High-Resolution Simulations of High-Impact Weather Using the Cloud-Resolving Model on the Earth Simulator

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1 Introduction

One of the most important objectives of limited-area models is a high-resolution simulation of high-impact weather systems for detailed studies and accurate predictions of them. High-impact weather systems are most significant phenomena in the atmosphere and sometimes cause huge disasters to human society. Understanding their mechanisms and structures is necessary for prediction and prevention/reduction of disasters. Most high-impact weather systems that cause heavy rainfalls and/or violent winds consist of cumulonimbus clouds and their organized systems. They are usually embedded within a larger weather system and occasionally have a multi-scale structure. It ranges from cloud-scale to synoptic-scale systems. Characteristic weather systems in East Asia are the Baiu front, typhoons, and winter snowstorms associated with a cold air outbreak.

In order to perform simulations and numerical experiments of the high-impact weather systems, we have been developing a cloud-resolving numerical model named “the Cloud Resolving Storm Simulator” (CReSS). Since the multi-scale structure of the weather systems 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 the weather systems. In particular, an explicit calculation of cumulonimbus clouds is essentially important for a quantitative simulation of precipitation associated with the high-impact weather. 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 individual clouds using a very fine grid system (less than 1 km in horizontal). This will clarify a detailed structure of the high-impact weather systems and make a quantitative prediction of the associated precipitation. This will contribute for accurate prediction of precipitation and for reduction of disasters caused by the high-impact weather.

In this research, we have improved the CReSS model and optimized it for the Earth Simulator. Objectives of the present study are detailed simulations of the cloud and precipitation systems associated with the Baiu front, typhoons and associated rainbands, and snowstorms in cold air polar streams over a sea. In the present paper, we will describe the basic formulation and characteristics of CReSS and summarize some results of the simulation experiments of high-impact weather systems such as a localized heavy rainfall associated with the Baiu front, typhoons, and snowstorms.

2 Description of CReSS

The basic formulation of CReSS is based on the non-hydrostatic and compressible equation system using terrain-following coordinates. Prognostic variables are three-dimensional velocity components, perturbations of pressure and potential temperature, water vapor mixing ratio, 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. Terms related to a sound wave of the basic equation are integrated with a small time step and other terms with a large time step.

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. The microphysical processes implemented in the model are described in Fig.1.

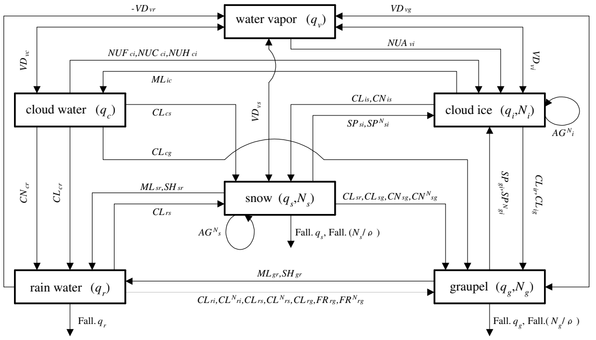

Figure 1: **Diagram describing of water substances and cloud micro-physical processes in the bulk scheme of CReSS.**

Parameterizations of the sub-grid scale eddy motions in CReSS are one-order closure of the Smagorinsky (1963) or the 1.5-order closer with turbulent kinetic energy (TKE). In the latter parameterization, the prognostic equation of TKE is used. The surface process of CReSS is formulated by a bulk method. The bulk coefficients are formulated by the scheme of Louis et al. (1981).

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 temperature perturbation. 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 stereographic projection and the Mercator projection.

For parallel computing of a large computation, CReSS adopts two-dimensional domain decomposition in horizontal (Fig.2). 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 to use.

