High Resolution Modeling of Multi-scale Cloud and Precipitation Systems Using a Cloud-Resolving Model

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The atmospheric water circulation of Earth is characterized by cloud and precipitation systems. They occasionally have a multi-scale structure ranging from the cloud-scale to the synoptic-scale. Each element of the multi-scale structure has individual roles to redistribute water in the atmospheric water circulation. The purpose of this research is explicit simulations of clouds and their organized systems using a cloud-resolving model in large domain and very fine grid system. In this research, we utilized the Cloud Resolving Storm Simulator (CReSS), which is a cloud-resolving model developed for the Earth Simulator. Using CReSS on the Earth Simulator, we performed simulation experiments of important cloud and precipitation systems in East Asia; multi-scale Baiu frontal lows, a localized heavy rainfall system associated with the Baiu front, typhoon and associated precipitation bands, and snow-cloud bands in cold air streams over the sea. These experiments showed both very detailed structure of individual clouds and overall structures of the cloud systems. The results clarified detailed structures and dynamics of cloud and precipitation systems, the roles of individual elements of the cloud systems, and interactions between clouds and their organized precipitation systems. This project also contributes for accurate prediction of localized heavy precipitation and disaster prevention.

Keywords: CReSS, multi-scale cloud system, localized heavy rain, typhoon, Baiu front, snow clouds

1. Introduction

Water vapor in the atmosphere is redistributed by cloud systems into the moisture in the atmosphere and precipitation. The cloud systems occasionally have a multi-scale structure ranging from clouds to synoptic-scale systems. Each element of the multi-scale structure has individual roles to redistribute water in the atmospheric water circulation. In particular, conspicuous cloud systems are usually composed of convective clouds such as the Baiu front, typhoon, and winter snow storms.

In order to perform simulations and numerical experiments of the cloud systems, we have been developing a cloud-resolving numerical model named "the Cloud Resolving Storm Simulator" (CReSS). Since the multi-scale structure of the cloud system has wide range in horizontal scale, a large computational domain and a very high resolution grid to resolve individual classes of the multi-scale structure are necessary to simulate evolution of convective cloud systems. It is also required to formulate accurately cloud physical processes as well as the fluid dynamic and thermodynamic processes. For this type of computation, a large parallel computing with a huge memory is necessary.

The purpose of this research is explicit simulations of clouds and their organized systems in a large domain (larger than 1000 × 1000 km) with resolving clouds using a very fine grid system (less than 1 km in horizontal). This will clarify a detailed structure of water circulation in the atmosphere, the roles of individual elements of the cloud systems, the relationship between clouds and their organized precipitation systems, and so on.

In this research, we have improved CReSS to be optimized for the Earth Simulator. Objectives of the study are detailed simulations of the cloud and precipitation systems associated with the Baiu front, a typhoon and its associated precipitation bands, and cloud bands and their related disturbances in cold air streams over a sea. In this paper, we will describe the basic formulation and characteristics of CReSS, and results of the simulation experiments.

2. Description of CReSS

The basic formulation of CReSS is based on the non-hydrostatic and compressible equation system with terrain-following coordinates. Prognostic variables are three-dimensional velocity components, perturbations of pressure and potential temperature, sub-grid scale turbulent kinetic energy (TKE), and cloud physical variables. A finite difference method is used for the spatial discretization. The coordinates are rectangular and dependent variables are set on a staggered grid: the Arakawa-C grid in horizontal and the Lorenz grid in vertical. For time integration, the mode-splitting technique is used.

Cloud physical processes are formulated by a bulk method of cold rain, which is based on Lin et al. (1983), Cotton et al. (1986), Murakami (1990), Ikawa and Saito (1991), and Murakami et al. (1994). The bulk parameterization of cold rain considers water vapor, rain, cloud, ice, snow, and graupel. Parameterizations of the sub-grid scale eddy motions in CReSS are one-order closure and the 1.5-order closer with turbulent kinetic energy (TKE). In the latter parameterization, the prognostic equation of TKE is used. CReSS implemented the surface process formulated by a bulk method.

