Structure of Mesoscale Convective Systems during the Late Baiu Season in the Global Warming Climate Simulated by a Non-Hydrostatic Regional Model

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Abstract

Mesoscale convective systems (MCSs) that bring rainfall in the vicinity of Kyushu Island, Japan during the late Baiu season in the present and global warming climates are examined by a non-hydrostatic regional climate model (NHM) with the horizontal grid of 5 km.

In the global warming climate, two types of MCSs appear in the vicinity of Kyushu Island. One travels from the Chinese Continent and the other from the southern part of the East China Sea to Kyushu Island. These two MCSs often merge over the sea southwest of Kyushu Island, and they rapidly develop to bring heavy precipitation to the vicinity of Kyushu Island. Among the latter, MCSs with low cloud-tops below 4 km MSL (Mean Sea Level) are found.

In the comparison with the present climate, the average cloud and rain water mixing ratios in the vicinity of Kyushu Island become much larger, and the peak altitude of the mixing ratios are about 0.5–1.0 km higher in the global warming climate. The cloud water mixing ratio between 2–4 km MSL increases in the global warming climate, corresponding to MCSs with low cloud-tops.

These results suggest one of the processes to produce heavy rainfall in the vicinity of Kyushu Island in July in the global warming climate.

1. Introduction

The impact of global warming on the present climate is one of the most highlighted subjects from the viewpoints of economic activity and the global environment (IPCC 2001). There have been many attempts to approach this subject by numerical simulations. However most of these simulations were performed by hydrostatic models with relatively coarse resolution, focusing on the large-scale circulation and the global climate change. In order to reveal the impact of global warming on the present regional climate change, a high-resolution non-hydrostatic regional model (NHM) which treats cloud microphysics explicitly should be adopted. Such model can represent not only the horizontal distributions of rainfall in detail but also the 3-dimensional structures of mesoscale convective systems (MCSs).

Yoshizaki et al. (2005) presented an overview of such NHM results with the horizontal grid of 5 km, and they reported that the monthly mean precipitation in the vicinity of Kyushu Island in July would become much larger under the conditions of the global warming than in the present climate. It is a great concern which factors of the following cause this increase: the structure-change of MCSs, the increase of supplied water vapor or the change on the appearance frequency of MCSs.

Multi-scale features of MCSs observed during the Baiu season have been statistically examined by Ninomiya and Akiyama (1992). The MCSs described in this study belong to the meso-α- and meso-β-scale cloud systems. The main purpose of this study is to investigate changes in the structures of MCSs that bring the heavy rainfall in the vicinity of Kyushu Island during the late Baiu season as a first step to reveal the impact of global warming on the regional climate by using a non-hydrostatic regional model with the horizontal resolution of 5 km.

2. Comparison of accumulated precipitation in the present and global warming climates

The NHM time-slice climate simulations in the present and global warming climates were performed from June to July for ten years, since the Baiu frontal activity in East Asia was one of our main targets. The NHM with a horizontal grid of 5 km was nested in the results of a hydrostatic global climate model (AGCM) with a horizontal grid of 20 km. The model domain of the NHM was 800 × 600 horizontal grids (4000 km × 3000 km) and 48 vertical layers (top height: 22 km), covering the wide region from the eastern part of the Chinese Continent to the Japan Islands. The detailed designs of the AGCM and the NHM are described in Kusunoki et al. (2005) and Yoshizaki et al. (2005), respectively.

According to Yoshizaki et al. (2005), the precipitation in the vicinity of Kyushu Island increases in the global warming climate. The Baiu season also often lasts until August or has no end in the extreme cases. The horizontal distribution of the monthly mean daily precipitation in July in the global warming climate is shown in Fig. 1a. An intense precipitation becomes concentrated around Kyushu Island and on its downwind side in the global warming climate. The temporal variations of 10yr-averaged daily precipitation averaged in the vicinity of Kyushu Island in the present and global warming climates from June to July are shown in Fig. 1b. The daily precipitation in the present climate increases at the beginning of June and decreases in the middle of July, showing the onset and the end of the Baiu season, respectively. On the other hand, the daily precipitation maintains a high intensity of nearly 10 mm day⁻¹ even at the end of July in the global warming climate. Note that the averaged daily precipitation during the first half of July becomes much larger in the global warming climate. The MCSs that bring this heavy rainfall are investigated in detail in the following sections.
3. Time-averaged characteristics of MCSs that bring rainfall in the vicinity of Kyushu Island in the present and global warming climates

The time-averaged characteristics of MCSs that pass over Kyushu Island during the late Baiu season are compared between the present and global warming climates.