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

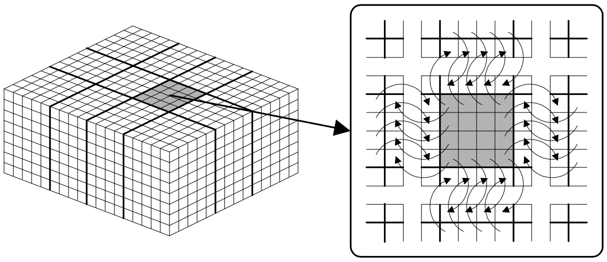

Figure 2: **Schematic representation of the two-dimensional domain decomposition and the communication strategy for parallel computations using MPI.**

3 Optimization for the Earth Simulator

The CReSS model was originally designed for parallel computers. We updated the code of CReSS from Fortran 77 to Fortran 90 and optimized it for the Earth Simulator. Communication procedures between computation 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. The vector and parallel operation ratios are sufficiently high enough to perform a large computation on the Earth Simulator.

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

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

After the performance CReSS was evaluated, we performed some simulation experiments of high-impact weather systems in East Asia: a localized heavy rainfall, typhoons, and winter snowstorms in cold air outbreak. The results are shown in the following sections.

4 Localized heavy rainfall

Precipitation systems associated with the Baiu front are occasionally cause heavy rainfall and flood while they are also important water resources in East Asia. The Baiu front extends zonally for several thousand kilometers while a localized heavy rainfall has a horizontal scale of a few hundred kilometers. Various types of multi-scale structure are indicated along the Baiu front. To clarify the processes in each class of the multi-scale systems of precipitation along the Baiu front, it is necessary to perform simulation experiment with a grid fine enough to resolve cloud-scale and with a domain large enough to calculate the whole system of the Baiu front. The explicit representation of cumulonimbus clouds in the model is essentially important for accurate and quantitative simulation of the localized heavy rainfall associated with the Baiu front.

The localized heavy rainfall occurred in Niigata and Fukushima prefectures on 13 July 2004 in Japan. Radar observation of the Japan Meteorological Agency (JMA) showed that an intense rainband extended zonally and maintained for more than 6 hours. The Baiu front was located to the north of Niigata and a subsynoptic scale low (SSL) moved eastward along the Baiu front.

The experimental setting of the simulation is summarized in Table 2. The initial and boundary conditions were provided by the JMA-RSM (the Regional Spectral Model). Initial time was 1200 UTC, 12 July 2004 and 24-hour simulation was performed.

The simulation showed that the SSL moved eastward along the Baiu front. Figure 3 shows that the SSL reaches Japan at 0020 UTC, 13 July 2004. Moist westerly wind is intense to the south of the SSL. Large precipitation area extends to the east of the SSL. On the other hand, a very intense rainband forms to the south of the SSL. Enlarged display (Fig.4) of the rainband shows that it extends from the northern part of the Noto Peninsula and reaches Niigata with intensification. The rainband forms between the southwesterly and westerly winds at the low level. The rainband is composed of intense convective cells. It maintains until the SSL moves to the Pacific Ocean. The long time maintenance of the intense rainband resulted in the severe flood in Niigata Prefecture.

Table 2: **Experimental design of the Niigata-Fukushima heavy rainfall event.**

domain	x 1792 km, y 1536 km, z 18 km
grid number	x 1795, y 1539, z 63
grid size	H 1000 m, V 100 $\sim$ 300 m
integration time	24 hrs
ES node number	128 nodes (1024 CPUs)

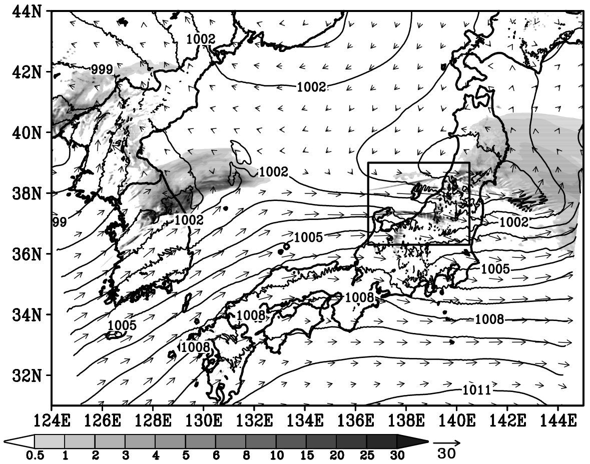

Figure 3: **Surface pressure (contour lines; hPa) and rainfall intensity (color levels; mm hr^{-1}) and horizontal velocity (arrows) at a height of 1610 m at 0020 UTC, 13 July 2004. The rectangle indicates the region of Fig.4.**

