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

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The purpose of this research is explicit simulations of clouds and organized precipitation systems using a cloud-resolving model in a large domain and very fine grid (less than 1 km). 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 the mid-latitude; the Niigata-Fukushima heavy rainfall event, Typhoon T0418, T0423 and associated heavy rainfall, and snow storms over the Sea of Japan and Canada. These experiments showed both very detailed structure of individual precipitation clouds as well as overall structures of the large-scale systems. The experiment of the heavy rainfall event shows that an intense rainband forms and maintains within the subsynoptic-scale low along the Baiu front. Typhoon experiments show both the movements of each typhoon and detailed structure of eyewall and spiral rainband. Snow storm experiments show various types of precipitation systems composed of intense convective clouds in the cold air streams. This project also intended to contribute for accurate and quantitative prediction of localized heavy precipitation and disaster prevention.

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

1. Introduction

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, which have the multi-scale structure, using a cloud-resolving model in large domain and very fine grid system. This will clarify detailed structures 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 utilized the Cloud Resolving Storm Simulator (CReSS) which is a cloud resolving numerical model developed for parallel computers such as the Earth Simulator. Objectives of simulation experiments are the cloud and precipitation systems associated with the Baiu front, typhoon and associated precipitation bands, and snow-cloud bands and the related disturbances in cold air streams. In this paper, we summarize some results obtained form simulation experiments using the CReSS model on the Earth Simulator; the Niigata-Fukushima localized heavy rainfall associated with the Baiu front, typhoons and snow storms caused by cold air outbreaks.

The characteristics of CReSS and evaluation of the performance of CReSS on the Earth Simulator are summarized by Tsuboki (2004)[1]. Detailed description of CReSS is found in Tsuboki and Sakakibara (2001)[2] or Tsuboki and Sakakibara (2002)[3].

2. Localized heavy rainfall

Precipitation systems associated with the Baiu front occasionally show a multi-scale structure. The Baiu front extends zonally for several thousand kilometers while a localized heavy rainfall has a horizontal scale of a few hundred kilometers. To clarify the water circulation process and the role of each class of the multi-scale systems, we performed a simulation experiment of the heavy rainfall in a large domain and with a high resolution. The explicit representation of cumulonimbus clouds in the model is essentially important for accurate and quantitative simulation of the localized heavy rainfall.

The localized heavy rainfall occurred in Niigata and Fukushima prefectures on 13 July 2004. 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 present to the north of Niigata and a sub-synoptic scale low (SSL) moved eastward along the Baiu front.

The experimental setting of the simulation is summarized in Table 1. The initial and boundary condition were provided by the JMA Regional Spectral Model (RSM). Initial time is 1200 UTC, 12 July 2004. The simulation showed that the SSL moved eastward along the Baiu front. Figure 1 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 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. 2) 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 results in the severe flood in Niigata Prefecture.

Table 1 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 100~300 m
integration time	24 hrs
ES node number	128 nodes (1024 CPUs)

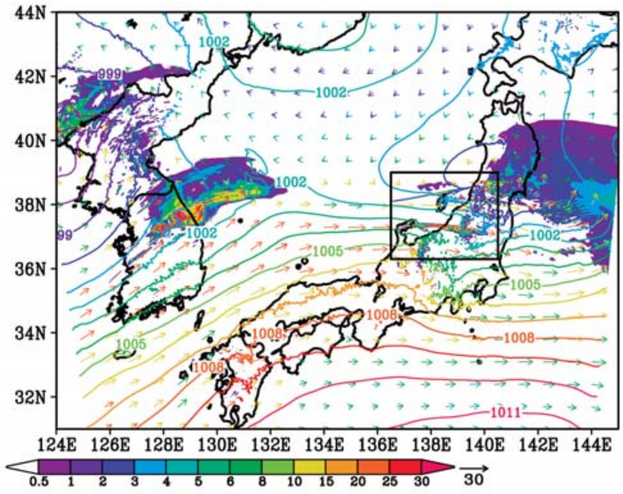

Fig. 1 Surface pressure (contour lines; hPa) and rainfall intensity (color levels; mm hr^{-1}) and horizontal velocity (arrows) at a height of 1610 m at 0020 UTC, 13 July 2004. Warmer colored arrows means moister air. The rectangle indicates the region of Fig. 2.