Several types of initial and boundary conditions are available. For a numerical experiment, a horizontally uniform initial field provided by a sounding profile will be used with an initial disturbance of a thermal bubble or random noise. Boundary conditions are rigid wall, periodic, zero normal-gradient, and wave-radiation type.

CReSS enables to be nested within a coarse-grid model and performs a prediction experiment. In the experiment, initial field is provided by interpolation of grid point values and boundary condition is provided by coarse-grid model. For a computation within a large domain, conformal map projections are available. The projections are the Lambert conformal projection, the polar stereo-graphic projection and the Mercator projection.

For parallel computing of a large computation, CReSS adopts two-dimensional domain decomposition in horizontal. Parallel processing is performed using the Massage Passing Interface (MPI). Communications between the individual processing elements (PEs) are performed by data exchange of the outermost two grids. The OpenMP is optionally available.

The readers can find the more detailed description of CReSS in Tsuboki and Sakakibara (2001) or Tsuboki and Sakakibara (2002).

3. Optimization for the Earth Simulator

Since the CReSS model is originally designed for parallel computers, no essential modification of the code was necessary to be optimized for the Earth Simulator. We, however, updated CReSS from the code of Fortran 77 to Fortran 90. Communication procedures between nodes using MPI were also improved to be more efficient. For the intra-node parallel processing, the OpenMP was introduced.

We evaluated the performance of CReSS on the Earth Simulator. The result is summarized in Table 1. The parallel operation ratio was measured using 128 nodes (1024 CPUs) and 64 nodes (512 CPUs) of the Earth Simulator.

After the performance test of CReSS, we performed simulation experiments of multi-scale cloud and precipitation systems which are important atmospheric water circulation systems in East Asia.

4. Snow cloud bands

When outbreak of a cold and dry polar airmass occurs over the sea, many cloud streets or cloud bands form in the polar air stream. Large amounts of sensible heat and latent heat are supplied from the sea to the atmosphere. Intense modification of the airmass results in development of the mixing layer and convective clouds develop to form the cloud bands along the mean wind direction. Their length reaches an order of 1000 km while individual convective cells have a horizontal scale ranging from a few kilometer to a few tens kilometers. In order to perform a 3-dimensional simulation of cloud bands, a large computation is necessary. In order to study the detailed structure of convective cells and their organized cloud bands, we performed 3-dimensional simulation using CReSS on the Earth Simulator.

The design for the experiment is summarized in Table 2. The initial condition was provided by a sounding observed on the east coast of Canada at 06 UTC, 8 February 1997.

The calculation domain in this simulation is 457 km and 153 km in x- and y-directions, respectively with a horizontal grid spacing of 300 m. Sea ice is placed on the upstream side. Each grid is occupied by ice or open sea according to the probability of sea ice or sea ice density. In the experiment, density of sea ice is 100% for x = 0 – 30 km and decreases linearly to 0% at x = 130 km and open sea of 1˚C extends for x = 130 – 457 km.

The atmosphere over the packed ice is stably stratified and the vertical shear is large. Mixing layer develops with the distance from the edge of the packed ice. The cloud bands develop within the mixing layer. Figure 1 shows for-

Table 1 Evaluation of the performance of CReSS on the Earth Simulator.

Vector Operation Ratio	99.4%
Parallel Operation Ratio	99.985%
Node number to use	128 nodes
Parallel efficiency	86.5%
Sustained efficiency	33%

Table 2 Experimental design of the snow cloud bands in the cold air stream.

domain	x 457 km, y 153 km, z 11 km
grid number	x 1527, y 515, z 73
grid size	H 300 m, V 50 – 150 m
integration time	20 hrs
node number	32 nodes (256 CPUs)

mation and development of cloud bands over the sea. They begin to form the region of sea ice density of 50 – 70% and intensify with a distance. A large number of cloud bands form on the upstream side. Some cloud bands merge each other and selectively develop. Consequently, the number of lines decreases with the distance along the basic flow.

Close view of the upstream region (Fig. 2) shows upward and downward motions are almost uniform in the x-direction. As a result, cloud ice and precipitation extend in the x-direction uniformly. This indicates that the convections are the roll convection type in the upstream region.

