Statistical analysis with CRM data set on seeding potential for winter orographic cloud in Japan

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1. INTRODUCTION

For efficient cloud seeding experiments, it is necessary to distinguish the clouds that are expected to have a desirable change due to the seeding, in advance of actual operation. For that purpose, the numerical simulation with cloud resolving model (CRM), as well as sounding and remote sensing techniques, is a powerful tool since it can provide information on cloud microphysics, such as the geometrical cloud depth, temperature in cloud, and ratio between precipitation and cloud water amounts in a required resolution of time and space. There are two aspects in the assessment of microphysical properties that are crucial for a seeding experiment (seedability assessment). First one is to assess the cloud properties with a short range forecasting simulation, whose informations will be provided for the briefing in advance of seeding flight in the morning of operational day. Second one is to assess the statistical properties of the clouds that form in a seeding area, with the data set provided by the simulations through the experimental season. Seasonal frequency of seedable clouds, its spatial distribution, and its dependency on large scale meteorological situation are important for the seasonal plan of seeding experiment.

It is difficult to assess the seeding effect on the surface precipitation in target area using observational data, because, once a seeding operation is carried out, natural meteorological situation, to be compared with the modified situation, is lost in the experimental area. For randomized seeding experiments, it will take more than ten years to conclude that seeding has a significant effect. We plan to estimate the natural precipitation amount in target area using the observational data obtained in the area upwind of seeding area, where meteorological properties are not affected by seeding. For this purpose, as a preliminary step, we test the same procedure but with the numerical simulation.

Meteorological Research Institute (MRI) had conducted in-situ and numerical seeding experiments in the Hokuriku district, Japan in winter for the last decade, in order to develop the technique of artificial snowfall enhancement in the catchment of dams which are located in the upper stream of Tone river providing water for the metropolitan area of Japan. The seedability assessment had also been made using observational data and two-dimensional numerical model. From 2006, the five-year programme, Japanese Cloud Seeding Experiment for Precipitation Augmentation (JCSEPA) is started with a support from the Ministry of Education, Culture, Sports, Science and Technology. In this programme, seeding experiments for the winter orographic clouds are planned in the same region in order to sophisticate the snowfall enhancement technique. It is still necessary to make the seedability assessment using advanced techniques such as three-dimensional numerical model.

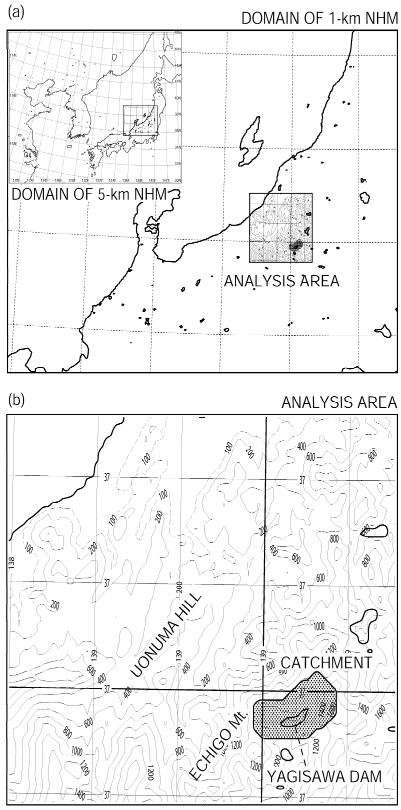

Fig. 1. (a) Calculation domain. (b) Analysis area.

In the present study, the data set from the simulations using a three-dimensional CRM is analyzed to evaluate the seedability of winter orographic clouds over the Echigo mountains, Japan through the winter season from 2005 to 2006. In addition, it is attempted to estimate the natural snowfall amount in target area using meteorological elements in the area upwind of seeding area, based on the same data set.

2. NUMERICAL EXPERIMENT

We applied the Japan Meteorological Agency Nonhydrostatic Model (JMANHM; Saito *et al.*, 2006) to simulate the winter orographic cloud in the Hokuriku district, Japan. The JMANHM explicitly calculates the microphysical processes relating to five categories of liquid and solid water substances: cloud water, rain, cloud ice, snow, and graupel with bulk parameterization scheme

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Table 1. Stratification of wind field.

