Numerical Experiments of Mesoscale Storms using a Cloud Resolving Model

—Present Status and Future Plan of CReSS (Cloud Resolving Storm Simulator)—

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1. Introduction

Convective clouds and their organized storms are highly complicated systems of flows and hydro-meteors. Their structure and dynamics are determined by a nonlinear interaction between the fluid dynamics and the cloud microphysics. In order to simulate an evolution of a convective cloud storm, it is essential to formulate cloud physical processes as well as the fluid dynamic and thermodynamic processes. A detailed formulation of cloud physics requires many prognostic variables even in a bulk method such as cloud, rain, ice, snow, hail and so on. If we categorize size distributions of each type of hydro-meteors, the number of prognostic variables could be very large. It is impossible to perform this type of simulation of cloud systems without a huge memory and parallel computing.

The purposes of this study are to develop a cloud resolving model and its parallel computing to simulate cloud-scale to storm-scale phenomena. A thunderstorm which is an organization of convective clouds produces many types of severe weather: heavy rain, hail storm, downburst, tornado and so on. The simulation of the thunderstorm will clarify the characteristics of dynamics and evolution and contribute to the storm-scale prediction. For example, micro-burst which prompted this study is caused by a complicated interaction between flow and cloud in the cloud-scale. The simulation of a micro-burst will provide a good opportunity for the development of parallel computing of the cloud model.

2. Characteristics of the cloud resolving model and parallel processing strategy

In this section, we will describe characteristic features of the cloud model that we are developing and show a performance of parallel computing. The cloud model was named CReSS (the Cloud Resolving Storm Simulator) and the source code and its documents were opened to the public.

CReSS is formulated in the non-hydrostatic and compressible equation system. In order to include the effect of orography, the coordinate system is a terrain-following coordinate in a two or three dimensional geometry. Prognostic Variables are three-dimensional velocity components, perturbations of pressure and potential temperature, subgrid-scale turbulent kinetic energy (TKE) and mixing ratios for water vapor and several types of hydrometeors. We adopted a finite difference method for the spatial discretization (explicit both in horizontal and vertical or explicit in horizontal and implicit in vertical) and the leap-frog time integration with the Asselin time filter for time integration. Turbulence is one of the most important physical parameterization in a cloud model. At present, the model includes the first order closer and 1.5 order closer with TKE. Cloud physics is another important physical process. It is formulated by a bulk method of cold rain. Prognostic variables are mixing ratios for water vapor, cloud water, rain water, cloud ice, snow and graupel. Radiation of cloud is not included. Numerical smoothing is the second or forth order computational mixing. Parallel processing is performed by the massage passing interface (MPI).

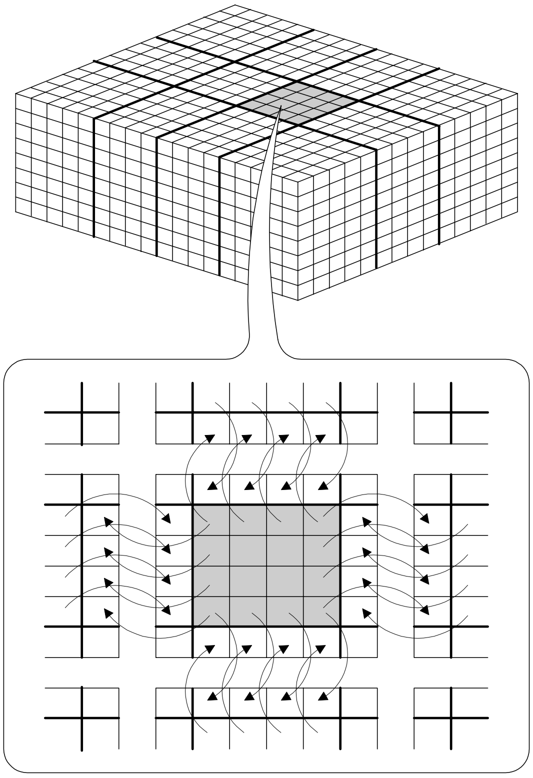

Figure 1: **Schematic representation of the domain decomposition and the communication strategy for the parallel computing.**

A large three-dimensional computational domain (order of 100 km) is necessary for the simulation of thunderstorm with a very high resolution (order of less than 1km). For parallel computing of this type of computation, we adopt a two dimensional domain decomposition (Fig.1). Communication between the individual processing elements (PEs) is performed by data exchange of the outermost grids.