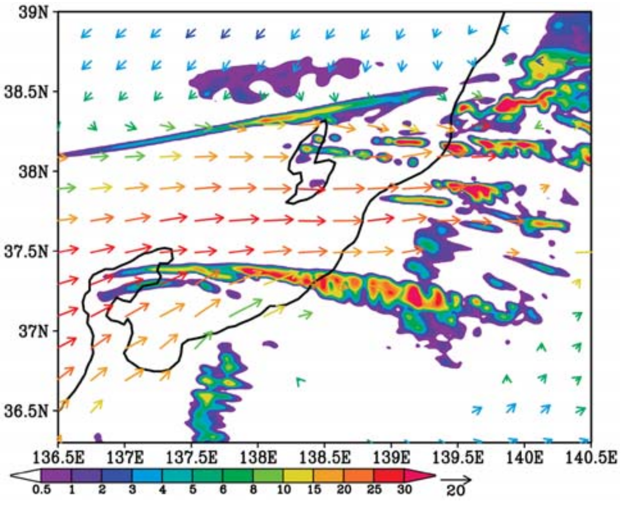

Fig. 2 Same as Fig.1 but for the region of the rectangle in Fig. 1 and at a height of 436 m.

3. Typhoon and 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. A typhoon often brings a heavy rain and an intense 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.

Some typhoons usually attack Japan and its surroundings and causes, 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 2.

The simulation experiment shows very detailed structure of the eye and the spiral rainbands (Fig. 3). Individual cumulus clouds are resolved. They are simulated within the eye

Table 2 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 numbers	128 nodes (1024 CPUs)

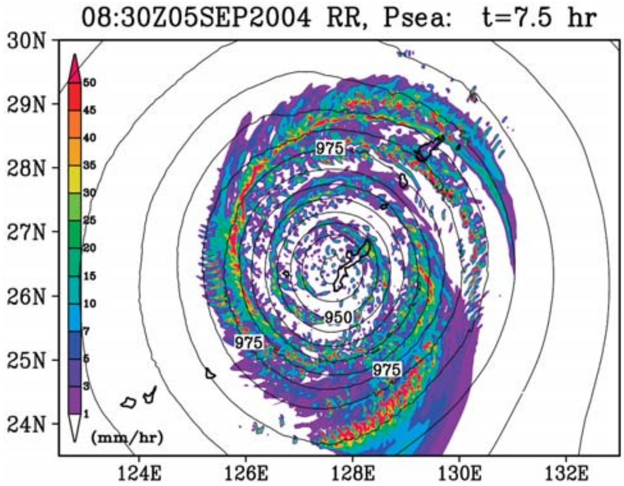

Fig. 3 Surface pressure (contour lines; hPa) and rainfall intensity (color levels; mm hr^{-1}) of the simulated Typhoon T0418 at 0830 UTC, 5 September 2004.

and along the spiral rainband. The high resolution experiment provides detailed data of the cloud and precipitation systems associated with the typhoon. 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}.

Typhoon T0423 moved along the Okinawa-Amami 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 Japan Sea side of the Kinki District. They caused severe floods and disasters in these region.

The purpose of the simulation experiment of T0423 is to study process of the heavy rainfall. Experimental design of T0423 is summarized in Table 3. At the initial time of 1200 UTC, 19 October 2004, T0423 was located to the SSW of Amami Island.

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 Japan Islands, heavy rainfalls occur along the Pacific Ocean side. The heavy rainfall moves 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 and intensifies at 0630 UTC, 20 October (Fig. 4). The distribution well corresponds to the radar observation.

Table 3 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 numbers	128 nodes (1024 CPUs)