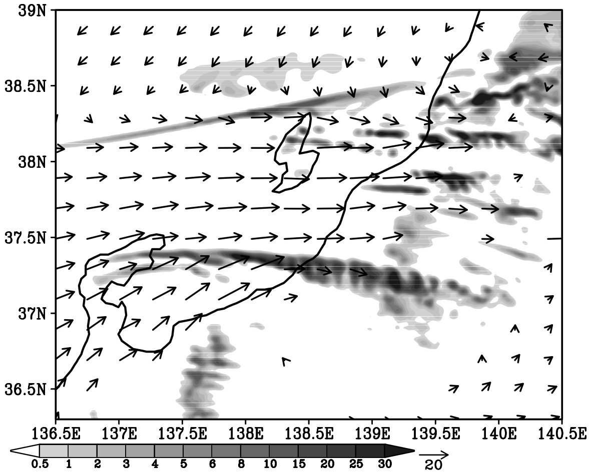

Figure 4: **Same as Fig.3 but for the region of the rectangle in Fig.3 and at a height of 436 m.**

5 Typhoons and the associated heavy rainfall

Typhoons develop by close interaction between the large-scale disturbance and the embedded intense cumulonimbus clouds. The horizontal scale of a typhoon ranges from several 100 km to a few 1000 km while that of the cumulonimbus clouds is an order of 10 km. Typhoons often bring a heavy rain and a strong wind. The heavy rain is usually localized in the eye-wall and spiral rainbands which develop within the typhoon. Since cumulonimbus clouds are essentially important for typhoon development, a cloud- resolving model is necessary for a detailed numerical simulation of typhoons.

Some typhoons usually attack Japan and its surroundings and cause severe disaster. In particular, ten typhoons landed over the main lands of Japan in 2004. In the present paper, we show two simulation experiments of typhoons. One is the typhoon T0418 which brought a very intense wind and caused huge disaster due to the strong wind. The other is the typhoon T0423 which brought a heavy rainfall and caused severe floods.

Typhoon T0418 moved northwestward over the northwest Pacific Ocean and passed Okinawa Island on 5 September 2004. Its center passed Nago City around 0930 UTC, 5 September with the minimum sea level presser of 924.4 hPa. When T0418 pass over Okinawa Island, double eye walls were observed. This is a distinctive feature of the typhoon. T0418 was characterized by strong winds and caused a large amount of disaster due to the strong winds over Japan.

The main objectives of the simulation experiment of T0418 are to study the eye-wall as well as spiral rainbands, and to examine structure of the strong wind associated with the typhoon around Okinawa Island. The simulation experiments of T0418 started from 0000 UTC, 5 September 2004. The experimental designs of T0418 are summarized in Table 3.

The simulation experiment shows very detailed structure of the eye and the spiral rainbands (Fig.5). Individual cumulus clouds are resolved. They are simulated within the eye and along the spiral rainband. A weak precipitation forms around the central part of the eye. The maximum tangential velocity is located along the eye-wall and at a height of 1 km. It is larger than 70 m s^{-1}. The high-resolution experiment shows detailed structure of the cloud and precipitation systems associated with the typhoon, and simulates the overall structure of the typhoon and its movement.

Table 3: **Experimental design of Typhoon T0418**

domain	x 1536 km, y 1280 km, z 18 km
grid number	x 1539, y 1283, z 63
grid size	H 1000m, V 150 ∼300m
integration time	18 hrs
ES node number	128 nodes (1024 CPUs)

