Impact of Convective Parameterizations on Mesoscale Precipitation Associated with the Baiu Front

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Abstract

Four cumulus parameterizations, including the moist convective adjustment (MA), Kuo-Anthes (KA), Kain-Fritsch (KF) and Arakawa-Schubert (AS) schemes, were coupled into the Japan Spectral Model (JSM) and tested in the case of successively developed cloud clusters along the Baiu front during the period from 16 to 17 July 1993 in western Japan. All four experiments with these four parameterizations simulated synoptic features well: locations of lows and the front. The mesoscale precipitation associated with the Baiu front was, in contrast, sensitive to the convective parameterization. Intense precipitation in the Kyushu district was caused by the successive development of cloud clusters. This characteristic feature was simulated by the experiment with the AS scheme. The other three schemes were, however, not so effective in describing the mesoscale precipitation system in the Baiu front. Three sensitivity tests in which the number of types of clouds was reduced to two from six in the AS scheme were also performed to examine the importance of cloud interaction. None of the three simulated the characteristics of the Baiu frontal precipitation. The results suggest that a sophisticated parameterization of convection is necessary to simulate mesoscale precipitation associated with the Baiu front, which is characterized by weakly baroclinic forcing and significant convective instability. An additional experiment for the latent heating in the AS scheme was also performed. The result showed that precipitation in the Baiu frontal zone was greatly affected by the diabatic heating.

1. Introduction

The cumulus convective parameterization technique is widely used in numerical forecasting models and simulating systems. In order to treat the moisture circulation accurately, we have to deal with the moist convection and phase transition of moisture; there are quite important in both large-scale and mesoscale models. Owing to the limitations of computer resources and macro-physical theory on cumulus convection, we have to parameterize convective effects in numerical models with a large grid size ($\geq \sim 10$ km). In a mesoscale numerical simulation, we usually use a grid interval of $20 \sim 80$ km to describe meso- α or meso- β scale systems. As we know, strong convection and intense precipitation are the main characteristics of most of the mesoscale systems. The convective parameterization is extremely

important in mesoscale simulation. Because the grid space in mesoscale models is much smaller than the large-scale models, some of the cumulus characteristics can be resolved directly by the model. The parameterization method should be different from that of large-scale models. Furthermore, the mesoscale parameterization must give a detailed description of the convection including updraft and downdraft. This makes it more difficult in mesoscale models to deal with the cumulus parameterization problem than in general circulation models.

In the 1960's, parameterization schemes for large-scale numerical models were developed (*e.g.*, Manabe and Strickler, 1964; Kuo, 1965). With respect to the mesoscale numerical weather prediction, Kreitzberg and Perky (1976), Fritsch and Chappell (1980) and Frank (1987) developed their parameterization schemes. Recently, Kain and Fritsch (1990) improved the original Fritsch-Chappell (1980) scheme with respect to the representation of detrainment and variable conservation according to observational and numerical investigations. Grell (1993) introduced downdraft into the

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original Arakawa-Schubert (1974) scheme and made it suitable for mesoscale simulation. These developments benefit the description of mesoscale systems and raise the forecasting ability of mesoscale numerical models.

In contrast to “implicit schemes” of parameterization, “explicit methods” that predict the amount of vapor phase transition by making use of the equations of cloud water, cloud ice *etc.* have been developed. We can not, however, recommend the use of explicit schemes generally in a mesoscale hydrostatic model instead of implicit schemes (Kuo and Low-Nam, 1990). A coupling of implicit and explicit schemes is also effective for the simulation of mesoscale precipitation (Zhang *et al.*, 1988; Molinari and Dudek, 1992). It is, therefore, necessary to find a more suitable convective parameterization for a mesoscale model.

The Japan Spectral Model (JSM), 1988 version (Segami *et al.*, 1989), was used in this study. Originally in this version, the convective adjustment scheme (Gadd and Keers, 1970) is used to remove local instability and describe subgrid-scale precipitation. Because of the drawback of the moist convective adjustment in a fine-mesh model (Frank and Molinari, 1993), three cumulus parameterizations, including the Kuo-Anthes scheme (Anthes, 1977), the Kain-Fritsch scheme (Kain and Fritsch, 1990) and the Arakawa-Schubert scheme (Grell, 1993), were implemented into JSM and were tested to simulate a mesoscale precipitation system associated with the Baiu front. Heavy precipitation in the Kyushu district was brought about by successive development of cloud clusters along the Baiu front during the period from 16 to 17 July 1993. In this study, this case was selected to test the capability of the above four schemes to simulate the mesoscale precipitation associated with the Baiu front.

