A Numerical Study on the Appearance of Target Clouds for Artificial Precipitation Experiments over Shikoku Island, Western Japan during the Baiu Season

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Abstract

The appearance frequency of clouds with much cloud water and less precipitating water, which significantly influences cloud seeding to increase rainfall, is examined from the simulation results of a cloud-resolving model with a horizontal resolution of 1 km. The area of Shikoku Island, located in western Japan, was analyzed in the 2007 Baiu season.

In this study, target clouds are judged using the threshold values of the vertically accumulated total amount of rainwater, snow and graupel (TRSG) less than 1.0 mm and that of cloud water exceeding 0.5 mm. Moreover, the available total rainfall amount is roughly estimated by vertically accumulating cloud water for $\text{TRSG} < 1.0$ mm.

Between May and July 2007, target clouds appear at a rate of 6.4% in average over the central area of Shikoku Island. Even in June 2007 when observed rainfall amount was less than 50% of the 10-year mean value published by the Japan Meteorological Agency, the cloud appearance rate of 7.6% is comparable with that in July when rainfall reached the 10-year mean value. The diurnal variation of the appearance rate of target clouds is also examined. In June, target clouds appear at a higher rate (~12%) in the afternoon. Moreover, available total rainfall amount of about 200 mm is estimated over the central area of Shikoku Island for three months.

1. Introduction

Shikoku Island, located in western Japan (see Fig. 1), sometimes experiences a water shortage in the summer season due to insufficient rainfall amount during the Baiu season. In June and July belonging to the Baiu season, Shikoku Island usually has an accumulated rainfall amount of 200–400 mm per month, while accumulated rainfall amounts in June 2005 and 2007 did not reach 100 mm. Therefore, the increase of rainfall by using weather modification techniques is expected to avoid a water shortage, in addition to the water resource management with dams. In the 2008 Baiu season, the Japanese Cloud Seeding Experiment for Precipitation Augmentation (JCSEPA) is planned in the central area of Shikoku Island to ascertain the effect of weather modification techniques.

Cloud seeding to increase precipitation amount is mainly divided into two types (Bruitjes 1999). One is glaciogenic seeding for super-cooled clouds. In the JCSEPA, seeding with dry ice pellets has been applied to orographic clouds observed over the upwind areas of mountains in middle Japan in the winter monsoon season. The other is seeding with hygroscopic particles

at the cloud base of warm clouds below the freezing level. Such particles can accelerate the condensation growth to increase the size of cloud droplets.

Around western Japan during the Baiu season, most cloud-top heights of moist convection could be lower than the freezing level (Kato and Hayashi 2008). This suggests that hygroscopic seeding will be the major method for weather modification techniques to increase rainfall. In order to find favorable conditions for hygroscopic seeding, several factors (e.g., size distribution of cloud droplets, number of background cloud condensation nuclei, possibility of forming ice crystals and environmental atmospheric conditions) must be considered in addition to the amount of cloud water. However, appropriate clouds for hygroscopic seeding have not been absolutely determined yet, because the relationships among the factors are very complicated in comparison with those for glaciogenic seeding. Moreover, the information on the appearance frequency of clouds with much cloud water is important for conducting seeding experiments, although such clouds are not completely suitable for hygroscopic seeding. However, the appearance frequency of such clouds is not well known around the Japan Islands, especially during the Baiu season.

The major goal of this study is to examine the appearance frequency of clouds with much cloud water and less precipitating water, which are necessary for cloud seeding, over the central area of Shikoku Island during the Baiu season, and to briefly compare it with that over Kyushu Island, which also sometimes experiences a water shortage in the summer season. Such target clouds are estimated from the simulation results of a cloud-resolving model with a horizontal resolution of 1 km (1km-CRM). Moreover, the available total rainfall amount that may be increased by cloud seeding is roughly examined from the total amount of cloud water in the target clouds.