The performance of parallel processing of the model was tested by a simulation whose grid size was 67x67x35 on HITACHI SR2201. With increase of the number of PEs, the computation time decreased almost linearly (Fig.2). The efficiency is almost 0.9 or more if the number of PEs is less than 32. When the number of PEs is 32, the efficiency decreased significantly. Because the number of grid is too small to use the 32 PEs. The communication between PEs becomes relatively large. The results of the test show a satisfactorily high performance of the parallel computing of CReSS.

3. Dry model experiments

In the development of the high resolution cloud model, we tested it with respect to several types of phenomena. In a dry system, the mountain waves, the Kelvin-Helmholtz billows and a dry downburst were chosen to test the model. The results were compared with those obtained by other models such as ARPS (Advanced Regional Prediction System) developed in the University of Oklahoma and the Nonhydrostatic Model developed by the Meteorological Research Institute, Japan Meteorological Agency.

In the simulation of mountain waves, we used a horizontal grid size of 400 m in a three-dimensional geometry. The result (Fig.3) shows that upward propagating mountain waves developed with time. This result is closely similar to that obtained by other models as well as that predicted by a linear theory.

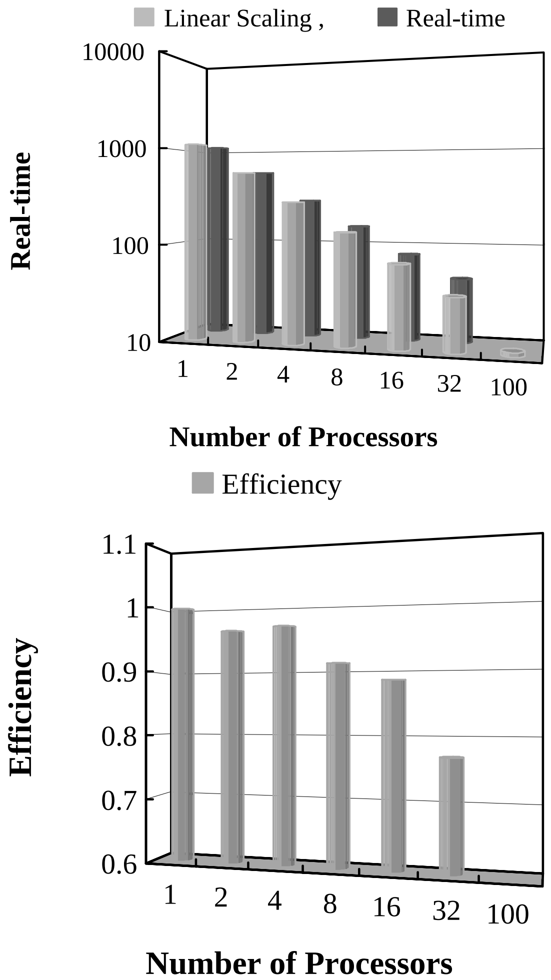

Figure 2: **Timings (upper panel) and efficiency (lower panel) of parallel processing of the cloud model. The model used in the test had 67x67x35 grid points and was integrated for 50 steps on HITACH SR2201.**

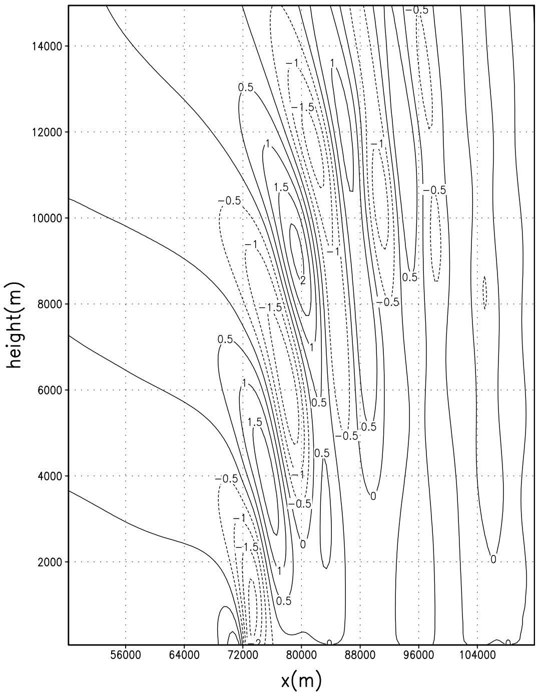

Figure 3: **Vertical cross section of the simulated mountain waves. Contour lines indicated the vertical velocity component (m/s).**

The K-H billows were simulated in a two-dimensional geometry with a grid size of 20 m. Stream lines of u and w components (Fig.4a) show a clear cats eye structure of the K-H billows. The model also simulated the overturning of potential temperature associated with the billows (Fig.4b). This result shows the model works correctly with a grid size of a few tens meters as far as in the dry experiment.