2. A brief description of the numerical model, convective parameterizations and experimental design

2.1 JSM and the convective parameterizations

JSM is a primitive equation model which was developed for mesoscale numerical prediction by the Japan Meteorology Agency (JMA) (Segami *et al.*, 1989). This is a spectral model working over a limited area. Model variables are represented at 97×97 horizontal grid points and 19 vertical σ levels. In this study, a one-way nesting technique was adopted. The coarse-mesh model had a grid space of 80 km, and the fine-mesh model had a grid size of 40 km. The domain of the fine-mesh model is the same as that shown in Fig. 1 of Segami *et al.* (1989), and that of the coarse-mesh model covered the domain of the fine-mesh model and its surroundings. A semi-implicit time integration scheme for the spectral limited-area is utilized to save compu-

tational time in this version. Surface fluxes are calculated with a bulk method. The Level-2 version of the turbulent closure model is used to calculate vertical diffusion. Ground temperature is forecasted with a 4-layer ground model.

In this study, JMA global objective analysis data were used as initial and boundary conditions for the coarse-mesh model. Moist convective adjustment was adopted in the coarse-mesh model. The results of the coarse-mesh model provided initial and boundary conditions for the fine-mesh model. A normal-mode initialization method was used to eliminate high-frequency gravity waves in the initial field. In addition to the moist convective adjustment, we incorporated three other convective parameterizations into JSM. Brief descriptions of the parameterizations will be given in the following part.

a. The moist convective adjustment

This scheme was described in Gadd and Keers (1970). Neutral air is defined in this scheme with a critical lapse rate of temperature (γ_c) and a critical relative humidity (Rh_c),

$$\gamma_c = \frac{1}{1 - Rh_c} [\gamma_d (1 - Rh) + \gamma_m (Rh - Rh_c)],$$

where γ_d and γ_m are the dry and moist lapse rates of temperature, respectively. If an unstable layer ($\gamma > \gamma_c$) satisfies the condition of $Rh \geq Rh_c$ in the model, it is adjusted to the neutral state ($\gamma = \gamma_c$) without changing the relative humidity at each layer.

b. The Kuo-Anthes Scheme

Anthes (1977) developed a one-dimensional cloud model which is similar to the Kuo (1965) scheme. This scheme correlates the subgrid scale convection to the amount of grid-scale moisture convergence. The vertical heating and moistening profiles of cloud are assumed to be simply a parabolic shape with height, which can be predetermined between cloud top and cloud base. The large-scale convergence of moisture is divided into two parts: moistening the air column and precipitation. The moistening parameter, b , is related to the mean relative humidity ($\overline{Rh}$) in the troposphere, *i.e.*

$$b = \begin{cases} 2(1 - \overline{Rh}), & \overline{Rh} \geq 0.5, \\ 1, & \overline{Rh} < 0.5. \end{cases}$$

It does not consider updrafts and downdrafts in convective clouds.

c. The Kain-Fritsch Scheme

The basic closure assumption is that the convective available potential energy in a grid element will be removed by convective effects within the period of convection being active. Both the effects of updraft and downdraft are considered explicitly in this scheme. Kain and Fritsch (1990) gave a new entraining-detraining plume model of updraft that

Fig. 1. Time series of infrared satellite images of GMS-4 at (a) 0000 UTC, 16 July, (b) 1200 UTC, 16 July, (c) 0000 UTC, 17 July and (d) 1200 UTC, 17 July 1993. Convective cloud clusters that developed around the Kyushu district are indicated by arrows with marks A, B, C, D and E.

allows detrainment of mass and moisture to occur at the mid-levels. It is proved that the detrainment is important for the development of a mesoscale convective system. This plume model provides more realistic cloud-environment interactions and thermodynamic processes than the original entraining model in the Fritsch-Chappell scheme without introducing much more computation. A mixing scheme, which computes the buoyancy variations induced by turbulent mixing in various proportions of clear and cloudy air, is used to determine the rates of updraft entrainment and detrainment. The magnitude and vertical structure of mesoscale cloud, such as the vertical distribution of environmental entrainment, updraft detrainment and total mass flux of updraft are all computed according to local environmental conditions. Both the updraft and downdraft thermodynamics are based on conservation of the equivalent potential temperature θ_e . The downdraft begins at the highest level where a minimum θ_e is located, and ends at the lowest layer of the model. Evaporation is assumed to maintain the relative hu-

midity at 100 % in cloud and 90 % below cloud.

d. The Arakawa-Schubert Scheme

A modified version of the Arakawa-Schubert scheme (Grell, 1993) that includes a moist downdraft is introduced here. The closure assumption is also that a quasi-equilibrium exists between the large-scale changes and changes of available buoyant energy by cumulus convection. It allows for interaction of sub-ensembles of cloud. The specific feature of the AS scheme is the introduction of the spectral cloud ensemble model. Entrainment of environmental air and detrainment of clouds are considered in this model. Both updraft and downdraft are parameterized to balance the large-scale forcing. Once a downdraft is generated, it will go down to the surface. In this version, the cloud-base mass flux of downdraft is considered to be a function of the updraft mass flux and re-evaporation of convective condensation. The efficiency of precipitation depends on the wind-shear. At most, six kinds of clouds are allowed to interact for the present simulation.