2. Numerical models and descriptions

This study used the nonhydrostatic model that is operationally used for numerical weather prediction in the Japan Meteorological Agency (JMA-NHM, Saito et al. 2006). The forecast of the JMA-NHM with a horizontal resolution of 5 km (5km-NHM) is performed to provide initial and boundary conditions to the 1km-CRM. Figure 1 shows the model domain and topography of each model. The model domain of the 5km-NHM (2500 km × 2000 km) covers almost the entire area of the Japan Islands, while that of the 1km-CRM (600 km × 500 km) covers the surrounding areas of Kyushu and Shikoku Islands. The vertical grid of both models contains 50 levels with variable grid intervals of 40 m (near the surface) to 886 m (at the top of the domain), and the model top is located at a height of 21.8 km. The same dynamical and physical processes but for precipitation ones are set in both models. In the 1km-CRM, a bulk-type microphysics scheme predicting the specific humidity of cloud water q_c , cloud ice q_{ci} , rainwater q_r , snow

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Fig. 1. Model domain and topography of (a) 5km-NHM and (b) 1km-CRM.

q_s , and graupel q_g is used, while a moist convection parameterization scheme (Kain and Fritsch 1990) is conjunctionally used in the 5km-NHM. The other model information is detailed in Saito et al. (2007).

The initial and boundary conditions of the 5km-NHM are produced from the JMA mesoscale objective analysis data with a horizontal resolution of 10 km (available every 3 hours). The initial times of the 5km-NHM are 00 UTC, 06 UTC, 12 UTC and 18 UTC between 1 May and 31 July 2007, while those of the 1km-CRM are produced by simply interpolating from the 3-hour forecast of the 5km-NHM. The integration times of the 5km-NHM and 1km-CRM are 12 hours and 9 hours, respectively. Three hundred and sixty eight simulations are conducted by using both models. Hourly data set for three months is produced from the hourly output, between 4-hour and 9-hour forecasts, of 1km-CRM simulations.

3. Judgment criteria for target clouds and determination of available total rainfall amount

The target clouds in this study have much cloud water but little precipitating water. Therefore, the vertically accumulated total amount of q_r , q_s , and q_g (TRSG) and that of q_c (TQC) are calculated from the simulation results of 1km-CRM, and the existence of such target clouds is judged using the following criteria with threshold values of TRSG and TQC:

$$\text{TRSG} < 1.0 \text{ mm}, \quad (1)$$

and

$$\text{TQC} > 0.5 \text{ mm}. \quad (2)$$

These values are determined by referring to glaciogenic seeding experiments in the JCSEPA. Moreover, the dependency of the appearance frequency of target clouds on the judgment criteria for TRSG and TQC is also examined.

When TRSG is large, precipitation reaches the ground after accreting with many cloud droplets. In such a case, cloud seeding is powerless for increasing rainfall amount. Therefore, the available total rainfall amount that may be increased by cloud seeding is calculated in this study by simply summing the TQC satisfying (1) for each hourly data (e.g., 2208 hourly data for 3 months). This estimation is too rough to examine the effect of cloud seeding, and the advection of cloud water should also be considered to examine its effect on the downstream side. However, it is very important to quantitatively understand the available cloud water amount. Moreover, the estimated available total rainfall amount

is compared with the simulated rainfall amount.

4. Results

In order to validate the forecast accuracy of 1km-CRM, the simulated rainfall amount is first compared with rain gauge observations. Figures 2a and 2b show the monthly accumulated rainfall amount of June 2007 observed by JMA's AMeDAS (Automated Meteorological Data Acquisition System) and that simulated by the 1km-CRM, respectively. Although a few heavy rainfall events that were observed over southern Kyushu failed to be forecasted, the rainfall distribution and amount on the land are successfully forecasted by the 1km-CRM, especially over Shikoku Island. In the other months, May and July 2007, the 1km-CRM also forecasted rainfall with good accuracy (not shown). This indicates that the appearance frequency of target clouds can be estimated based on the simulation results of 1km-CRM, although simulated cloud water can not be evaluated due to fewer observations. Simulated cloud water is planned to be evaluated in the JCSEPA. Moreover, sensitivity experiments with the JMA-NHM demonstrated that a horizontal grid of 1 km is fine enough to reproduce the vertical profile of cloud water simulated by using a further finer grid (Eito and Aonashi 2007).