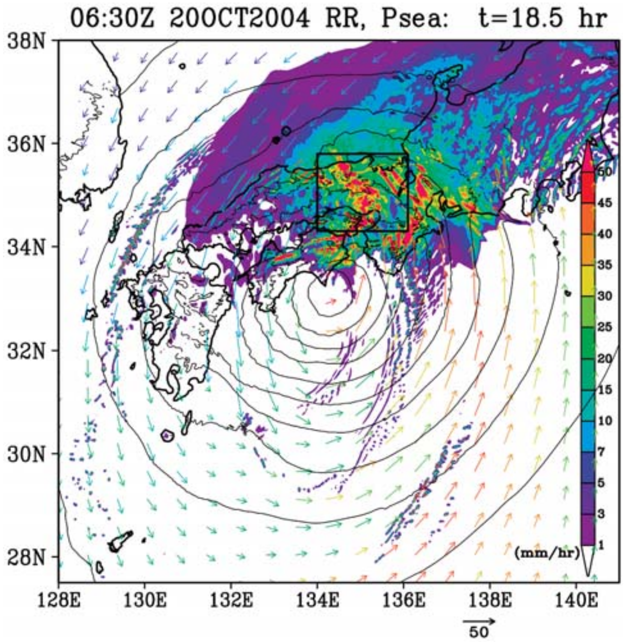

Fig. 4 Same as Fig. 3 but for the Typhoon T0423 at 0630 UTC, 20 September 2004. Arrows are horizontal wind velocity at a height of 974 m and warmer colored arrows means moister air. The rectangle indicates the region of Fig. 5.

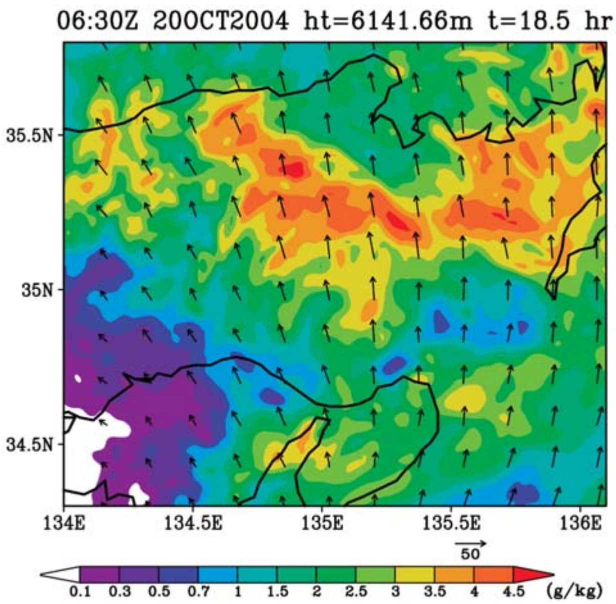

Fig. 5 Mixing ratio of precipitation (color levels; g kg^{-1}) and horizontal velocity (arrows) at a height of 6142 m at 0630 UTC, 20 September 2004.

The 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. 5). 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 intensified significantly. Consequently, orographic rainfall forms in the norther part of the Kinki District. As a result, the accumulated rainfall was large and the severe flood occurred.

4. Snow stroms

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 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 4).

Snow cloud bands over the Sea of Japan is realistically simulated (Fig. 6). An intense and thick cloud band composed of cumulonimbus clouds extends from the root of the Korean Peninsula to the Japan 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. 7). This is consistent with the dynamic theory shown by Asai (1972)[4].

Cold air outbreak and associated precipitation systems occurs over the Great Lakes region and the Labrador Sea to the east of Canada. The snow cloud bands over the Great Lakes are known as the 'lake effect storm (LES)' and have been studied observationally and numerically. Liu et al. (2004)[5] studied snow cloud bands using CReSS. The LES is also composed of cumulonimbus clouds and brings severe snowfall. We performed a simulation experimet (Table 5) to study the formation of the LES associated with a cold air outbreak. Figure 8 shows vertically integrated cloud and precipitation obtained from the simulation experiment. Cloud bands begin to develop from the lake on the upwind side (Lake Superior). They are composed of convective clouds over the lake while they become stratiform over the land. When they arrive at the lakes on the downwind side (Lakes Michigan and Huron), convection in the cloud bands is restored. The pattern and structure of cloud are very similar to those observed by meteorological satellites.

Table 4 Experimental design of the snow storm 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)