The dry downburst is initiated by a denser airmass placed in the upper layer at the initial time. The gravity acceleration caused the downward motion (Fig.5). When it reached to the surface, a divergent flow was formed. At the leading edge of the divergent outflow formed a gust front.

These results of the dry experiments showed that the fluid dynamics part and the turbulence parameterization of the model worked correctly and realistic behavior of flow were simulated.

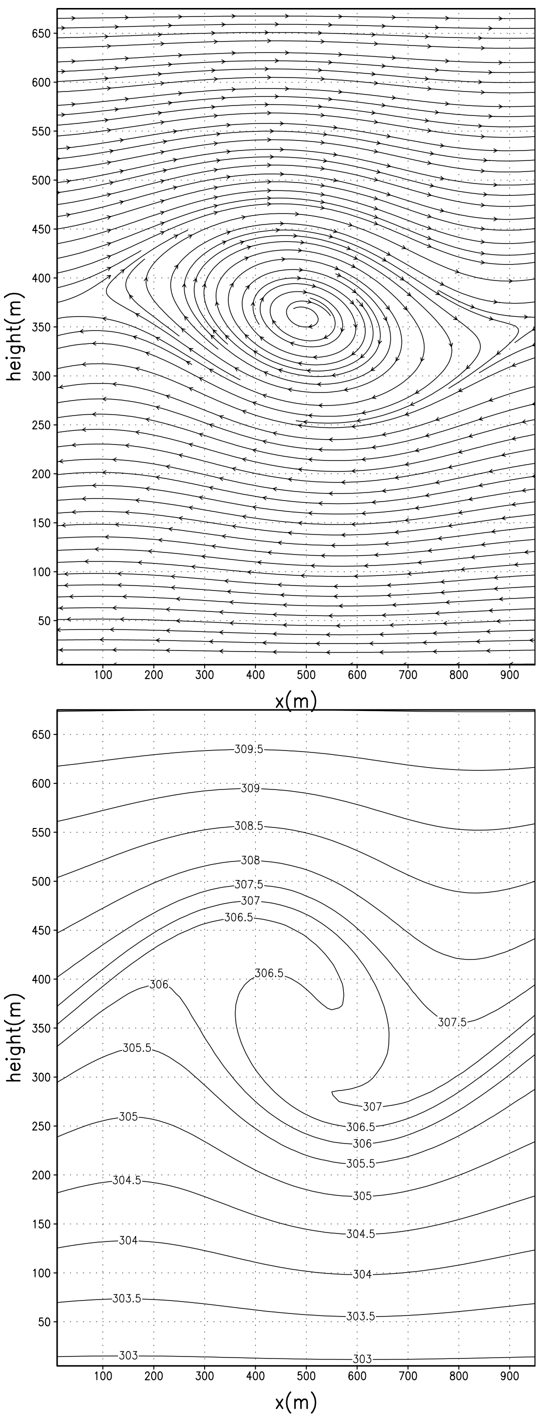

Figure 4: **The structure of the Kelvin-Helmholtz billow simulated in the two-dimensional geometry. Stream lines (upper panel) and potential temperature (lower panel).**

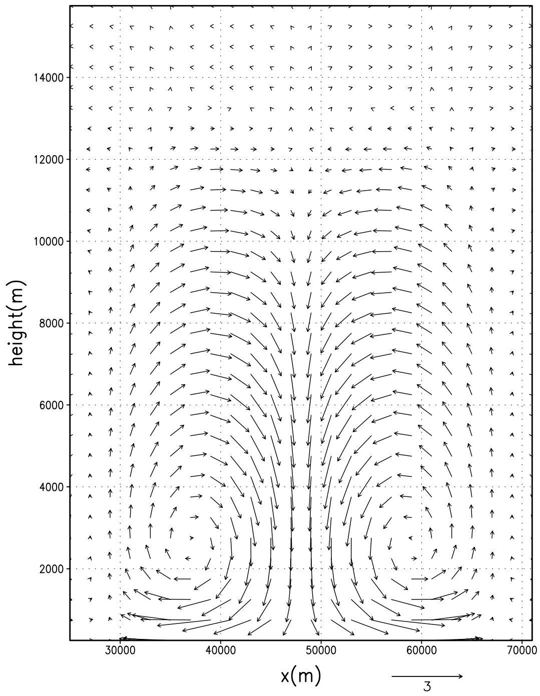

Figure 5: **Vertical cross section of velocity field of the simulated dry downburst.**

4. Simulation of a tornado with a supercell

In a simulation experiment of a wet system, we chose a tornado-producing supercell observed on 24 September 1999 in the Tokai District of Japan. The simulation was aiming at resolving the vortex of the tornado within the supercell.