In the downstream region, the roll convections change to alignment of cellular convections (Fig. 3). While the upward motions are centered and downward motions are located on their both side, cloud and precipitation show cellular pattern. In this region, the mixing layer fully developed and the vertical shear almost vanishes in the mixing layer. In the region of far downstream, convections change to randomly distributed cells. Band shape of cloud almost disappears and convections become closed cell type.

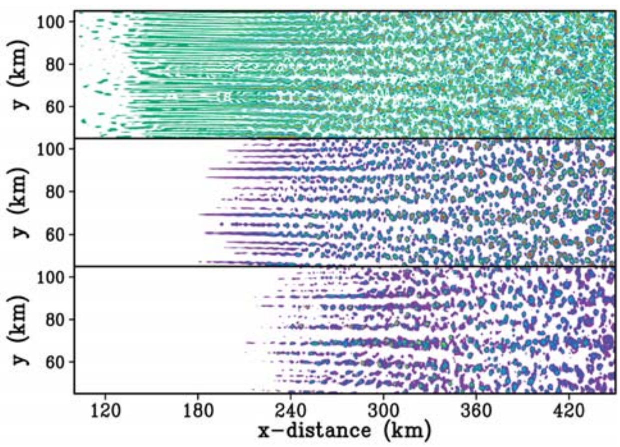

Fig. 1 Horizontal cross sections of vertical velocity (upper panel), mixing ratio of precipitation (snow, graupel and rain) (middle panel) at 1000 m in height and mixing ratio of cloud ice at 1300 m in height (lower panel) for x = 100 – 450 km at 18 hours from the initial time.

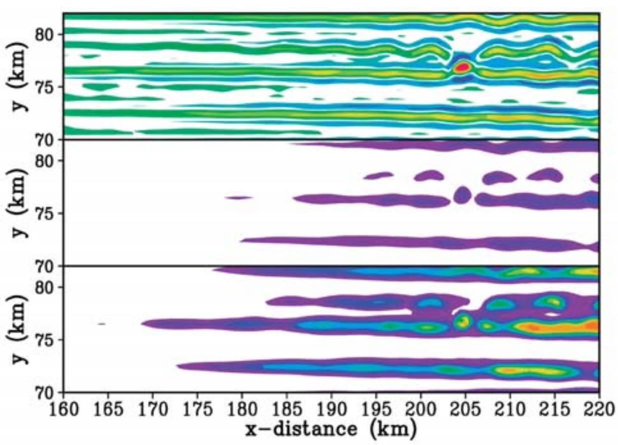

Fig. 2 Horizontal cross sections of vertical velocity (upper panel), mixing ratio of precipitation (middle panel) at 900 m in height and mixing ratio of cloud ice at 1100 m in height (lower panel) for x = 160 – 220 km.

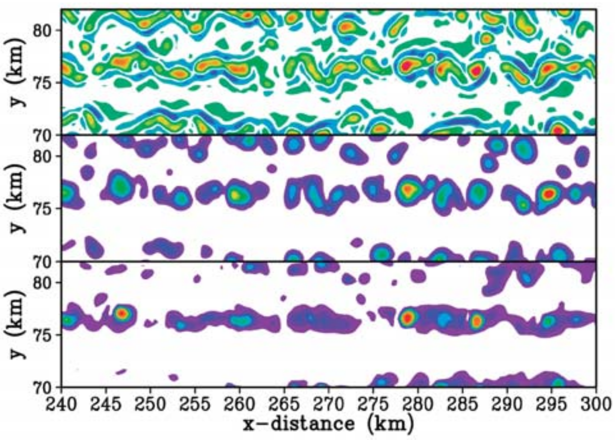

Fig. 3 Horizontal cross sections of vertical velocity (upper panel), mixing ratio of precipitation (middle panel) at 1000 m in height and mixing ratio of cloud ice at 1300 m in height (lower panel) for x = 240 – 300 km.