Wind speed	$\geq$ 0 ms^{-1}			
	$\geq$ 24 ms^{-1}			
	W	WNW	NW	NNW
Wind direction	270 $\pm$ 11.25^o	292.5 $\pm$ 11.25^o	315 $\pm$ 11.25^o	337.5 $\pm$ 11.25^o

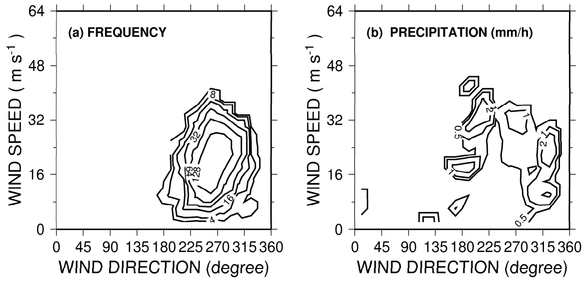

Fig. 2. (a) Frequency of the wind speed and direction averaged in the analysis area at the height of 3 km. (b) hourly precipitation averaged in the range bins of wind speed and direction.

(Ikawa and Saito, 1991).

The calculation domain of outer model (5km-NHM) has the area of 2500 km $\times$ 2000 km covering East Asia, with a horizontal resolution of 5 km (Fig. 1a). The top height of the model domain is about 22 km. Fifty variable vertical layers are employed. The time integration up to 12 hours was conducted with a time step of 12 sec for the outer model. The RANAL data provided by JMA were used as initial and boundary conditions. As shown in Fig. 1a, the inner model (1km-NHM), the domain of which has the area of 500 km $\times$ 400 km with a horizontal resolution of 1 km, were nested into the outer model in a one-way interaction manner. The vertical grid spacing were the same as that of outer model. For the inner model, the initial time were set 3 hours after the initiation of outer model. Integration were conducted for 9 hours. That sequence of simulations were performed successively through the winter from 1 December, 2005 to 31 March, 2006. Data for the first 3 hours were discarded in each simulation with inner model, in order to avoid a spin-up effect, and the last 6-hour data were used for analysis.

3. ANALYSIS

3.1 Seedability assessment

The simulation data are output at 1-hour intervals. The data in the area of 80 km $\times$ 80 km (Fig. 1b) are extracted from the output, for analysis. Liquid water path (LWP), cloud top temperature, and the mass ratio of cloud water to total condensate water are computed, based on the extracted data.

For the seedability assessment, we defined the *seedable cloud*, from which snowfall is expected to be enhanced by seeding, as the grid which satisfies following three conditions; the mass ratio of cloud water to total condensate water is greater than 0.4 in the grid, cloud boundary above the grid has the temperature lower than -5 degree Celsius, and LWP is greater than 0.2 mm in the air column including the grid. With this definition, three-dimensional distribution of seedable cloud is acquired every 1 hour through the winter in the analysis area. Further, the occurrence of seedable cloud is counted in each grid, so as to obtain the three-dimensional distribution of occurrence number of seedable cloud (N_{SDAB}).

Since the distribution of seedable cloud changes depending on meteorological conditions, such as wind field, we stratified the distribution of seedable cloud with the wind speed and direction, as shown in Table 1, using the wind data averaged in the analysis area at the height of 3 km. Finally, the N_{SDAB} are divided by the occurrence number of each stratified wind class so that the probability of occurrence of seedable cloud P_{SDAB} is determined for each class. The cases of wind speed greater than 24 ms^{-1} and wind direction of west-norhwestly wind (WNW) and northwestly wind (NW) will be shown in the next section.