Table 1. Summary of numerical prediction experiments.

Expt.	Convective parameterization	Latent heat release
MAt	moist convective adjustment (MA)	yes
KAt	Kuo-Anthes (KA) scheme	yes
KFt	Kain-Fritsch (KF) scheme	yes
ASt	Arakawa-Schubert (AS) scheme	yes
DADt	Arakawa-Schubert (AS) scheme	no

2.2 Experimental design

All of the numerical simulations presented here are the results of the fine-mesh model. As a summary, the main characteristics of the experiments are listed in Table 1. Expts. MAt, KAt, KFt and ASt are simulations with the moist convective adjustment, Kuo-Anthes, Kain-Fritsch and Arakawa-Schubert schemes, respectively. Expt.DADt is called the “dry adiabatic test” in which we performed Expt.ASt without latent heat release of condensation in order to study the impact of latent heating on the Baiu front and associated precipitation. In other words, the model atmosphere is still moist and includes water vapor phase changes. We treat moisture as a passive variable. The latent heat was not added to the thermodynamic equation.

In all the other experiments except Expt.MAt, dry convective adjustment was performed to remove the unstable layers whenever there was a super-adiabatic state in a non-saturated layer.

3. Results

3.1 Observational essentials

According to surface weather charts published by JMA (not shown), from 0000 UTC to 1200 UTC, 16 July 1993, a Baiu front was quasi-stationary over Kyushu. A mesoscale cyclone developed over the China continent. When the meso-cyclone moved eastward, the surface pressure in Kyushu dropped 2.5 hPa during the this 12 hours. At 0000 UTC, 17 July, the surface pressure in Kyushu decreased to 1001 hPa. The central surface pressure of the meso-cyclone dropped to 996 hPa. A large meridional surface pressure gradient was observed until 1200 UTC, 17 July in the Kyushu district.

The infrared satellite imagery from GMS-4 (Fig. 1) reveals a convective cloud cluster (marked by A) was developing to the west of the Kyushu district in the frontal zone at 0000 UTC, July 16 (Fig. 1a). The cloud cluster moved slowly eastward along the Baiu front and was in its mature stage at 0300 UTC,

16 July. When the cloud cluster A began to decay near Kyushu, a new convective cloud cluster B was generated to the west of the Kyushu district (32°N,128.5°E) at 0800 UTC, July 16 (not shown). The cloud cluster B developed rapidly within the next two hours, and moved over Kyushu at 1200 UTC, 16 July (Fig. 1b). This cloud cluster remained there until 0000 UTC, 17 July. The cloud cluster B moved to the east of the Kyushu district (Fig. 1c) after 0000 UTC, 17. Meanwhile, a cloud cluster C developed over the western part of Chugoku. After the frontal cloud moved eastward, another cloud cluster D generated over Kyushu at 0600 UTC, 17 July. This cloud cluster developed over Kyushu rapidly in the next 6 hours, and dominated the Kyushu district for more than 4 hours. Figure 1d shows this strongly developed convective cloud cluster D which had already moved to the east of Kyushu at 1200 UTC, 17 July. A cloud cluster E was developing in the northern part of Kyushu (Fig. 1d) at 1200 UTC, 17 July. This successive development of convective cloud clusters indicates that convective activity was intense in this area. These observational facts show that the heavy rainfalls in the Kyushu district and its surrounding areas were associated with these 5 cloud clusters.

The hourly rainfall rate from AMeDAS (the Automated Meteorological Data Acquisition System) is shown in Fig. 2. Owing to the lack of observations over the sea, the actual rainfall in this figure is limited over the land. The rain area of the cloud cluster B mainly extended over the western part of Kyushu at 1200 UTC, 16 July (Fig. 2a). Heavy rainfall was observed all over the Kyushu island during the period from 1500 UTC, 16 July to 0000 UTC, 17 July. The maximum hourly rainfall was 65 mm h⁻¹ at 1800 UTC, 16 July (Fig. 2b). A large region of rainfall rate more than 20 mm h⁻¹ was sustained for 5 hours in Kyushu, until the cloud cluster B moved to the east of Kyushu at 0000 UTC, 17 July. At 0000 UTC, 17 July, an hourly rainfall of 30 mm

Fig. 2. Rainfall rate (mm h^{-1}) observed by AMeDAS at (a) 1200 UTC, 16 July, (b) 1800 UTC, 16 July, (c) 0000 UTC, 17 July, (d) 0600 UTC, 17 July and (e) 1200 UTC, 17 July 1993. The contour levels are 1, 2, 5, 10, 20, 40 and 80 mm h^{-1} . Shaded areas show rainfall rate larger than 10 mm h^{-1} .

was observed in the western part of Chugoku, which was associated with the cloud cluster C (Fig. 2c). The development of the cloud cluster D in Kyushu brought another heavy rainfall from 0600 UTC to 1000 UTC, 17 July (Fig. 2d). When the cloud cluster E moved into the Kyushu district at 0900 UTC, 17 July, the next heavy rainfall began in the northern part of Kyushu. The precipitation of the cloud cluster E intensified while the cloud cluster slowly propagated southeastward along the Baiu front. A strong rainfall of 80 mm h^{-1} in Kyushu was observed at 1200 UTC, 17 July (Fig. 2e). The rainfall associated with these cloud clusters was successive in Kyushu during the period from 0000 UTC, 16 to 1200 UTC, 17 July 1993.