The morphological transformation from alignment of cells to random cells is often observed by satellite. The experiment successfully simulates the formation process of cloud bands, their extension and merging processes, and the morphological changes of convection from the roll to cellular types.

5. Multi-scale systems in Baiu front

Since 1970's, it has been recognized that a low with a horizontal scale of 1000 km develops along the Baiu front and causes heavy rainfall. In the present study, we will refer to the low as the sub-synoptic-scale low (SSL). SSLs are one of classes of a hierarchical structure or multi-scale structure of the Baiu frontal system. However, the relationship of SSL and heavy rain is still unclear.

In order to understand the multi-scale structure of the precipitation system along the Baiu front, a simulation experiment of Baiu frontal lows and associated heavy rain is performed using CReSS. The experimental design is summarized in Table 3. The initial time is 12 UTC, 06 June 2003 and 24-hour experiment was performed. The initial and boundary conditions are provided by the JMA objective analysis every 6 hours. The real topography and observed sea surface temperature were used.

The result of the simulation shows that a mesoscale low

Table 3 Experimental design of the Baiu frontal system and associated heavy rain observed on 7 June 2003.

domain	x 1020 km, y 1024 km, z 18 km
grid number	x 2040, y 2048, z 63
grid size	H 500 m, V 100 – 300 m
integration time	24 hrs
node numbers	128 nodes (1024 CPUs)

(ML) develops within the SSL (Fig. 4) between Okinawa Island and the Miyako Islands. The horizontal scale of the ML is about 200 km. The ML develops along a shear line which forms between the easterly on the north side and the southwesterly on the south side. Its central pressure at the surface is 996 hPa at 05 UTC, 7 June 2003.

The ML has a long rainband which extends westward from the center of the ML. Close view of the rainband (Fig. 5) shows detailed structure of the rainband. It develops along the shear line of the mesoscale front and is composed of convective cells. Figure 6 shows a magnified view of the convective cells embedded within the rainband. Each cell has a horizontal scale of about 10 km and develops up to a height of about 10 km. The simulation shows the very detailed structure of the convective cells as well as mesoscale and sub-synoptic scale features without nesting technique.

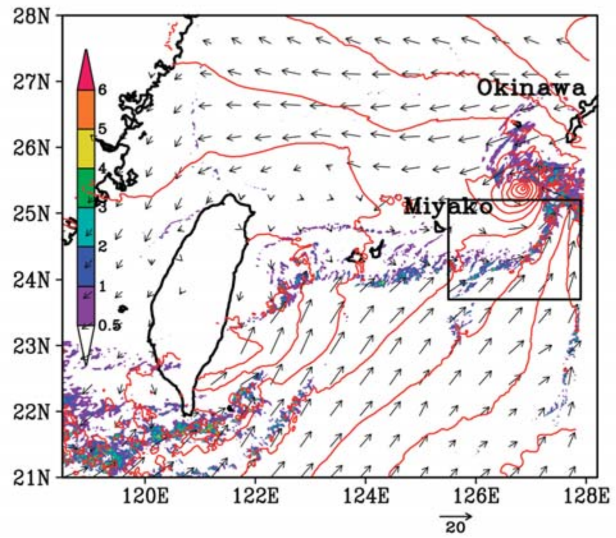

Fig. 4 Mixing ratio of rain water (grey scale; g kg^{-1}), pressure (contour lines every 1 hPa), and horizontal velocity (arrows) at a height of 289 m at 17 hours from the initial time in the simulation experiment.

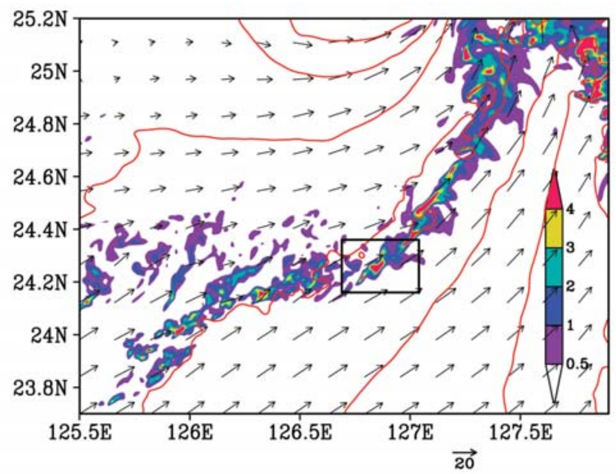

Fig. 5 As in Fig. 4, but for a close view of the rainband at a height of 1000 m. The area of the figure is indicated by the rectangular in Fig. 4.