Table 2. Summary of regression analysis.

variables	elements	correlation coefficient	β_i
x_1	UV	0.50	0.22
x_2	W	0.34	0.062
x_3	Q_c	0.44	0.13
x_4	Q_s	0.67	0.44
x_5	T_{top}	-0.45	-0.15
x_6	LWP	0.37	0.086
$\hat{y}$	mult. reg. model	0.76	–

3.2 Estimation of snowfall in catchment area

We define the catchment area of Yagisawa dam as indicated with the hatch in Fig. 1b. The hourly snowfall data are averaged over the hatched area to specify the snowfall amount in dam catchment area. Although there may be a lot of candidates for the meteorological elements to affect the snowfall in catchment area, we adopt those to be measured by some instruments; horizontal wind speed, vertical air velocity, mixing ratios of cloud water and snow, cloud top temperature, and LWP.

Firstly, we attempt the linear regression in order to investigate the correlation between each of elements and the snowfall amount in catchment area. The snowfall amount in catchment area that is of 1-hour behind the upwind meteorological elements are adopted. Secondly, the linear multiple regression model (Eq. 1) is tested in order to improve the correlation.

$$\hat{y} = \beta_0 + \sum_{i=1}^{6} \beta_i \; x_i \tag{1}$$

The correlation coefficients are computed in each grid over the analysis area. For the correlation analysis, the data are sampled when the wind direction ranges from 290 to 340 degrees on average in the analysis area.

4. RESULTS AND DISCUSSIONS

4.1 Seedability assessment

In the Hokuriku district, a large part of annual precipitation is brought by winter monsoon. The cold airmass

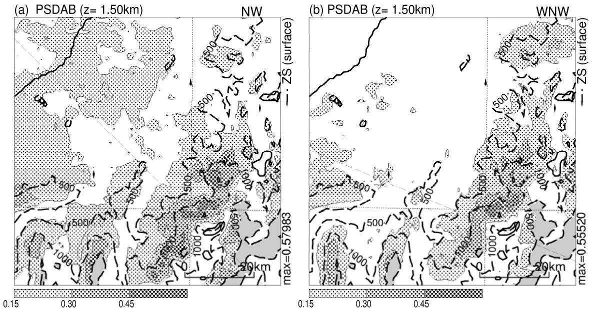

Fig. 3. Occurence probability of seedable clouds at the height of 1.5 km in the case of (a) NW and (b) WNW.

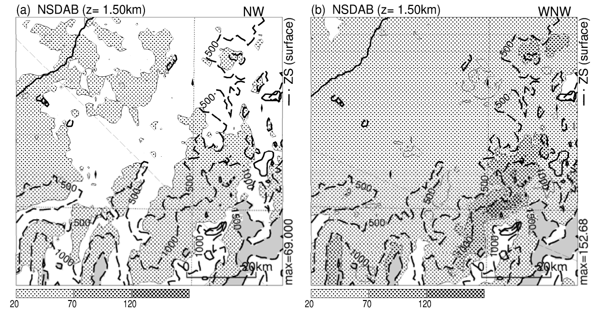

Fig. 5. Same as Fig. 3, but for the occurrence number of seedable clouds.

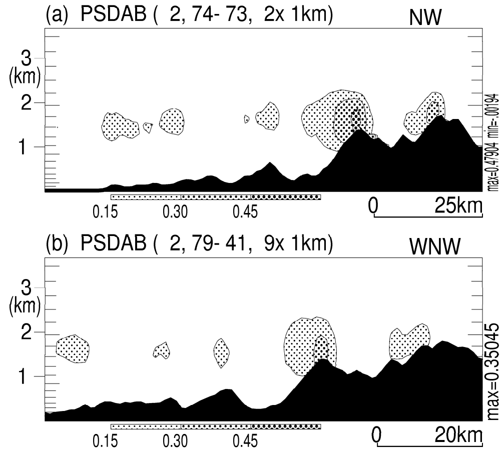

Fig. 4. Same as Fig. 3, but in the vertical cross section along the broken line in Fig. 3.

which originates in the Eurasian continent flows across the Sea of Japan, receiving a large amount of heat and water vapor from a warmer sea surface. Finally, the airmass runs ashore and on the Echigo mountains, and brings heavy snowfall in this region.