Figure 3 shows the JMA global objective analysis (GANAL) of surface wind, temperature and sea level pressure at 1200 UTC, 16 July 1993. In Fig. 3,

a cold northeasterly came from the sea of Okhotsk, and converged with a warm southwesterly around Kyushu. The convective cloud clusters developed around the surface convergence. A vertical cross section of equivalent potential temperature θ_e , and absolute momentum M along 130.5°E at 1200 UTC, 16 July is shown in Fig. 4. The absolute momentum M is defined as $fy - u$, following Eliassen (1962), in the meridional cross section, where f is the Coriolis parameter, y the distance from the southern end of the section and u is the zonal component of horizontal wind. A convectively unstable region ($\partial\theta_e/\partial p > 0$) and concentrated M -lines are found in the convective region of $32^\circ\text{N}\sim 33^\circ\text{N}$, where the cloud cluster B developed.

3.2 Results of numerical simulation

By using JSM with the convective parameterizations mentioned in Section 2, we performed simu-

Fig. 3. JMA global objective analysis (GANAL) of surface wind (vector, in m s^{-1}), temperature (dashed lines, with a contour interval of 1°C) and sea level pressure (solid lines, with a contour interval of 1 hPa) at 1200 UTC, 16 July 1993.

lation experiments of the successive development of the cloud clusters associated with the Baiu front, which brought a large amount of rainfall in western Japan between 0000 UTC, 16 July and 1200 UTC, 17 July 1993. All simulations were initiated at 0000 UTC, 16 July 1993.

a. Surface frontal system

Figure 5 exhibits the horizontal distributions of simulated surface wind vectors, surface temperature and sea level pressure at 1200 UTC, 16 July 1993 obtained from the four experiments with different convective parameterizations. Generally, all of the four experiments gave the proper position of the mesocyclone (centered at 123°E , 37°N in the Yellow sea) and the Baiu front. A strong, cold wind from the sea of Okhotsk along the east coast of the Asian Continent and the strong southwesterly to the west of sub-tropical high were all well simulated in the four experiments. The four schemes provided adequate description of the synoptic field. If we define the Baiu front by the discontinuity of horizontal wind, the predicted Baiu front corresponds well to the observation.

b. Precipitation and the evolution of cloud clusters

In order to examine the impact of convective parameterizations on the Baiu frontal precipitation, we will use the simulated rainfall in this subsection. The hourly rainfall rate averaged over an area from 126°E to 132°E and from 31.5°N to 33°N is shown in Fig. 6. The total rainfall (Fig. 6a) was considerably different between the four parameterizations. The Arakawa-Schubert (AS) scheme predicted the strongest rainfall rate and sustained con-

Fig. 4. Vertical cross section along 130.5°E of GANAL equivalent potential temperature θ_e (dashed lines, K) and absolute momentum M (thick solid lines, m s^{-1}) at 1200 UTC, 16 July 1993.

siderable rainfall intensity until the end of the simulation. The moist convective adjustment (MA) scheme gave the weakest rainfall intensity and it decreased to almost zero after 1800 UTC, 16 July. The Kain-Fritsch (KF) scheme produced a peak value of precipitation at 1200 UTC, 16 July, but its rainfall intensity also decreased to almost zero after 1800 UTC, 16 July. The Kuo-Anthes (KA) scheme predicted almost constant rainfall intensity of about 2 mm h^{-1} during the simulation period.

To present the rainfall features produced by the different convective parameterization schemes, we will, hereafter, refer to the subgrid-scale rain as “convective rainfall”, and to the grid-scale rain as “large-scale rainfall”. In Figs. 6b and 6c, both the AS and KA schemes sustained the convective rainfall throughout the simulation period, while the large-scale rainfall decreased considerably after 1800 UTC, 16 July. The precipitation in Expt.ASt was mainly convective in the region where cloud clusters developed. The total averaged rainfall amount in Expt.ASt is also in accord with the heavy rain in western Japan of this period. Expt.KAt showed that the precipitation was mainly convective in the model domain and its large-scale rainfall was almost zero throughout the simulation. The precipitable water was mainly consumed as convective rain in the KA scheme. These results suggest that the KA scheme is easily activated and consumes most of the available water vapor of large-scale convergence as convective precipitation. As a result, it leaves little water vapor for large-scale condensation. This is a weak point of the KA scheme, which can not distribute water vapor properly. In contrast, most precipitation was as large-scale rainfall and the

Fig. 5. Surface wind (m s^{-1}), temperature (dashed lines, in $^{\circ}\text{C}$) and sea level pressure (solid lines, hPa) at 1200 UTC, 16 July 1993, which are predicted in experiments (a) AS, (b) KF, (c) KA, and (d) MA. The contour intervals for surface temperature and sea level pressure are 4°C and 2 hPa, respectively. The square in (a) indicates the area of averaging of Fig. 6.

convective rainfall was approximately 0 mm h^{-1} in Expt.MA.