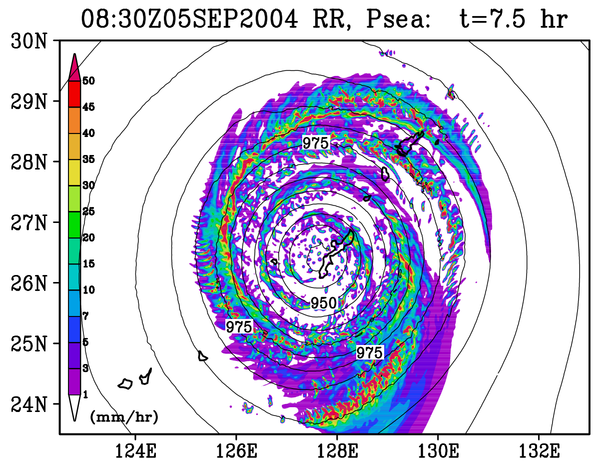

Figure 5: **Surface pressure (contour lines; hPa) and rainfall intensity (color levels; mm hr^{-1}) of the simulated Typhoon T0418 at 0830 UTC, 5 September 2004.**

Typhoon T0423 moved along the Okinawa Islands on 19 October 2004 and landed over Shikoku Island on 20 October. In contrast to T0418, T0423 is characterized by heavy rainfall over Japan. Heavy rainfalls associated with T0423 occurred in the eastern part of Kyushu, Shikoku, the east coast of the Kii Peninsula, and the Japan Sea side. They caused severe floods and disasters in these regions.

The purpose of the simulation experiment of T0423 is to study process of the heavy rainfall. Experimental design of T0423 is summarized in Table 4. At the initial time of 1200 UTC, 19 October 2004, T0423 was located to the NNE of Okinawa.

Table 4: **Experimental design of Typhoon T0423**

domain	x 1536 km, y 1408 km, z 18 km
grid number	x 1539, y 1411, z 63
grid size	H 1000m, V 200 ∼300m
integration time	30 hrs
ES node number	128 nodes (1024 CPUs)

The movement of T0423 and the rainfall were successfully simulated. In the simulation, a northward moisture flux is large in the east side of the typhoon center. When the large moisture flux reaches to the Japanese Islands, heavy rainfalls occur along the Pacific Ocean side. The heavy rainfall moves eastward with the movement of the typhoon from Kyushu to Shikoku. When the typhoon reaches to the south of Shikoku, heavy rainfall begins in the Kinki District (the rectangle in Fig. 6) and intensifies at 0630 UTC, 20 October (Fig.6). The distribution of precipitation well corresponds to the radar observation.

The close view of Northern Kinki shows that a large amount of precipitation are accumulated around a height of 6 km and intense convective clouds are embedded within the precipitation region (Fig.7). The heavy rainfall along the Pacific Ocean sides moved eastward, while that in the Kinki District lasted until 12 UTC, 20 October. After the typhoon moved to the east of the Kinki District, the northeasterly was intensified significantly. Consequently, orographic rainfall formed in the northern part of the Kinki District. As a

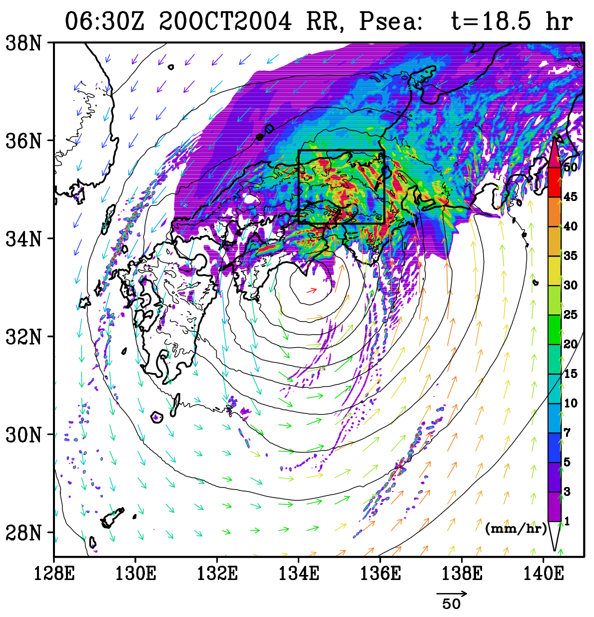

Figure 6: **Same as Fig.5 but for the Typhoon T0423 at 0630 UTC, 20 September 2004. Arrows are horizontal wind velocity at a height of 974 m and warmer colored arrows means moister air. The rectangle indicates the region of Fig.7.**

result, the accumulated rainfall became a large amount and the severe flood occurred.