Figure 2a shows the frequencies of occurrence of wind speed and direction averaged in the analysis area at 3-km height. The dominant wind direction is from north to west. The occurrence of westly wind is more frequent than that of northly wind. This is consistent with annual feature in this region. Figure 2b shows the dependency of snowfall intensity on the wind field. Snowfall intensity is found to be larger in the case that northly wind component is strong than in the case of westly wind component is strong. It is also found that snowfall intensity becomes larger when the wind speed is larger.

Figure 3 shows the horizontal distribution of P_{SDAB} at the height of 1.5 km. The probability of occurrence of seedable cloud indicates high values more than 30 % over the upwind slope of Echigo mountains, regardless of wind direction. It means that the upwind side of Echigo mountains is adequate for a seeding operation. We consider the area extending from Uonuma hill to Echigo mountains as the seeding area. In this area, it is clear that the probability is higher for the NW wind than for the WNW wind, which means that a seeding plane can find the seedable clouds more efficiently in the case of NW wind. As shown in Fig. 4, the seedable clouds tends to appear in the height of 1.5 km to 2.5 km in the seeding area, regardless of wind direction. In the vicinity of the ridge of mountain, the depth of seedable cloud is less than 1 km and cloud base touches the mountain slope. For safety of seeding flight, it is impossible to use the seeding agent, such as liquid carbon dioxide, for which seeding plane has to fly below the cloud base near the mountain slope. It is rather adequate to adopt the dry ice pellets as the seeding agent for this region.

The analysis of wind field (Fig. 2) indicates that the WNW wind tends to occur in larger number through the winter than the NW wind. We look into the occurrence number of seedable clouds in Fig. 5. It is found that seedable clouds occur in more times through the winter in the case of WNW wind, because the WNW wind occurs more frequently than the NW wind.

As a result, a simple guideline for seeding experiment may be available from the analysis. If the wind field is concerned in the planning of seeding experiment so as to limit the clouds to be seeded to those in the NW wind, seeding operations are expected to be conducted efficiently (economically). From the view point of water resource augmentation, on the other hand, it will be necessary to have a lot of operations, including the case of WNW wind, in order to obtain the significant sign of increase of water resource through a winter.

4.2 Estimation of snowfall in catchment area

Figure 6 shows the single regression between each of meteorological elements and the snowfall in dam catchment area. The horizontal wind speed (UV) and vertical air velocity (W) well correlate in the coastal area and the upwind sides of swells, respectively (Figs. 6a, 6b). In both the places, the cloud water mixing ratio (Q_c) and LWP tend to have good correlations (Figs. 6c, 6f). It means that the general wind in lower layer and orography-induced updraft have an effect on the snowfall in catchment area through the production of cloud water. The mixing ratio of snow (Q_s) and cloud top temperature (T_{top}) show good correlations near the mountain (Figs. 6d, 6e). This is because the snow is a terminal product of precipitation process and its vertical distribution is reflected to the cloud top temperature.

As indicated with the cross symbol in each panel in Fig. 6, we arrange virtual observational points in the area extending from the coast to Uonuma hill (*estimation area*), so that each element at corresponding point