Figure 7 shows the simulated horizontal distributions of hourly rainfall rate obtained from Expts. AS, KF, KA and MA at 12, 24 and 36-hour. The mesoscale precipitation pattern in Expt.AS corresponds to the convective cloud clusters (Fig. 1) around Kyushu. The maximum hourly rainfall rate was more than 22 mm h^{-1} after 12 hours. This rainfall corresponds to the cloud cluster B in Fig. 1b. The intense mesoscale precipitation was simulated in the Kyushu district throughout the simulation period. This is the most obvious feature of the experiment with the AS scheme and is consistent with the successive development of cloud clusters. There are, on the other hand, some discrepancies between results and observation. Expt.AS predicted a considerable precipitation area to the west of Kyushu at 0000 UTC and 1200 UTC, 17 July, while the GMS images of this time (Fig. 1) show almost no significant convective cloud in the area.

The KA scheme also simulated precipitation around Kyushu (Fig. 7b), but the amount of precipitation was very small and its pattern is different from cloud the pattern of GMS images (Fig. 2). This suggests that the large-scale moisture convergence

is not sufficient to account for the mesoscale heavy rainfall in this case. In the KA scheme, the latent heat release is assumed to be parabolic with height within the cloud body. The heating and moistening profiles largely influence rainfall rate. This can also be a reason for the inaccuracy of simulated precipitation in Expt.KA.

While the KF and MA schemes simulated the heavy rain in the Kyushu district at 12 hours (Figs. 7c and 7d), they failed to simulate the feature of the successive development of cloud clusters. The main rain area moved quickly eastward away from Kyushu. Almost no rain in Kyushu was predicted after 12 hours with the KF and MA schemes.

c. Sensitivity of cloud types in the AS scheme

In the AS scheme, the precipitation and latent heating are parameterized using a spectral cumulus ensemble model considering the effects of updraft and downdraft. Three sensitive numerical simulations with only two of the six types of clouds in the AS scheme were also carried out (not shown) to test the importance of cloud interaction. All of the three tests failed to simulate the precipitation pattern which was simulated in Expt.AS in western Japan. One kind of cloud can only account for

Fig. 6. Time series of averaged hourly rainfall rate over the area of 126°E to 132°E, 31.5°N to 33°N in the experiments with the four convective parameterizations listed in Table 1. (a) total rainfall rate, (b) convective rainfall rate, and (c) large-scale condensation rate.

a part of the rainfall. The distribution of rain varied greatly in the three sensitivity tests. This shows that the multi-scale interaction of clouds is important to the Baiu frontal precipitation.

d. The vertical structures of cloud clusters and the Baiu front

To illustrate structures of the cloud clusters and the Baiu front simulated in the experiments with different parameterization schemes, we show the vertical cross sections of equivalent potential temperature θ_e , wind vectors, latent heating and absolute momentum M averaged in the zonal direction between 130°E and 132°E at 1200 UTC, 16 July 1993 in Fig. 8. There are some common features between the four experiments. A moist, warm airmass was located below 800 hPa on the south side of each panel. A dry, cold airmass was quite deep and dominated the lower troposphere to 500 hPa on the north side with a minimum θ_e at the surface. The Baiu front was formed between the two airmasses although it was broad and characterized by a weak horizontal temperature gradient. The cloud clusters were also developed between the two airmasses. High humidity regions, where condensation occurred, are shaded to show possible clouds. In addition to the warm airmass and the cold airmass, a mid-tropospheric low- θ_e airmass was present from 850 hPa to 300 hPa over the warm airmass on the south side of the front.

Thermodynamic features of the cloud clusters were strongly affected by the parameterization of convection. The result of Expt.ASt (Fig. 8a) shows that the absolute momentum M -lines were well concentrated in the frontal zone, which shows large horizontal wind shear. They were almost vertical and parallel to θ_e -lines within the cloud band from 900 hPa up to 500 hPa. An intense vertical ascent was present within the Baiu frontal cloud cluster. A maximum in vertical motion is located at 500 hPa. The location of latent heat release indicates that the precipitation in the Baiu front generally occurred in the frontal zone and immediately adjacent to the warm air where vertical ascent was intense. The vertical distribution of θ_e -lines suggested convective neutrality ($\partial\theta_e/\partial p = 0$) in the lower and middle levels of the cloud cluster. The thick convective neutrality resulted from convective mixing produced by convection.