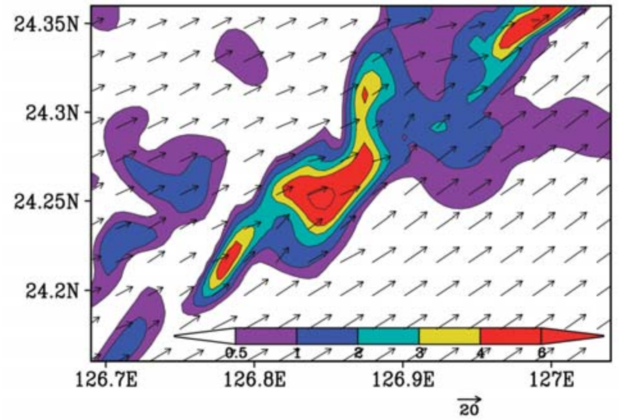

Fig. 6 Mixing ratio of rain water (grey scale; g kg^{-1}), and horizontal velocity (arrows) at a height of 1000 m at 17 hours from the initial time in the simulation experiment. The area of the figure is indicated by the rectangular in Fig. 5.

The numerical experiment using CReSS successfully simulated the multi-scale structures of the precipitation system associated with the Baiu front. The SSL develops along the Baiu front. The ML forms in the eastern part of the SSL and is accompanied by the mesoscale fronts. Rainbands develop along the fronts and are composed of intense convective cells.

6. Localized heavy rain

The heavy rain event occurred on 19–20 July 2003 in Kyushu which is the western part of Japan. During this period, the Baiu front was located to the north of Kyushu. The most intense rain occurred during the period of 16–22 UTC, 20 July and the area of the heavy rain was roughly 100×100 km. The total amount of rain of this period reached about 210 mm at Minamata which is located in the western Kyushu. We consider that this is a localized heavy rain. The heavy rain caused a flood and 21 people were killed.

Satellite images show that a convective cloud cluster developed on the west coast of Kyushu. The AMeDAS-radar composite data provided by JMA (the Japan Meteorological Agency) shows that intense echo systems developed within the cloud cluster and moved into the west coast of Kyushu (Fig. 7). Figure 7 shows that an intense rainband extends in east-west direction and some orographic rainfall echo developed in the western Kyushu.

We performed a prediction experiment of the localized heavy rain using CReSS. The experimental design is summarized in Table 4. The initial time is 00 UTC, 19 July 2003 and 24-hour experiment was performed. The horizontal domain is centered at the west coast of Kyushu.

The experiment successfully simulated the localized heavy rain. Figure 8 shows that an intense rainband developed to the west of Kyushu and the intense rain occurred along the west coast of Kyushu. The rainfall pattern in Fig. 8 is quite similar to the observation (Fig. 7) with regard to the pattern and intensity of rain. The intense rain in the western Kyushu is

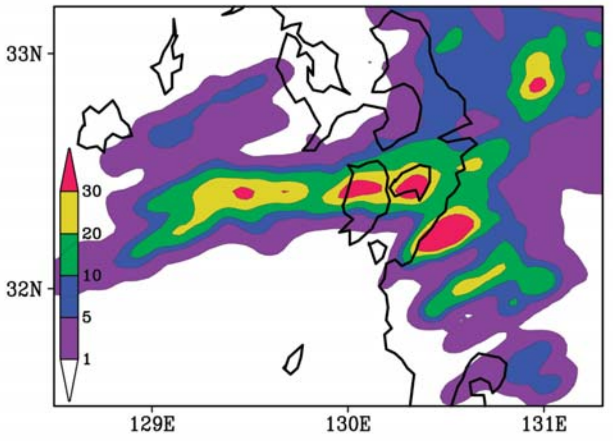

Fig. 7 Rainfall rate of AMeDAS-radar composite (mm hr^{-1}) at 16 UTC, 19 July 2003.