6 Snowstorms

6.1 Idealized experiment of snow cloud bands

When an 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 the formation process of the organized cloud bands, we performed 3-dimensional simulation using the CReSS model on the Earth Simulator.

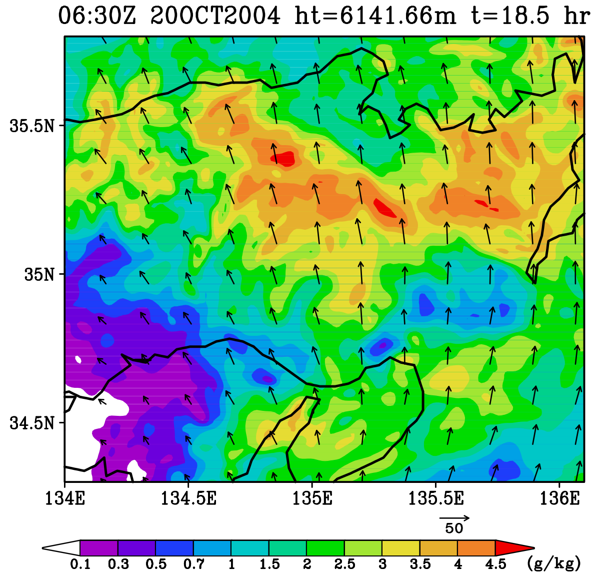

Figure 7: **Mixing ratio of precipitation (color levels; g kg^{-1}) and horizontal velocity (arrows) at a height of 6142 m at 0630 UTC, 20 September 2004.**

The experimental setting is summarized in Table 5. The initial condition was provided by a sounding observed on the east coast of Canada at 06 UTC, 8 February 1997.

Table 5: **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
ES node number	32 nodes (256 CPUs)

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 model grid of the surface 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 sounding of a cold air outbreak is used for the initial condition.

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 8 shows formation 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.9) 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.10). 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 (Fig.11). Band shape of cloud almost disappears and convections become closed cell type. 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.

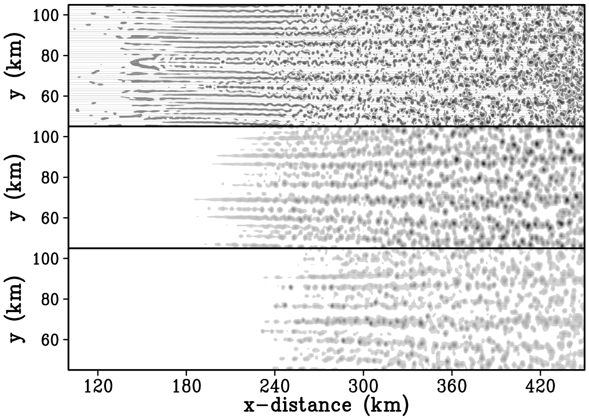

Figure 8: **Horizontal cross sections of vertical velocity (upper panel), mixing ratio of precipitation (snow, graupel and rain) (middle panel) at 1000 m in height and mixing ratio of cloud ice at 1300 m in height (lower panel) for x=100–450 km at 18 hours from the initial time.**

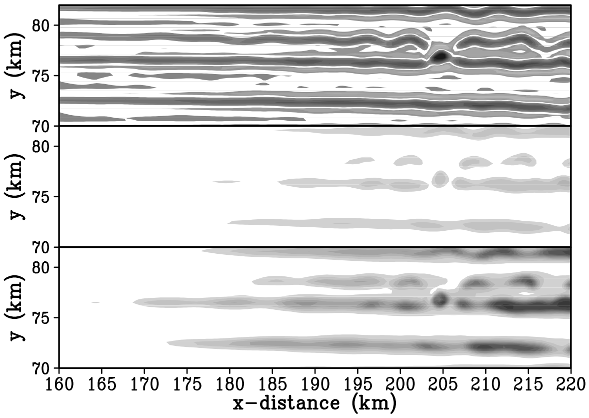

Figure 9: **Horizontal cross sections of vertical velocity (upper panel), mixing ratio of precipitation (middle panel) at 900 m in height and mixing ratio of cloud ice at 1100 m in height (lower panel) for x=160–220 km.**