Numerical simulation experiments of a supercell thunderstorm which has a horizontal scale of several tens kilometers using a cloud model have been performed during the past 20 years (Wilhelmson and Klemp, 1978; Weisman and Klemp, 1982, 1984). Recently, Klemp and Rotunno (1983) attempted to increase horizontal resolution to simulate a fine structure of a meso-cyclone. It was still difficult to resolve the tornado. An intense tornado occasionally occurs within the supercell thunderstorm. The supercell is highly three-dimensional and its horizontal scale is several tens kilometer. A large domain of order of 100 km is necessary to simulate the supercell using a cloud model. On the other hand, the tornado has a horizontal scale of a few hundred meters. The simulation of the tornado requires a fine resolution of horizontal grid spacing of order of 100 m or less. In order to simulate the supercell and the associated tornado by a cloud model, a huge memory and high speed CPU are indispensable.

To overcome this difficulty, Wicker and Wilhelmson (1995) used an adaptive grid method to simulate tornado-genesis. The grid spacing of the fine mesh was 120 m. They simulated a genesis of tornadic vorticity. Grasso and Cotton (1995) also used a two-way nesting procedure of a cloud model and simulated a tornadic vorticity.

These simulations were used a two-way nesting technique. This type of nesting method includes complication of communication between the coarse-grid model and the fine-mesh model through the boundary. On the contrary, the present research do not use any nesting methods. We attempted to simulate both the supercell and the tornado on the same grid size. In this type of simulation, no complication of the boundary communication. The computational domain of the present simulation was about 50 x 50 km and the grid spacing was 100 m. The integration time was about 2 hours.

The basic field was give by a sounding at Shionomisaki, Japan at 00 UTC, 24 September 1999. The initial perturbation was given by a warm thermal bubble placed near the surface. It caused an initial convective cloud. After 1 hour from the initial time, a quasi-stationary super cell was simulated by the cloud model (Fig.6). The hook-shaped precipitation area and the bounded weak echo region (BWER) which are characteristic features of the supercell were formed in the simulation. An intense updraft occurred along the surface flanking line. At the central part of BWER or of the updraft, a tornadic vortex were formed at 90 minutes from the initial time.

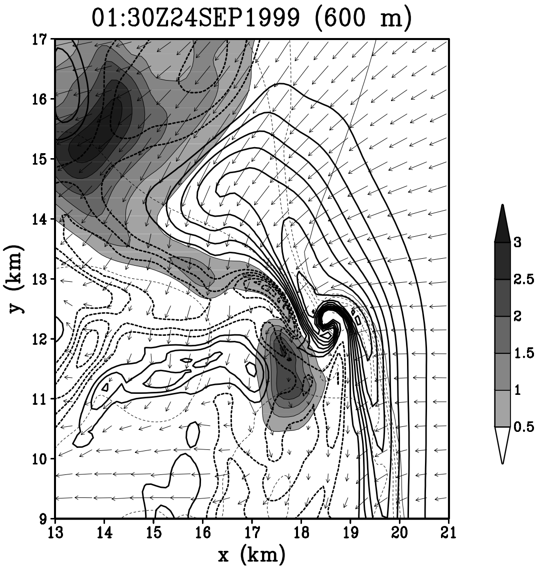

Figure 6: **Mixing ration of rain water (shaded areas), vertical component of velocity (thick lines), and horizontal velocity field at a height of 600 m and potential temperature at the surface (dashed lines) of the central part of the supercell obtained from the simulation experiment.**

The close view of the central part of the vorticity (Fig.7) shows closed contours of the pressure perturbation and the flow in the cyclostrophic balance. The diameter of the vortex is about 500 m and the maximum of vorticity is about 0.1. This is considered to be corresponded to the observed tornado.