A similar structure of the Baiu front was obtained from Expt.KFt (Fig. 8b). Compacted M -lines were also evident in this experiment. The convective neutrality was also obviously simulated in the cloud cluster.

In contrast to Expts.ASt and KFt, Expt.KAt (Fig. 8c) produced a deeper warm airmass which was convectively unstable below 700 hPa in the frontal zone and on its south side. The M -lines was not concentrated so tightly in frontal cloud region, which indicates horizontal shear was smaller along the Baiu front than in Expt.ASt. The strongest vertical motion was located at an upper level (400 hPa) of the troposphere.

The MA scheme produced a convectively neu-

Fig. 7. Simulated hourly rainfall rate around the Kyushu district with (a) AS, (b) KA, (c) KF and (d) MA schemes at 12 hours, 24 hours and 36 hours. The contour levels are 2, 5, 10 and 20 mm h⁻¹.

tral layer between 700 hPa and 900 hPa in the frontal cloud band (Fig. 8d). It was not so evident in Expt.MAt that *M*-lines concentrated in the frontal zone. While the airmasses to the south of the Baiu front were convectively unstable below 700 hPa, the atmosphere to the north of the Baiu front was convectively stable. The largest ascent was located at 700 hPa, which is the lowest level for the four schemes. In comparison with the other three schemes, Expt.MAt predicted a much wider moist region.

The latent heating patterns are largely different from each other in the four simulations. The latent heatings in Expts.ASt and KFt were rather similar. They had a maximum value of about 7 K h⁻¹. The heating intensity in Expt.KAt was about 2 K h⁻¹ which was much smaller than that in Expt.ASt. The maximum heating center was located at 400 hPa, higher than that in Expt.ASt. A heating intensity of 4 K h⁻¹ was located at 700 hPa in Expt.MAt. Because the precipitation was mainly due to the large-scale condensation in Expt.MAt, the latent heating was also mainly large-scale, which concentrated at a lower level. The heat release occurred in the south-

ern part of the moist region (about 31.5°N).

A vertical uniform distribution of moist static energy $h = c_p T + gz + Lq$ was predicted in Expt.ASt (Fig. 9), where c_p is the specific heat at constant pressure for dry air and L the latent heat of condensation. In contrast, the KA scheme failed to simulate the vertical homogeneous structure of the moist static energy. A thick static unstable layer formed under 700 hPa in the frontal cloud of Expt.KAt. The most obvious difference of h is located where the convection was active. It suggests that the convection in the KA scheme can not effectively prevent the moist static energy from accumulating locally, even in the center of a convective region. In the AS scheme, the convection is based on the energy. The rate of available potential energy supplied by large-scale systems determines the development of mesoscale convection. In other words, convection consumes available potential energy and redistributes moisture and heat vertically according to their budget equations. In contrast, the vertical distributions of heating and moistening are simply assumed to be parabolic shape functions with height in the KA scheme. This simple assumption redis-

Fig. 8. Vertical cross sections of zonally averaged equivalent potential temperature θ_e (dashed lines, K), absolute momentum M (thin solid lines, m s^{-1}) and total latent heating (thick solid lines, K h^{-1}) between 130°E and 132°E at 1200 UTC, 16 July 1993 in (a) Expt.ASt, (b) Expt.KFt, (c) Expt.KAt, and (d) Expt.MAt. The vectors denote vertical motion (hPa h^{-1}) and meridional motion v (m s^{-1}). Shaded regions are possible cloud body with high relative humidity.

tributed moisture inadequately and caused insufficient moistening in the middle level of the troposphere. Consequently, the low-level unstable layer remained.

e. Impact of latent heating on Baiu front

Ignoring the latent heat release in the thermodynamic equation, we carried out a sensitivity test (Expt.DADt) with the same initial fields and parameterization as in Expt.ASt. Little rain was simulated in the Kyushu district, as shown in Fig. 10a. On average, Expt.DADt predicted only 15 % of the total rainfall of Expt.ASt. It suggests that the latent heating is important for sustaining rainfall along the Baiu front. Though the unstable layer was quite thick in the lower frontal zone (Fig. 10b), vertical convection was not excited. The precipitation was totally large-scale rainfall. It shows that a positive

interaction between latent heating and convection existed in the development of the cloud clusters. The convectively neutral state in the lower and middle levels was not formed. The moist static energy largely concentrated in the lower level, and formed a deep static unstable layer. The cloud pattern in Expt.DADt was different from that in Expt.ASt. No significant vertical ascent occurred in the frontal zone.