Yasunaga et al. (2005) showed that the number of MCSs that appear in the vicinity of Kyushu Island in July increases in the global warming climate. MCSs, appearing in the global warming climate, travel from both the eastern coast of the Chinese Continent and the southern part of the East China Sea to Kyushu Island. They concentrate in the vicinity of Kyushu Island and on its downwind side. However, in the present climate, most of MCSs travel from the eastern coast of the Chinese Continent through the northern part of the East China Sea to Kyushu Island.

Since our focus is on the relation between the increase of precipitation in the vicinity of Kyushu Island during the late Baiu season and the above-mentioned MCSs, rainfall events that last longer than 2 days over Kyushu Island in July are chosen for the analysis. Rainfall events associated with typhoons are excluded. A total of 12 cases are found in the present climate. The same number of 12 cases is selected from the results of the global warming climate. A time-averaged horizontal distribution of the cloud water mixing ratio qc averaged vertically around the melting layers for each climate is shown in Fig. 2. The regions with moderate qc (6×10⁻⁵ kg kg⁻¹) are located around northern Kyushu in the present climate (Fig. 2a), while the qc is less than 5×10⁻⁵ kg kg⁻¹ over the southern part of the East China Sea. On the other hand, two regions with large qc are found in the global warming climate (Fig. 2b): one extends from the eastern coast of the Chinese Continent and the other from the southern part of the East China Sea to Kyushu Island. They merge over the sea southwest of Kyushu Island, on the downwind side of which an abrupt increase of qc exceeding 8×10⁻⁵ kg kg⁻¹ is found.

These regions with large qc are caused by 1) MCSs traveling from the eastern coast of the Chinese Continent (hereafter referred to as Type-1 MCS), 2) MCSs traveling from the southern part of the East China Sea (referred to as Type-2 MCS), and 3) the merger Type-1 and Type-2 MCSs (referred to as Type-3 MCS). Among the 12 selected cases in the global warming climate, the merger of Type-1 and Type-2 MCSs was found for 5 cases, while only one merger occurred in the present climate.

Figure 3 shows the time-averaged longitude-height cross-sections of qc averaged between 30 and 31 N in the present and global warming climates. In the present climate, qc larger than 4×10⁻⁵ kg kg⁻¹ is found only over the northern part of the East China Sea (120–130 E). On the other hand, the qc in the global warming climate starts to increase around 124 E and attain 5×10⁻⁵ kg kg⁻¹ in the southern part of Kyushu Island (130–134 E). Other area with moderate qc larger than 4×10⁻⁵ kg kg⁻¹, corresponding to Type-1 MCSs, is found over the northern part of the East China Sea. In the global warming climate, the peak altitude of qc is about 0.5–1.0 km higher than that in the present climate. The depth of the high qc layer (qc >1×10⁻⁵ kg kg⁻¹) in the global warming climate extends widely from a height of 2.5 km to 6.5 km MSL in the vicinity of Kyushu Island.

Figure 4 shows the vertical profiles of qc and the rain water mixing ratio qr averaged in the rectangle shown.
in Fig. 1a. Both $q_c$ and $q_r$ in the vicinity of Kyushu Island in the global warming climate become much larger than those found in the present climate, and the peak altitudes of $q_c$ and $q_r$ become about 0.5 km higher than those of the present climate. Note that a remarkable increase in $q_c$ is found between 2–4 km MSL in the global warming climate.