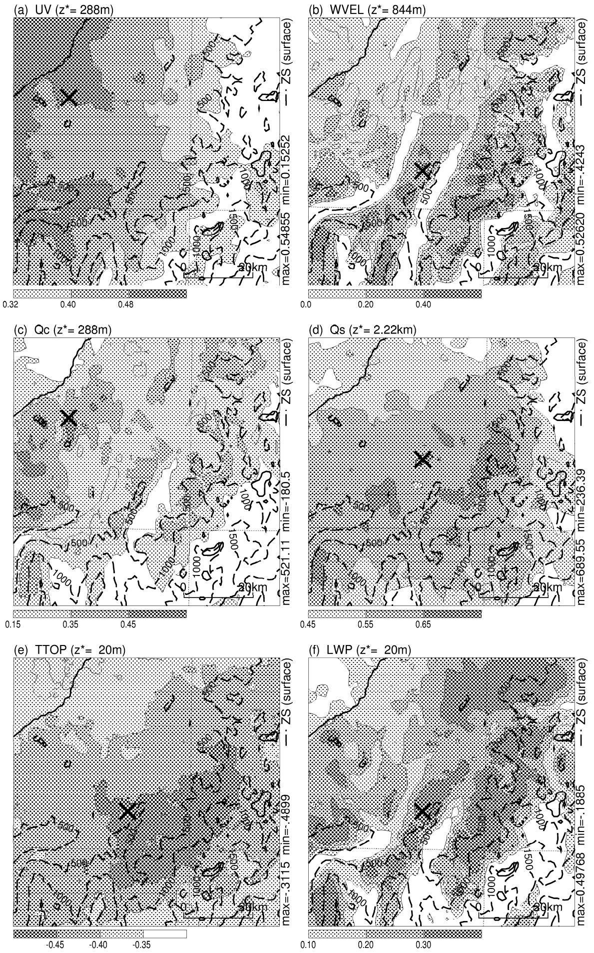

Fig. 6. Single regression between each of the meteorological elements and snowfall amount in catchment area. Panels (a) to (f) corresponds to UV, W, Q_c, Q_s, T_{top}, and LWP, respectively.

shows relatively better correlation in the estimation area. The corresponding correlation coefficients are shown in Table 2. The UV and Q_s are found to be good indicators of snowfall variation in dam catchment area. For the multiple regression analysis, those data of elements at the points are adopted as independent variables x_i $(1 \leq i \leq 6)$ in Eq.(1). Figure 7 shows the correlation between the multiple regression model $\hat{y}$ and the snowfall in catchment area. The correlation coefficient is 0.76, which is better than those of single regression for UV (0.50) and Q_s (0.67). It is fair to say that accuracy of estimation will be improved by the adequate arrangement of observational points and combination of meteorological elements. The β_i in Eq.(1) represents the contribution to multiple regression model. Those resulted values are shown in Table 2. The contributions of UV (0.22) and Q_s (0.44) are the largest among the elements. It means that the UV and Q_s in estimation area are strong factors to determine the snowfall in catchment area.

5. SUMMARY

The data set obtained from 3-D CRM simulations is analyzed to evaluate the seedability of winter orographic clouds over the Echigo mountaions, Japan through the winter season from 2005 to 2006. In addition, it is attempted to estimate the natural snowfall amount in target area using meteorological elements in the area upwind of seeding area (estimation area), based on the same data set.

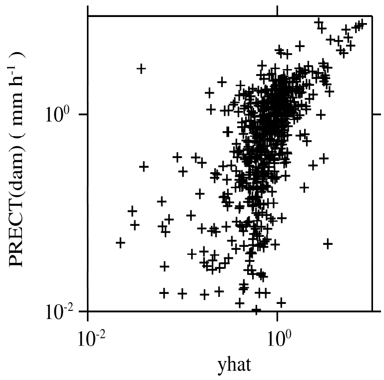

Fig. 7. Correlation between the snowfall in dam catchment and the multiple regression model.

The probability of occurrence of seedable cloud becomes more than 30 % over the upwind slope of Echigo mountains, regardless of wind direction. In the seeding area, extending from Uonuma hill to Echigo mountains, the probability is clearly higher for the NW wind than for the WNW wind. On the other hand, since the WNW wind occurs in more times than the NW wind, the occurrence number of seedable clouds through the winter is higher in the case of WNW wind. The seedable clouds tends to appear in the height of 1.5 km to 2.5 km in the seeding area, regardless of wind direction.

It is suggested that if the wind field is concerned in the planning of seeding experiment so as to limit the clouds to be seeded to those in the NW wind, seeding operations are expected to be conducted efficiently (economically). From the view point of water resource augmentation, on the other hand, it will be necessary to have a lot of operations, including the case of WNW wind, in order to obtain the significant sign of increase of water resource through a winter.

The UV and Q_s in estimation area are found to be good indicators of snowfall variation in dam catchment area, as a result from single regression analysis. The multiple regression model shows better correlation with the snowfall in catchment area than any of single regressions. It is fair to say that accuracy of estimation will be improved by the adequate arrangement of observational points and combination of meteorological elements. It is found that the UV and Q_s in estimation area are strong factors to determine the snowfall in catchment area.

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