4. Discussion

4.1 Comparison of the four experiments

The four simulations with the four different convective parameterizations showed that the simulated synoptic patterns were generally similar to each other and corresponded to the weather charts. The meso-cyclone over the Yellow sea, location and movement of the Baiu front, and the associated syn-

Fig. 9. Vertical cross section of the moist static energy ($10^{-3} \text{ J kg}^{-1}$) averaged between 130°E and 132°E of Expts. ASt (solid) and KAt (dash) at 1200 UTC, 16 July 1993.

optic rainfall distributions were generally similar to each other. In this paper, however, we focused on the mesoscale precipitation associated with the Baiu front and found that a significant difference was observed between the four experiments. In particular, the simulation of the successive development of the Baiu frontal mesoscale cloud clusters was sensitive to the convective parameterization.

The Baiu front is characterized by a weak baroclinic forcing and a significant convective instability due to the strong warm and moist southwesterly in the lower troposphere (Figs. 5 and 8). A sophisticated parameterization is necessary to simulate this type of precipitation. As far as this study is concerned, the experiment with the AS scheme was mostly successful in simulating the precipitation which corresponds to the successively developed cloud clusters. Expts. MAT and KFT simulated well the eastward-moving precipitation system associated with a mesoscale cyclone. These, however, failed to simulate the precipitation under question in this study. Although successive rainfall is simulated in Expt. KAT, the rainfall amount was too small to compare with the observations (see Figs. 2 and 7). The result shows that the large-scale water vapor convergence was not enough to account for the mesoscale precipitation.

In the AS scheme, convection is parameterized by considering a spectrum of clouds. The effects of both updraft and downdraft are calculated in the process of convective cloud activation. Entrainment and detrainment are allowed to make an interaction between the cloud and cloud environment. The realistic result of the Baiu frontal precipitation produced by the AS scheme is, therefore, attributed to the

Fig. 10. (a) Hourly rainfall rate (mm h^{-1}) and (b) vertical cross section of θ_e (dashed lines, K), M (thick solid lines, m s^{-1}), possible cloud and flow averaged between 130°E and 132°E of Expt. DADt at 1200 UTC, 16 July 1993.

detailed and adequate parameterization of convective cloud. This was also revealed by the sensitivity experiments in which the number of cloud types in the AS scheme was reduced to two. None of these experiments simulated the precipitation pattern simulated in Expt. ASt.

We could infer that the sophisticated parameterization of convection is essential for simulations of precipitation in a weakly forced and convectively unstable system such as the Baiu front.

We must note that the performance of cumulus parameterization may be different from case to case. We, however, learned that the AS scheme performed better than the other three schemes in this case study. Kuo and Low-Nam (1990) also suggested that the AS scheme produced realistic rapid development of cyclones. The detailed consideration of the spectrum of cumulus cloud is one of the factors that the AS scheme successfully predicted the rainfall associated with the successive development of cloud clusters over the Kyushu district.

4.2 Effects of latent heating

In comparing with the analysis (Fig. 4), the basic distribution of airmasses around the Baiu front was simulated in Expt.DADt (Fig. 10b). The mesoscale structure was, however, quite different. Expt.DADt (Fig. 10) also shows that the evolution of flow structure and precipitation in the frontal zone largely depended on the latent heat release. This is similar to other mesoscale precipitation systems (Kuo *et al.*, 1988; Kuo and Low-Nam, 1990; Peng and Cheng, 1994).

As shown in Fig. 8, the latent heat release of all the four schemes was located in the frontal zone or to the immediately south. The latent heating is essential for the enhancement of ascent in the frontal zone. Strong ascent in the frontal zone produced further condensation and precipitation. The different distributions of latent heating of the four schemes largely affected the flow structure of the Baiu front. The latent heat release in the frontal zone increased positive vorticity and enhanced frontogenesis at the lower level.

The simulated frontal structure noticeably varied with the heating pattern in the cumulus parameterizations (Fig. 8). The AS and KF schemes predicted strong vertical motion in the frontal region, while weak ascent was produced in Expt.MAt. It shows that the impact of convection on a large-scale environment is sensitive to the vertical distribution of latent heating. In other words, the intensity and vertical distribution of simulated ascent in the frontal zone are sensitive to the convective parameterization.

Although convective instability existed in the lower troposphere of the frontal zone, weak vertical ascent was produced in Expt.MAt. The redistribution of θ_e can not be successfully carried out by the convection. In the MA scheme the state after the moist convective adjustment is neutral with a critical lapse rate. Redistribution of heat and moisture by convection can not be properly arranged in the frontal cloud cluster, which might further influence the development of convection in the MA scheme.

5. Summary and conclusions

In this study, the impact of convective parameterizations on the simulation of a mesoscale precipitation associated with the Baiu front has been examined using JSM. The case used for this study was of heavy precipitation caused by the successive development of cloud clusters over western Japan during the period from 0000 UTC, 16 to 1200 UTC, 17 July 1993. Four convective parameterizations, the AS, KF, KA and MA schemes, were tested in four simulation experiments. All the four experiments simulated the synoptic scale features well. They, however, gave different features with respect to the mesoscale precipitation. It was shown that

the mesoscale precipitation and structure of cloud clusters associated with the Baiu front were sensitive to the convective parameterization.