Figure 3a shows the horizontal distribution of the target cloud appearance rates between May and July 2007, judged from conditions (1) and (2). High appearance rates (exceeding 10%) are found over mountainous regions, especially over Kyushu Island. Meanwhile, target clouds appear at relatively low rates over the sea, which differs from the distribution of rainfall amount (Fig. 2b). This is caused by the easier formation of cloud water due to terrain-forced updrafts. The appearance rate averaged in the central area of Shikoku Island that almost corresponds to the target dam catchment area of JCSEPA, denoted by the pink rectangle in Fig. 3a, is es-

Fig. 2. Monthly accumulated rainfall amount of June 2007 (a) observed by the AMeDAS and (b) simulated by the 1km-CRM.

Fig. 3. (a) Horizontal distribution of the target cloud appearance rates between May and July 2007, judged from the 1km-CRM simulation results. Judgment criteria of target clouds are that the vertically accumulated amount of rainwater, snow and graupel (TRSG) is less than 1.0 mm and that of cloud water (TQC) exceeding 0.5 mm. (b) Dependency of the appearance rate of target clouds, averaged over the pink rectangle of (a), on the judgment criteria for TRSG (y-axis) and TQC (x-axis). Pink curve denotes the dependency of the available total rainfall amount (shown in upper x-axis) on the judgment criterion for TRSG.

timated to be 6.4%. Next, the dependency of this rate on judgment conditions (1) and (2) for TRSG and TQC is examined (Fig. 3b).

The appearance rate of target clouds increases slightly as the threshold value in (1) for TRSG exceeds 1.0 mm, but it decreases rapidly as the threshold value becomes smaller than 1.0 mm. This indicates that the target clouds seldom appear when there is little precipitating water, such as rainwater, snow and graupel, in the atmosphere. On the other hand, the appearance rate strongly depends on judgment condition (2) for TQC. For example, the appearance rate becomes double ($\sim 12\%$) for $TQC > 0.25$ mm, and one-third ($\sim 2\%$) for $TQC > 1.0$ mm.

The available total rainfall amount of about 200 mm for three months is roughly estimated over the central area of Shikoku Island, denoted by the pink rectangle in Fig. 3a. The pink curve in Fig. 3b shows the dependency of the available total rainfall amount on judgment condition (1) for TRSG. The available rainfall amount increases slightly as the threshold value in (1) for TRSG exceeds 1.0 mm, but it decreases rapidly as the threshold value becomes smaller than 1.0 mm. This dependency has the same characteristic features as the appearance rate of target clouds.

Figure 4 shows the monthly change of the appearance rate of target clouds. The appearance rate over Kyushu Island becomes the highest in June, and relatively low in July. Over Shikoku Island, however, the

target clouds appear at almost the same rate between June and July, although the observed rainfall amount in June was less than 50% of the 10-year mean value published by the JMA and that in July reached the 10-year mean value (not shown). The averaged appearance rate in the central area of Shikoku Island is estimated to be 7.6% in June and 7.3% in July. Moreover, the areas with high rates ($\sim 10\%$) move from the Pacific Ocean side to the Seto Inland Sea side between June and July. In May, the target clouds over both Kyushu and Shikoku Islands appear at almost half the rates of June and July. The appearance rate averaged in the central area of Shikoku Island is estimated to be only 4.3%.

