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 monitored more accurately by the intensification of precipitation. Among such disturbances, those with intense precipitation and heavy rainfall are found in high-pass-filtered fields, which are more frequently seen in the warming climate. They are considered to be meso-α-scale baroclinic instability modified by diabatic heating due to large precipitation. Our results suggest that the changes in the numbers of disturbances are induced by an increase in the water vapor to the Baiu frontal zone and convectively unstable stratifications in the lower atmosphere.

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 has 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. The Baiu fronts are seen as wide and quasi-stationary zones of precipitation and clouds extending in an east-west direction from China to the Japan Islands. 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 are 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 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 (AOGCM) 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 × 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

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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 700–850 hPa is greater than 8 m s$^{-1}$, and the relative humidity ($R_{Hb}$) at 500–600 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, especially on the southern side of the Baiu front, intensifying the convectively unstable stratification (not shown).

### 4. Changes in the number of disturbances

Yasunaga et al. (2005) analyzed the changes in the number of mesoscale precipitation systems in the experiment domain due to global warming by classifying rainfall areas. They reported that the number of meso-$\alpha$-scale precipitation systems significantly increases in the warming climate while that of meso-$\beta$-scale (horizontal scale of 20–200 km) systems does not.

In this section, disturbances are defined as intense precipitation features around the Baiu front over western Japan. This definition is similar to that of Yasunaga et al. (2005); however, they did not consider the intensity of precipitation. Here, when the local maximums of the 6-hour precipitation accumulations averaged within the circle with a radius of 100 km (R) are larger than the threshold value of 20 mm, the peak points are considered as disturbances. In this definition, it is anticipated that most meso-$\alpha$-scale precipitation systems are sampled as ‘disturbances.’ These include disturbances making up groups referred to as “cloud system families” by Ninomiya and Shibagaki (2003). An example of these disturbances is shown in Fig. 2, where meso-$\alpha$-scale precipitation systems with depressions align along the Baiu front and are counted as individual disturbances. The analysis domain is limited around the western part of Japan (brown box region in Fig. 2). The number and structures of such disturbances are studied hereafter.

#### Table 1. Numbers of disturbances in the Baiu frontal zone

<table>
<thead>
<tr>
<th></th>
<th>June</th>
<th>July</th>
<th>Total</th>
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<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 $70 < R_{Hb} < 80$, the changes of the increase rate are small.

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.
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 (not shown). Relatively warm (cold) regions at 850 hPa are located on the southeastern (northwestern) sides of the depression. Such features might be seen around the precipitation center in both types (not shown). The vertical axes of the upward motions are also seen around the precipitation center in both types (not shown). 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 -5 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°. 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 1.5-2.0 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° 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 (northern) 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) sides 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.
7. Summary and discussion

Regional climate experiments were performed using a non-hydrostatic model with a 5 km resolution in order to clarify the changes in the characteristic features of disturbances in the Baiu frontal zone over western Japan due to global warming. The main changes in the environmental atmosphere are the increase in the supply of water vapor to the Baiu front and the intensification of the convectively unstable stratification in the lower atmosphere.

An increase in the number of disturbances is found in the Baiu frontal zone over western Japan in the warming climate. This increase is brought by the intensification of precipitation as well as the lengthening of the Baiu duration. The disturbances appeared along the Baiu front are classified into three types, such as type 1 (westward-tilting) and type 3 (eastward-tilting) in the high-pass-filtered fields. The increase rate of the number for type 3 with intense precipitation is significantly large in the global warming climate.

The disturbances with the eastward-tilting structures have been studied theoretically by Tokioka (1973) and Yanase and Niino (2004). They showed that an eastward-tilting structure with a shorter wavelength as 1000–2000 km appears when the baroclinic instability disturbances are modified by the diabatic heating. To generate such disturbances, a small Richardson number (Ri) is required. In this experiment, the small Ri is found in the lower atmosphere along the Baiu front (not shown). Additionally, in the warming climate, the diabatic heating around the levels of 800–600 hPa and precipitation intensities around the precipitation center are strongly enhanced in type 3 but not in type 1 (not shown). Therefore, it is considered that the type 3 disturbances are those of the baroclinic instability modified by diabatic heating in association with larger precipitation. Moreover, it is suggested that the large increase rate of the number for type 3 in the warming 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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