A region with $q_c$ larger than $5 \times 10^5$ kg kg$^{-1}$ appears at a height of approximately 3 km over the East China Sea (127–129 E, 29.5 N). This region will hereafter be called a low cloud-top (LCT) system. Another region with moderate values of $q_c$ widely extends to the west (123–127 E) of the LCT system at a height of 6 km. The LCT system travels slowly to the northeast, maintaining its low cloud top lower than 4 km until 3 hr. At 6 hr, these two regions merge over the sea southwest of Kyushu Island (129 E, 30.4 N), and after then they rapidly develop while increasing $q_c$ and $q_r$ (6 and 12 hr). At 9 hr, the MCSs reach Kyushu Island, and at 12 hr, they extend over Kyushu Island, accompanying with the wide precipitation.

4. Temporal variations of Type-3 MCS in the global warming climate

In this section, one case of the Type-3 MCSs defined in the last section, is selected to study the merger of Type-1 and Type-2 MCSs in detail. This MCS corresponds to the meso-$\beta$-scale cloud system, described in Ninomiya and Akiyama (1992).

Figure 5 shows the horizontal distributions of $q_c$ and the temporal variations of vertical cross-sections of $q_c$ and $q_r$ for the selected case. Each vertical cross-section displays the most intense part in $q_c$ of the MCSs. At 0 hr, these results show one of the possible processes to produce heavy rainfall in the vicinity of Kyushu Island.
during the late Baiu season in the global warming climate. A remarkable increase of $q_c$ between 2–4 km MSL in Fig. 4a supports the frequent appearance of LCT systems in the global warming climate.

Now, the formation and maintenance mechanisms of the LCT systems are considered. The annual mean surface air temperature and the sea surface temperature over the East China Sea in the global warming climate are expected to become about 2–3 degrees higher than those in the present climate (Uchiyama et al. 2003), and abundant water vapor is supplied from the East China Sea in the global warming climate (Wakazuki et al. 2005). However, LCT systems maintain their characteristics for more than 3 hrs, while the other MCSs with cloud tops exceeding a height of 6 km also appear in the global warming climate (Fig. 5).

Figure 6 shows the longitude-height cross-section of the vertical velocity along 28N in the vicinity of the East China Sea before a MCS with high cloud-tops catches up with the LCT system and the LCT system described in the last section intensifies. Several shallow cores of the cloud water mixing ratio are located at a height of 3 km (125–127E and 131–133E). Downdrafts widely prevail above a height of 3 km, while weak downdrafts and updrafts intermingle below that height. Some cloud water begins to be formed around 3 km MSL just on the boundary of these layers. According to Kusunoki et al. (2005), the North Pacific high in July tends to extend westward in the global warming climate, covering a wide area over the southern part of the East China Sea. Therefore the subsidence in the North Pacific high suppresses the activity of MCSs there. The places where the downdrafts above a height of 3 km found in Fig. 6 correspond to the periphery of the subsidence. However, more detailed studies are needed to reveal the formation and maintenance mechanisms of the LCT system by using the results of both the present and global warming climates simulations.

5. Summary

In this study, mesoscale convective systems (MCSs) in the vicinity of the East China Sea and Kyushu Island during the late Baiu season are compared between the present and global warming climates by using the results of the NHM time-slice climate simulations with the horizontal grid of 5 km.

In the comparison with the present climate, the averaged cloud and rain water mixing ratios in the vicinity of Kyushu Island become much larger and their peak altitudes become about 0.5–1.0 km higher in the global warming climate. A remarkable increase of the cloud water mixing ratio is found between 2–4 km MSL.

In the global warming climate, two types of MCSs appear in the vicinity of Kyushu Island. One travels from the Chinese Continent and the other from the southern part of the East China Sea to Kyushu Island. These two MCSs often merge over the sea southwest of Kyushu Island, and after then they rapidly develop to bring heavy rainfall in the vicinity of Kyushu Island.

Among the MCSs from the southern part of the East China Sea, MCSs with low cloud-tops below a height of 4 km MSL are found. In the present climate, however, fewer MCSs travel from the southern part of the East China Sea, and little merger events are seen over the sea southwest of Kyushu Island.

These results suggest one of the processes to produce heavy rainfall in the vicinity of Kyushu Island in July in the global warming climate. Further studies are needed to clarify whether or not the characteristics and structures of MCSs are changed in the global warming climate. The formation and maintenance processes of the low-cloud top systems and their influence on heavy rainfall in the vicinity of Kyushu Island should be also clarified in near future.

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