Table 4 Experimental design of the localized heavy rain in Kyushu using 2 km horizontal resolution.

domain	x 600, y 600, z 18 km
grid number	x 603, y 603, z 63
grid size	H 2 km, V 100 – 150 m
integration time	24 hrs
node number	10 (80 CPUs)

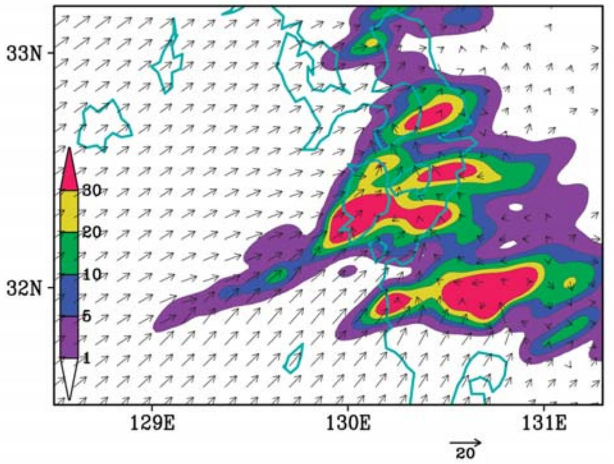

Fig. 8 Rainfall amount during 15 – 16 UTC and horizontal wind at 500 m ASL at 16 UTC, 19 July 2003 obtained from the prediction experiment of 2 km resolution.

simulated during the period from 16–22 UTC, 19 July 2003.

We also performed prediction experiment with a fine gird size of 500 m (Table 5). The increase of horizontal resolution shows the detailed structure of the convective system (Fig. 9). The rainband extends from SW to NE direction. It is composed of intense convective cells. The simulation resolves individual convective cells. The experiment with the high resolution also shows orographic precipitation. Figure 9 shows that another rainband is present to the south of the main rainband. It forms on the lee side of the small islands over the sea, which is named the Koshiki islands. We consider that both the two rainbands is related to the

Table 5 Experimental design of the localized heavy rain in Kyushu using 500 m horizontal resolution.

domain	x 600, y 600, z 18 km
grid number	x 1203, y 1203, z 63
grid size	H 500 m, V 100 – 150 m
integration time	21 hrs
node number	120 (960 CPUs)

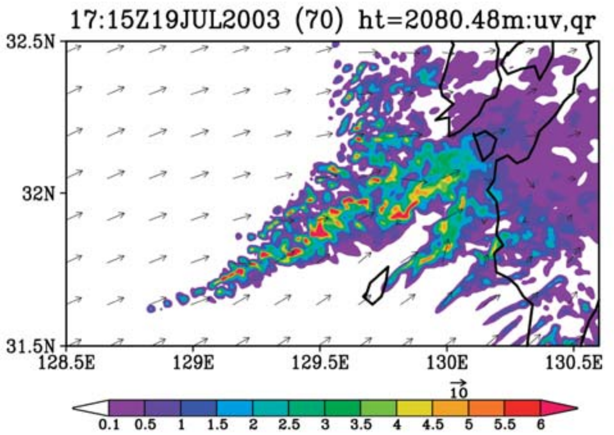

Fig. 9 Mixing ratio of rain (gray scale; g kg^{-1}) and horizontal velocity (arrows) at a height of 2080 m at 1715 UTC, 19 July 2003 obtained from the experiment of 500 m resolution.

localized heavy rainfall.

7. Typhoon

Typhoon often brings heavy rain and intense wind. The heavy rain is usually localized in the eye-wall and spiral bands. A very fine resolution within a large computation domain is, therefore, necessary for a simulation of heavy rain associated with a typhoon.