The diurnal variation of the target cloud appearance rates, averaged in the central area of Shikoku Island, is shown by red lines in Fig. 5 in order to examine the favorable time for the cloud seeding experiments that is planned in the JCSEPA. In June, the diurnal variation of the appearance rate has considerably larger amplitude than that in May and July, and it becomes higher in the afternoon and reaches a maximum of about 12% at 19 JST (= UTC + 9 hours). Associated with this variation, the available total rainfall amount (blue line in Fig. 5b) increases in the afternoon. In contrast, the diurnal variation of the simulated rainfall amount (black lines in Fig. 5) has two peaks around the noon and in the evening in June and July, while it has a peak in the morning in May. Moreover, the ratio of the available total rainfall amount to the simulated rainfall amount is considerably larger in June than in May and July. This indicates that in June 2007, when the observed rainfall amount over Shikoku Island was less than 50% of 10-year mean value, the target clouds necessary for seeding experiments appeared at a considerably higher rate, especially in the afternoon.

5. Summary and conclusions

In this study, in order to examine the appearance frequency of clouds with much cloud water and less precipitating water, which is necessary for cloud seeding, numerical experiments with a 1km-CRM were performed targeting mainly on Shikoku Island during the 2007 Baiu season. A simulation using the 1km-CRM with 9-hour integration time was conducted four times per day. Vertically accumulated amount of rainwater, snow and graupel (TRSG) and that of cloud water (TQC) were calculated using hourly data set, produced from 368 simulations of 1km-CRM, and the target clouds were judged using the criteria of $TRSG < 1.0$ mm and $TQC > 0.5$ mm. The available total rainfall amount, which may be increased by cloud seeding, was also roughly estimated by simply summing TQC for $TRSG < 1.0$ mm.

The appearance rate of target clouds averaged between May and July 2007 is 6.4% over the central area of Shikoku Island where seeding experiments are planned during the 2008 Baiu season by the JCSEPA. The target clouds appear at the highest rate over Kyushu Island in June. On the other hand, although the observed rainfall amount over Shikoku Island was less than 50% of the 10-year mean value, the appearance rate is comparable with that in July when rainfall reached the 10-year mean value. Available total rainfall amount of about 200 mm is estimated over the central area of Shikoku Island for three months.

This study also examined the favorable time for conducting cloud seeding experiments from the diurnal variation of the target cloud appearance rates over the central area of Shikoku Island. In June 2007, the appearance rate has considerably larger amplitude in diurnal

Fig. 4. Same as Fig.3a, but for monthly averages in (a) May, (b) June, and (c) July 2007.

Fig. 5. Diurnal variation of the target cloud appearance rates, averaged over the pink rectangle of Fig. 3a, in (a) May, (b) June and (c) July 2007 (red lines). Blue and black lines denote available total rainfall amount (mm) and simulated rainfall amount (mm) by the 1km-CRM, respectively. The scale of the appearance rate is shown on the left side of each panel, and those of the rainfall amount on the right side. It should be remarked that the scale of the simulated rainfall in July is different from the others.

variation than those in May and July, and it becomes higher in the afternoon (~12%). Since the observed rainfall amount over Shikoku Island in June was less than 50% of the 10-year mean value, the target clouds appear at a considerably higher rate even in the period with less rainfall during the Baiu season.

The target clouds in this study are not completely suitable to appropriate clouds for cloud seeding that should be determined using several factors, such as size distribution of cloud droplets, number of background cloud condensation nuclei, in addition to the amount of cloud water. Therefore, appropriate clouds should be determined in observational and numerical cloud seeding experiments (e.g., JCSEPA; Cotton et al. 2006). However, the statistical results in this study provide significant information for conducting cloud seeding in the warm season, especially in JCSEPA, because such target clouds are necessary for cloud seeding. Moreover, the available total rainfall amount was estimated in this study by simply summing TQC. This should also be validated in numerical cloud seeding experiments. Furthermore, the appearance rate of target clouds should be examined for other Baiu seasons. These issues are for future studies.

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Comments and supplements

Further information on the JCSEPA can be seen on the URL <<http://jcsepa.mri-jma.go.jp/en/>>.

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