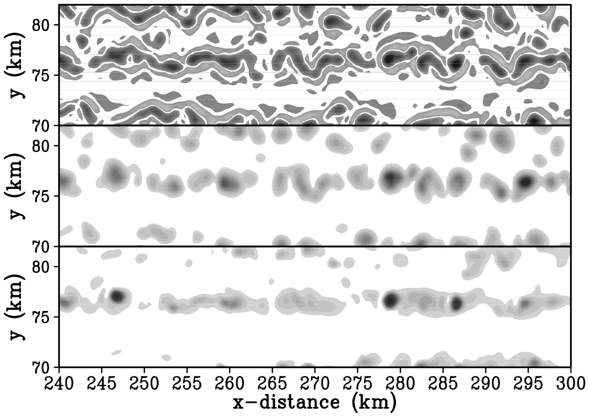

Figure 10: **Horizontal cross sections of vertical velocity (upper panel), mixing ratio of precipitation (middle panel) at 1000 m in height and mixing ratio of cloud ice at 1300 m in height (lower panel) for x=240–300 km.**

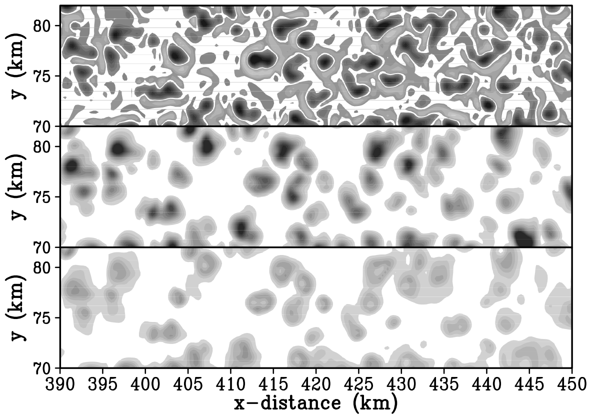

Figure 11: **As in Fig.10, but for x=390–450 km.**

6.2 Snowstorms over the Sea of Japan

One of the major precipitation systems in East Asia is snow cloud in a cold polar air stream. In particular, various types of precipitation systems develop over the Sea of Japan: longitudinal and transversal cloud bands, convergence zone (the Japan-Sea Polar-airmass Convergence Zone; JPCZ) and vortexes. Their horizontal scale ranges from a few hundred kilometers to 1000 km while they are composed of convective clouds whose horizontal scale is a few kilometers.

To study development process and detailed structure of longitudinal and transversal cloud bands, we performed simulation experiment of the cold air outbreak over the Sea of Japan on 14 January 2001. The initial field at 0600 UTC, 13 January 2001 and boundary condition were provided by the JMA-RSM. The Domain of the simulation covered most part of the Sea of Japan and horizontal resolution was 1 km to resolve convective clouds (Table 6).

Table 6: **Experimental design of the snowstorm over the sea of Japan.**

domain	x 1350, y 1350, z 16 km
grid number	x 1353, y 1353, z 43
grid size	H 1000 m, V 200 ∼400m
integration time	18 hrs
ES node number	36 (288 CPUs)

Snow cloud bands over the Sea of Japan are realistically simulated (Fig. 12). An intense and thick cloud band composed of cumulonimbus clouds extends along the JPCZ from the root of the Korean Peninsula to the Japanese islands. Plenty of thin cloud bands develop over the sea. Longitudinal and transversal cloud bands form to the west and east of the intense cloud band, respectively. The enlarged display of the transversal cloud bands shows that the cloud bands extend the SW-NE direction, which is almost parallel to the vertical wind shear between levels of the top of clouds and the surface (Fig. 13). This is consistent with the dynamic theory shown by Asai (1972).