A typhoon named RUSA attacked Korea on 31 August 2002 and caused a heavy rain and flood. In particular, a large amount of rainfall was brought to the southern part of Korea and the east coast. We performed a simulation experiment of Typhoon RUSA with a very high resolution using CReSS. The horizontal resolution is 1 km and the domain is 1320 times 1440 km in horizontal and 18 km in vertical (Table 6). The initial and boundary conditions are provided by the Regional Spectral Model of JMA.

Typhoon RUSA moved northward over the East China Sea and landed on the southern part of the Korean Peninsula. The experiment well simulated the track of the typhoon. The

Table 6 Experimental design of Typhoon RUSA

domain	x 1000, y 1000, z 18 km
grid number	x 1323, y 1443, z 63
grid size	H 1000 m, V 300 m
integration time	24 hrs
node number	120 (960 CPUs)

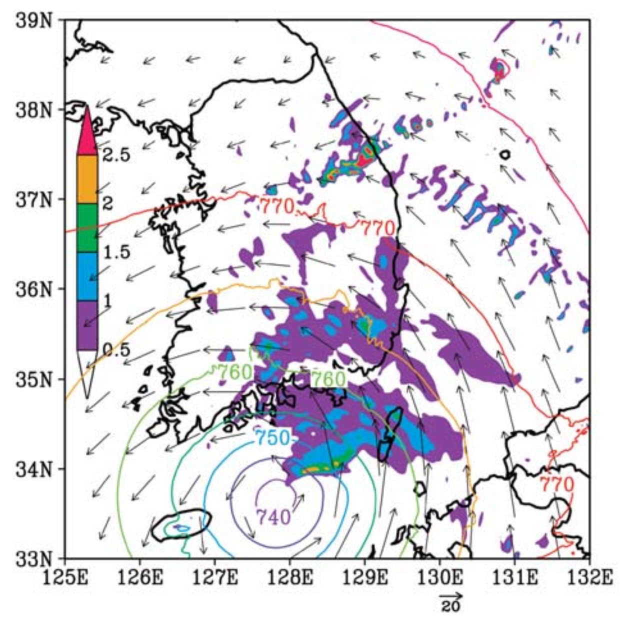

Fig.10 Pressure (hPa), mixing ratio of rain (gray scale; g kg^{-1}) and horizontal wind at a height of 2.15 km at 03 UTC, 31 August 2002 obtained from the simulation experiment.

distribution of total amount of rainfall well corresponds to observation. The overall characteristics of Typhoon RUSA are successfully simulated.

The result shows that an intense spiral band forms on the northeast side of the typhoon center (Fig.10). When the spiral band approaches to the southernmost part of the Korean Peninsula, the rain is intensified by the topographic forcing. This causes the heavy rainfall in the southern Korean Peninsula.

Another intense rainfall occurs along the east coast of the Korean Peninsula. It was caused by convergence of a northeasterly wind and the cyclonic flow around the typhoon. The topography along the east coast also intensifies the rainfall. As a result, the intense rainfall occurs along the east coast of the peninsula.

The experiment with the high resolution and the large domain successfully simulated the whole typhoon and individual spiral bands as well as the intensification of rain due to topography. This experiment enables to study the formation and development processes of the intense rain within the typhoon.

8. Summary

We have been developing the cloud-resolving numerical model CReSS for numerical experiments and simulations of clouds and storms. Parallel computing is indispensable for these computations because most cloud systems have multi-scale structures whose horizontal scales range from cloud-scale to synoptic-scale. In this paper, we described the basic formulations and important characteristics of CReSS and showed some results of the numerical experiments.

CReSS has been improved and optimized for the Earth Simulator and its performance was evaluated as sufficiently high. Using CReSS on the Earth Simulator, we performed simulation experiments of intense cloud and precipitation systems; winter snow-cloud bands, multi-scale lows and precipitation system along the Baiu front, the localized heavy rain, and the intense rainfall associated with Typhoon RUSA in Korea. These results show that detailed structure of individual convective cells and overall structures of multi-scale cloud systems are successfully simulated using CReSS on the Earth Simulator.

This project contributes for advanced studies of atmospheric water circulation in East Asia as well as accurate predictions of localized heavy precipitation and disaster prevention.

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