. In addition, the disturbances are likely to be much more detected by the intensification of precipitation. Among such disturbances, those with intense precipitation and heavy rainfall events significantly increase over western Japan in the Baiu frontal zone in the warming climate. The present study is an extension of their work. It focuses on the occurrence and three-dimensional structures of the meso-α-scale disturbances and their changes in the warming climate.

1. Introduction

The climate changes due to global warming are receiving much attention from the viewpoints of economic activity and the global environment (IPCC 2001). Among them, the change in the frequency of heavy rainfall is an urgent and important problem. This problem had been investigated, primarily by using general circulation models (GCMs) or regional models with coarse resolutions. However, heavy rainfall events cannot be well simulated by such low-resolution models. Therefore, high-resolution models are required to forecast heavy rainfall events, although the calculation domain is restricted to small regions by the limitations of current technology and computers.

The Baiu is a rainy season in East Asia that is formed by the monsoon circulation in early summer. Heavy rainfall, which sometimes results in serious disasters, is accompanied by meso-α-scale disturbances over the Baiu frontal zone. Here, the meso-α-scale is a horizontal scale of 200–2000 km based on Orlanski (1975). The Baiu fronts have complicated multi-scale structures of disturbances (e.g., Ninomiya and Akiyama 1992). Among the disturbances, those of meso-α-scale play a key role in the heavy rainfall. These disturbances were studied mainly in the 1970s (e.g., Tokioka 1973; Yoshizumi 1977). From theoretical studies and observational analyses, some disturbances have eastward-tilting vertical structures for pressure and are considered to be baroclinic instability modified by diabatic heating due to precipitation. However, the formation and maintenance mechanisms of the disturbances over the Baiu frontal zone are not thoroughly understood. Moreover, the changes in the occurrence and structures of such disturbances in the global warming climate are unknown.

Yoshizaki et al. (2005) introduced the results of a non-hydrostatic regional climate model (NHM) with a horizontal resolution of 5 km and showed that the amount of precipitation and number of heavy rainfall events significantly increase over western Japan in the Baiu frontal zone in the warming climate. The present study is an extension of their work. It focuses on the occurrence and three-dimensional structures of the meso-α-scale disturbances and their changes in the warming climate.

2. Design of the experiment

To examine the climate changes due to global warming, two steps were considered. First, the experiments were performed with a time-slice method using an atmospheric GCM (AGCM) with a horizontal resolution of 20 km (Kusunoki et al. 2005). In the present climate experiment, the observed climatological sea surface temperature (SST) averaged from 1982 to 1993 was used as the bottom boundary of AGCM. In the warming climate (around 2080 (2099) experiment, on the other hand, the difference in the SST from the present climate, estimated by the prediction using a coupled atmosphere-ocean GCM (AOOGCM) under the A1B CO2 scenario (Yukimoto et al. 2005), was added to the climatological SST.

Second, regional climate experiments were performed by the NHM with a horizontal resolution of 5 km in the present and warming climates. The NHM is developed with some improvements from the Japan Meteorological Agency (JMA) non-hydrostatic model to be used as a regional climate model. The lateral boundaries of the NHM were made from the outputs of the AGCM experiments. The domain of the experiment was 4000 km x 3000 km over East Asia. Integration up to 40 days was performed in June and July every 10 years in both the present and warming climates. For the cloud and precipitation processes, the NHM explicitly calculates the microphysical processes by separating five categories of liquid and solid water substances; cloud water, rain, cloud ice, snow, and graupel. Convective parameterization schemes are not used, although the horizontal grid size is slightly larger for resolving each cloud. Further descriptions of the numerical experiments are found in Yoshizaki et al. (2005).

3. Changes in the environment around the Baiu front

One of the main changes in the atmospheric conditions due to global warming is the significant increase...
of water vapor in the lower atmosphere. The increase of water vapor causes convectively unstable stratification in the lower atmosphere. Yasunaga et al. (2005) pointed out that the intensification of precipitation in western Japan is due to unstable stratification. In this section, composite meridional distributions relative to the Baiu front are extracted to examine the environmental conditions around the Baiu front. The Baiu fronts are defined as follows: the wind speed ($V_b$) of the low-level jet (LLJ) at 700 hPa is greater than 8 m s$^{-1}$, and the relative humidity ($R_{H_b}$) at 500 hPa is higher than 70%. These definitions follow studies of the Baiu fronts conducted mainly in the 1970s.

Figure 1a shows a composite meridional distribution of the water vapor mixing ratio in the present climate. The areas of high relative humidity over the Baiu front are sometimes called the moist tongue. In the warming climate (Fig. 1b), the water vapor increases in the lower atmosphere, especially on the southern side of the Baiu front, and the meridional gradient of the water vapor increases. The water vapor on the southern side of the Baiu front is a main source of precipitation over the Baiu frontal zone. Moreover, a significant increase in the equivalent potential temperature (EPT) is found in the lower atmosphere. Yasunaga et al. (2005) pointed out that the number of disturbances increases in the warming climate, especially in July (1.5). Compared with the present climate, the large increase rate changes. Figure 3 shows the increase rate for the Baiu duration, the increase rate for the number of disturbances is larger.

Table 1 shows the number of disturbances. It is noticed that the number of disturbances increases in the warming climate, especially in July (1.5). Compared with the increase rate for the Baiu duration, the increase rate for the number of disturbances is larger.