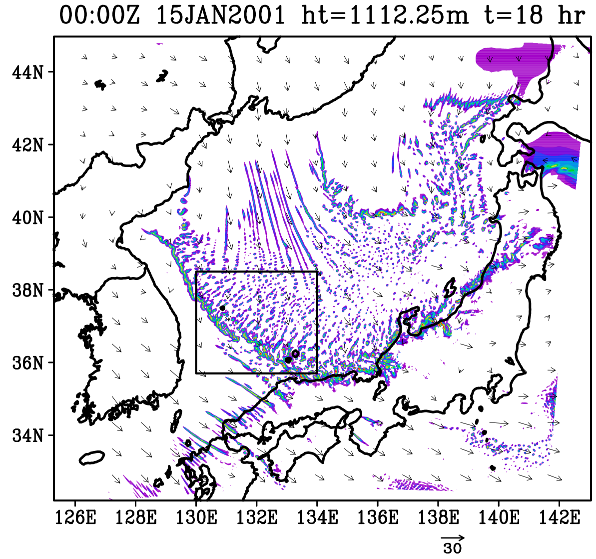

Figure 12: **Mixing ratio of precipitation (color levels; g kg^{-1}) and horizontal velocity (arrows) at a height of 1112 m at 0000 UTC, 15 January 2001.**

7 Summary

Accurate and quantitative simulation of high-impact weather systems using a high-resolution numerical model is essentially important for understanding mechanism and structure of conspicuous phenomena in the atmosphere. This will contribute to reliable weather prediction and to prevention/reduction of disasters due

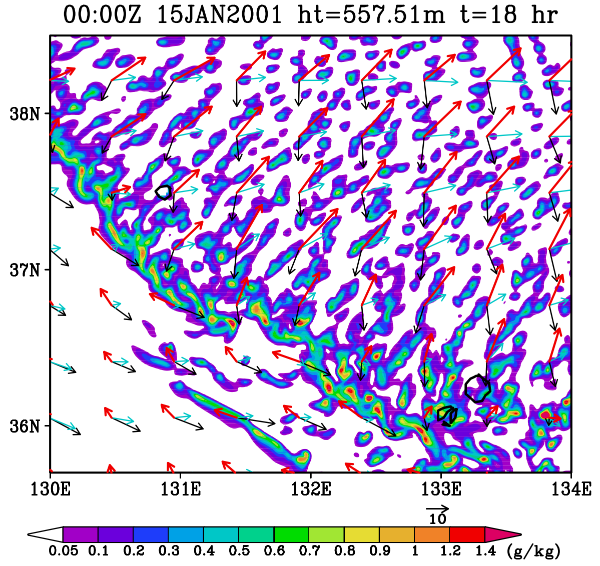

Figure 13: **Mixing ratio of precipitation (color levels; g kg^{-1}). Black and blue arrows are horizontal wind velocity at a height of 315 and 2766 m, respectively. Read arrows are wind shear between these levels.**

to a severe weather. Since most high-impact weather systems consist of intense cumulonimbus clouds and they have a multi-scale structure, it is necessary to use a cloud-resolving model for a quantitative simulation. Each class of the multi-scale components has a wide range of horizontal scale from cloud-scale to synoptic-scale. It is necessary to perform calculation within a large domain and with a very fine grid.

We have been developing a cloud-resolving numerical model named CReSS (the Cloud Resolving Storm Simulator) for numerical experiments and simulations of clouds and storms. Parallel computing is indispensable for these computations because most cloud systems have multi-scale structures. In this paper, we described the basic formulations and important characteristics of CReSS and showed some results of the numerical experiments of high-impact weather systems.

CReSS has been optimized for the Earth Simulator and its performance was evaluated as sufficiently high. Using CReSS on the Earth Simulator, we performed high-resolution simulations of high-impact weather systems: the localized heavy rainfall in Niigata area in 2004, typhoons of T0418 and T0423, and snowstorms in cold polar air streams. These results show that both detailed structures of individual convective clouds and overall structures of storm systems are successfully simulated using CReSS on the Earth Simulator. These experiments will contribute for accurate and quantitative prediction of high-impact weather systems and disaster prevention/reduction.

Acknowledgements

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