The experiment of the AS scheme simulated well the mesoscale precipitation caused by the successive development of cloud clusters developed along the Baiu front. We performed some sensitivity tests in which the cloud types of the AS scheme were reduced to two types. None of them simulated the mesoscale precipitation which was predicted in Expt.ASt. The mesoscale rainfall in Expt.ASt was the integral effect of the cloud ensembles. The detailed parameterization of clouds in the AS scheme was essentially important for simulation of the mesoscale precipitation associated with the Baiu front which is characterized by a weak baroclinic forcing and a significant convective instability.

Though successive precipitation was also simulated by the KA scheme, the rainfall was weak and the precipitation pattern was different from the observation, because the large-scale moisture convergence was not sufficient to account for the heavy mesoscale rainfall in this case. The precipitation produced by the KA scheme was mostly convective. This suggests that the convection in the KA scheme consumed most of the vapor in the convective rainfall.

The KF scheme predicted heavy rainfall in the first 18 hours of simulation. It was able to redistribute grid-scale properties quite well, and produced a similar large-scale rainfall and frontal structure as the AS scheme. The precipitation system, however, moved eastward rapidly after that time and this experiment failed to predict the successive development of cloud clusters in western Japan.

The MA scheme produced little convective rainfall in this case. Most precipitation in this experiment was the grid-scale condensation in the Kyushu area. The experiment of the MA scheme did not predict the mesoscale feature of precipitation caused by the successive development of cloud clusters over the Kyushu district.

The diabatic process largely affected the structure of cloud clusters and the mesoscale structure of the Baiu front. Corresponding to the latent heating, strong ascent was simulated in the frontal zone by the AS scheme. The latent heating was mainly located at 850 hPa $\sim$ 300 hPa, with a peak at 500 hPa. A convectively neutral state was predicted in the middle of the troposphere in the cloud clusters developed along the Baiu front in Expt.ASt. The redistribution of heat and moisture by the vertical convection produced the convectively neutral state. Tightly concentrated *M*-lines in the Baiu frontal zone in Expt.ASt show large positive vorticity.

Compared with the AS scheme, the KA and MA schemes produced weaker ascent in the frontal band. Less-concentrated *M*-lines in the Baiu front were

shown in both Expts.KAt and MAt. Though convection was active in the KA scheme, no convectively neutral air was predicted in the frontal zone, because the latent heating and moisture are arbitrarily distributed. The departure of the peak value of prescribed heating (or moistening) profile from the actual one in vertical levels led to a local accumulation of θ_e and h . A strong convectively unstable layer was formed in the lower troposphere in Expt.KAt. Little convective precipitation and very thin convectively neutral air were predicted in Expt.MAt.

A sensitivity test of latent heat release in thermodynamic equation (Expt.DADt) shows that the precipitation and flow structure of Baiu frontal zone were largely affected by the diabatic process. Without latent heat release, almost no ascent was predicted in the frontal zone and the frontal precipitation was reduced to 15 %. A positive interaction between the diabatic heating and the convection was important for the mesoscale precipitation of the Baiu front.

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梅雨前線に伴うメソスケールの降水に対する対流の パラメタリゼーションのインパクト

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日本域スペクトルモデル (JSM) に、湿潤対流調節の他に、Kuo-Anthes (KA)、Kain-Fritsh (KF)、Arakawa-Schubert (AS) の 3 つのパラメタリゼーションを組み込み、1993 年 7 月 16~17 日に西日本で見られた梅雨前線に伴って連続的に発達したクラウドクラスターについてシミュレーションを行なった。これら 4 種類のパラメタリゼーションを用いた数値実験は、低気圧や前線の位置などの総観規模の全体的な様相についてはどれもよくシミュレートした。しかしながら、梅雨前線に伴うメソスケールの降水は対流のパラメタリゼーションに敏感であった。この期間、九州地方では連続して発達したクラウドクラスターによって強い降水がもたらされた。この特徴は、AS の方法を用いたモデルでシミュレートされたが、そのほかのものではこれが十分表現されなかった。次に AS のパラメタリゼーションの雲のタイプを 2 個に減らし、敏感度テストを行った。その結果はどれもこのようなメソスケールの降水を表現することができなかった。これらの結果は、傾圧性が弱く対流不安定が強いことで特徴づけられる梅雨前線とそれに伴うメソスケールの降水のシミュレーションには、AS スキームのような詳細な対流のパラメタリゼーションが必要であることを示している。また、AS スキームにおける潜熱についての敏感度テストも行ない、梅雨前線の構造が潜熱加熱の仕方により大きく影響を受けることを示した。

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