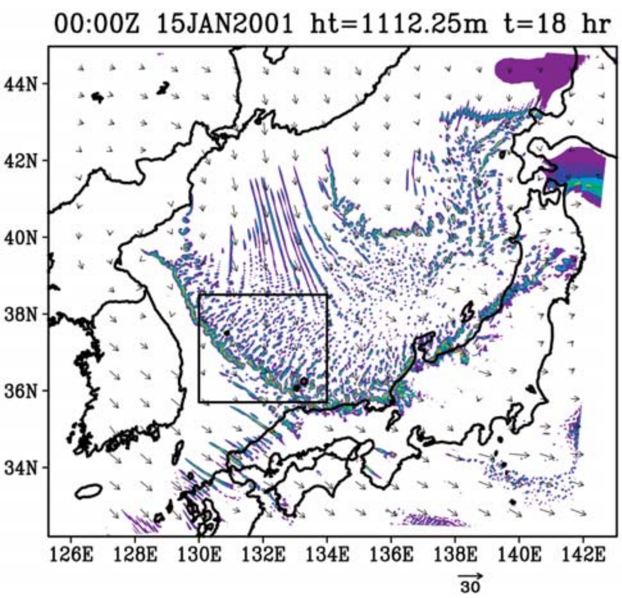

Fig. 6 Mixing ratio of precipitation (color levels; g kg^{-1}) and horizontal velocity (arrows) at a height of 1112 m at 0000 UTC, 15 January 2001.

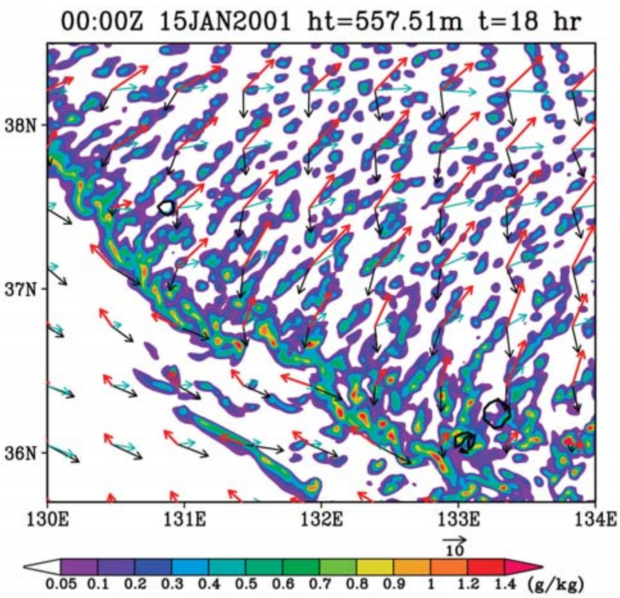

Fig. 7 Mixing ratio of precipitation (gray scale; g kg^{-1}). Black and blue arrows are horizontal wind velocity at height of 315 and 2766 m, respectively. Red arrows are wind shear between these levels.

Table 5 Experimental design of the snow storm over the Great Lakes.

domain	x 1300, y 660, z 18 km
grid number	x 2603, y 1323, z 43
grid size	H 500m, V 40~250m
integration time	12 hrs
ES node number	120 (960 CPUs)

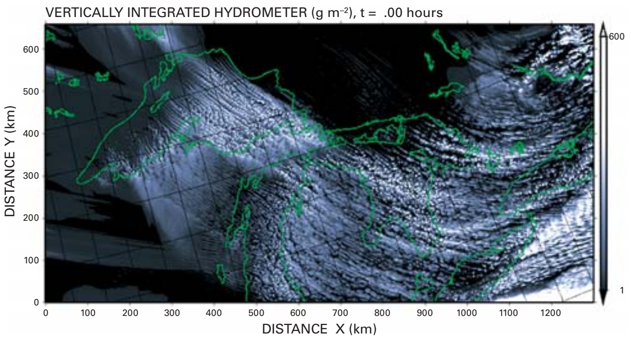

Fig. 8 Vertically integrated mixing ratio of precipitation (gray levels; g m^{-2}) over the Great Lakes at 12 hours from the initial time.

Cold air outbreak over the Labrador Sea is similar to that over the Sea of Japan. Sea ice is present along the east coast of Canada. Observation shows that plenty of snow cloud bands develop over the sea. Some of them begin to form over the sea ice. Liu et al. (2005)[6] studied the effect of the sea-ice zone on the development of the band clouds using CReSS. In order to study more detailed structure and formation process of cloud bands and a vortex over the Labrador Sea, we performed a simulation experiment using a large calculaton domain and very fine horizontal grid size (Table 6). In the simulation experiment, sea ice is placed along the coast according to the density of sea ice.

Figure 9 shows that cloud bands begin to develop from the sea ice region and convection composing the cloud bands intensifies over the open sea. In this experiment, a vortex is also simulated over the Labrador sea as observed. This is a sort of polar lows. The simulation experiment shows the mesoscale vortex, cloud bands as well as convective clouds composing these precipitation systems with the very high resolution.