The vertical cross section of the vortex (Fig.8) shows that the axis of the vorticity and the associated pressure perturbation is inclined westward and extends to a height of 1.5 km. At the center of the vortex, the downward extension of cloud is simulated.

While this is a preliminary result of the simu-

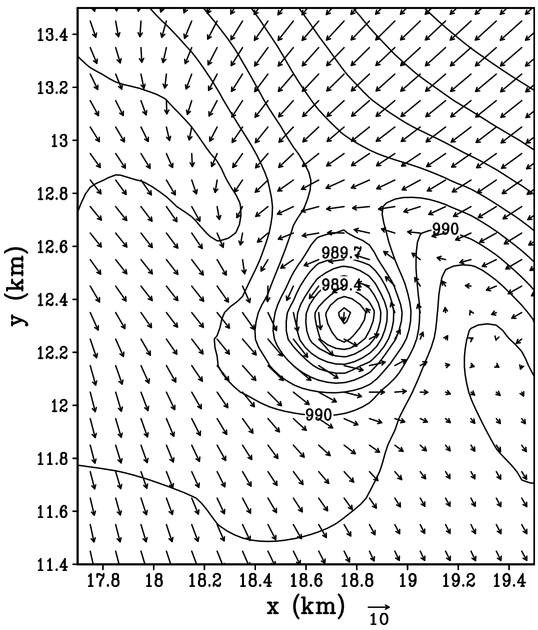

Figure 7: **Close view of the simulated tornado. The contour lines are pressure (hPa) and the arrows are horizontal velocity field. The arrow scale is shown at the bottom of the figure.**

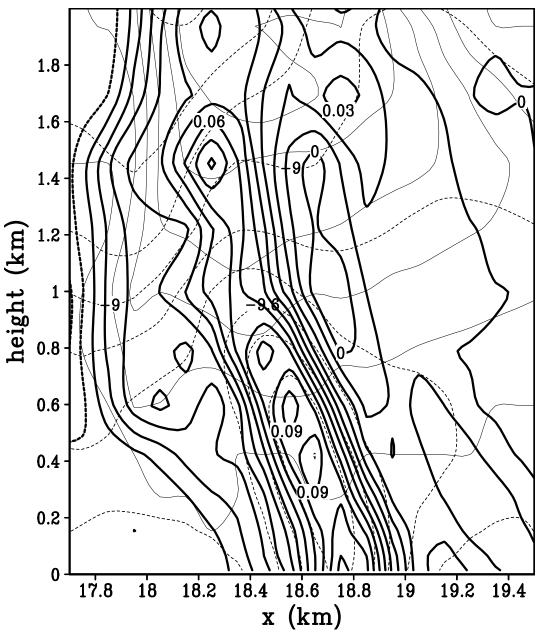

Figure 8: **Vertical cross section of the simulated tornado. Thick lines are vorticity (/s), thin lines are cloud mixing ratio and dashed lines are pressure.**

lation of the supercell and tornado, some characteristic features of the observation were simulated well. The important point of this simulation is that both the supercell and the tornado were simulated in the same grid size. The tornado was produced purely by the physical processes formulated in the cloud model. A detailed analysis of the simulated data will provide an important information of the tornadogenesis within the supercell.

5. Summary and future plan

We are developing the cloud resolving numerical model, CReSS for simulations of cloud-scale to storm-scale phenomena. Parallel computing is necessary for the simulations. In this paper, we summarized the present status of CReSS. Its characteristic features and some result obtained in dry experiments were presented. We also showed a preliminary result of the simulation experiment of the supercell and the associated tornado. The model simulated both disturbances with a uniformly fine grid spacing. The result suggested that the model is capable to simulate a thunderstorm and a related phenomenon.

Another target of this model is a micro-burst in Japan. We expect that ice-phase processes are necessary for the simulation. Because the micro-burst or downburst occurs in a highly moist environment in Japan. Loading of precipitation could be important for the downward acceleration. Our preliminary experiment of the downburst showed that a plenty of graupel production and its melting are important for a large mixing ratio of rain to produce the loading force. The next step, therefore, is simulation experiments of micro-burst with the ice-phase physics.

In the future, we will extend CReSS to include detailed cloud microphysical processes which resolve size distributions of hydrometeors. The parameterization of turbulence is another important physical process in cloud. The large eddy simulation is expected to be used in the model. We will extend CReSS to be nested in a coarse-grid model for a simulation of a real weather system. Data assimilation of Doppler radar is also our nest target. Because initial conditions are essential for a simulation of mesoscale storms.

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