With different threshold values of $R$, the feature of the large increase rate changes. Figure 3 shows the number of disturbances as a function of the threshold values of $R$. The increase rates are larger with larger threshold values of $R$. This result also supports the intensification of precipitation. It is suggested that the significant increase in the number of disturbances is largely due to the intensification of precipitation. This also results in the increase in precipitation amount over western Japan in the warming climate pointed out by Yoshizaki et al. (2005).

These results in Fig. 3 are statistically evaluated from $F$- and $t$-tests with a significance level of 5%. The changes in the number of disturbances are found to be statistically significant with the threshold values of $R$ larger than 30. However, the numbers of disturbances involve large standard deviations. They are mainly due to large year-to-year variations, although the SST has no year-to-year variation. In order to validate the statistical evaluations, more numerical experiments are needed.

Table 1. Numbers of disturbances in the Baiu frontal zone

<table>
<thead>
<tr>
<th></th>
<th>June</th>
<th>July</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Climate</td>
<td>267</td>
<td>219</td>
<td>486</td>
</tr>
<tr>
<td>Warming Climate</td>
<td>255</td>
<td>323</td>
<td>578</td>
</tr>
<tr>
<td>Increase Rate</td>
<td>1.0</td>
<td>1.5</td>
<td>1.2</td>
</tr>
</tbody>
</table>

From the results of the AGCM, Kusunoki et al. (2005) and Yasunaga et al. (2005) pointed out that the durations of the Baiu seasons are prolonged and their ends are delayed or become less clear in the warming climate. However, they did not estimate the lengthening of the Baiu duration quantitatively. In this study, the Baiu duration is defined by the occurrence days of the Baiu front defined in Section 3. The increase rate of the Baiu duration is estimated to be 1.15 in July. Even by using different definitions of the Baiu front: such as $8 < V_b < 10$ m s$^{-1}$ and $70 < R_{H_b} < 80\%$, the changes of the increase rate are small.
5. Averaged structures of disturbances

Most disturbances defined by precipitation accompany depressions. Hereafter, the structures of disturbances are studied in association with the depressions. In this section, mean fields are obtained by averaging in the whole disturbances. The mean composite horizontal distributions relative to the centers of precipitation are shown in Fig. 4. The depression is located on the northwestern side of the precipitation center on the average. The mean depression is shallow and confined below 500 hPa (Fig. 4c). The high-EPT air in the lower atmosphere is brought from the south of the precipitation center by the cyclonic circulation around the depression (Fig. 4a). Heavy precipitation is caused over the area with a large temperature gradient associated with the LLJ (Fig. 4b). The main changes in the mean fields due to global warming are the enhancement of the southerly water vapor flux in the lower atmosphere due to the increase of water vapor (not shown).

6. Changes in the characteristic features of classified disturbances

The disturbances over the Baiu frontal zone have several types. In order to investigate changes in the characteristic features of disturbances due to global warming, analyses are made by applying a high-pass filter and picking up only components shorter than 4 days. The vertical inclinations of pressure, temperature, and winds are studied in the zonal direction. Figure 5 shows the numbers of disturbances for the different inclinations of depression centers for (a) moderate precipitation (20 < R < 25 mm) and (b) strong precipitation (R > 25 mm) cases. In both the present and warming climates, the high-pass-filtered disturbances are categorized into three types: westward-tilting (type 1), non-tilting (type 2), and eastward-tilting (type 3). The ranges of the inclinations are from ±20 to ±45 for type 1, from ±2.5 to 2.5 for type 2, and from 5 to 20 for type 3, with a unit of 10 m/°. Δ is the height difference between 700 and 975 hPa, Δ = ln (700/975). In the warming climate, large differences in number are not found among these types for the moderate precipitation case (Fig. 5a). On the other hand, large increase rates estimated to be 1.5 to 2.0 are found for type 3 for the strong precipitation case (Fig. 5b). These changes in numbers of disturbances are also statistically examined by the t-test for each category for the inclinations. Significant changes in numbers are evaluated only with the inclination from 10 to 30 ° and with a significance level of 10%.

Next, the high-pass-filtered structures of types 1 and 3 are examined. The horizontal and vertical structures in the high-pass-filtered fields are not found to be very different in both the present and warming climates (not shown). Therefore, the composite horizontal structures of types 1 and 3 are shown in Fig. 6. The top levels of types 1 and 3 are found around 500 and 600 hPa, respectively. The vertical axes of the upward motions are also seen around the precipitation center in both types (not shown). In type 1, warm (cold) regions at 600, 850, and 975 hPa are located on the southeastern (northeastern) side of the depression. Such features might be seen in classical baroclinic instability without diabatic heating. On the other hand, in type 3, a warm region is found around the center of the depressions at 600 hPa. Relatively warm (cold) regions at 850 hPa are located on the southwestern (northeastern) side of the depression. The large values of temperature are located above the axes of the depressions with the vertical tilting structures. Similar structures with these characteristics in a high-pass-filtered field have been already pointed out by Yoshizumi (1977), although his study was an observational case analysis.
climate is due to the enhancement of convections associated with the increase of water vapor in the lower atmosphere.

The present method, in which the disturbances are defined by intense precipitation, is effective to estimate climatological changes in the number of disturbances in association with the precipitation intensities. However, some problems remain to be solved. The method is not applicable to analyze the mechanisms and fine structures of disturbances, because it neglects the life cycles of disturbances and does not carefully treat the scale variability of disturbances. Further studies are thus necessary.

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