5. Summary

Most of intense precipitation systems are composed of cumulonimbus cloud. To clarify the detailed structure of them, it is essential to use a cloud resolving model. In this project, we performed several simulation experiments of multi-scale weather systems using the Cloud Resolving Storm Simulator (CReSS). Since the multi-scale weather systems have wide range of horizontal scale, it is necessary to perform calculation within a large domain and with a very fine grid spacing. The results of the present study showed that the simulation experiments using CReSS on the Earth Simulator show both whole precipitation systems and convective clouds composing them. These experiments could contribute for accurate and quantitative prediction of localized heavy precipitation and disaster prevention.

Table 6 Experimental design of the snow storm over the Labrador Sea.

domain	x 1000, y 840, z 12 km
grid number	x 2003, y 1683, z 48
grid size	H 500m, V 60~250m
integration time	10 hrs
ES node number	80 (640 CPUs)

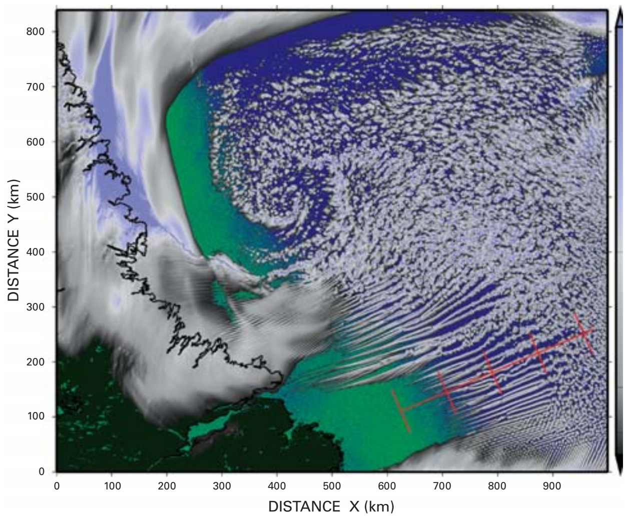

Fig. 9 Verticall integrated mixing ratio of prcipitation (gray levels; g m^{-2}) over the Labrador Sea at 10 hours from the initial time. Dark green and light green mean land and sea ice, respectively.

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階層構造を持つ水循環システムの雲解像モデルを用いた高解像度モデリング

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1. プロジェクトの目的

地球大気の水循環は、大規模スケールから積乱雲までの様々なスケールが階層構造をなす雲・降水システムによって特徴づけられる。本研究では、雲を詳細に表現しかつ雲スケールから大規模スケールまでを同時にシミュレーションすることにより、対象領域内の水循環に関わる現象を、対流をパラメタリゼーションすることなく、陽にシミュレーションすることを目的とする。これにより各スケールの水循環に果たす役割、メカニズム、実態、さらにスケール間の関係を明らかにする。

2. 今年度の計画

本研究では雲解像モデルCReSS(Cloud Resolving Storm Simulator)を用いる。階層構造を持つ主要な水循環システムは、梅雨、台風、及び冬季の降雪システムで、これらの雲・降水システムを主な対象とする。具体的には以下の計画を実施する。

1. 梅雨前線帯の降水システムの階層構造と、それに伴う集中豪雨の予測実験。
2. 台風とそれに伴う降雨帯の実験。実際の台風のシミュレーション実験及びAFESのデータを利用した台風発生時のシミュレーション実験を行う。
3. 冬季寒気流中の降雪システムの実験。日本周辺域を対象とするほかにカナダの研究者と協力してカナダ五大湖およびカナダ東岸を対象とする。

3. 今年度得られた成果

3.1. 梅雨に伴う局地豪雨

2004年の梅雨期から秋雨期にかけて、国内では多くの集中豪雨が発生した。これらのうち特に顕著であった新潟・福島豪雨についてシミュレーションを行った。その結果、梅雨前線、前線帯小低気圧、さらにその小低気圧の南東端の降雨帯という階層構造と、その降雨帯の持続によって豪雨がもたらされたことを示した。

3.2. 台風

台風についても今年度は多くの事例が発生した。そのうちの強風災害をもたらしたT0418と、豪雨災害をもたらしたT0421,T0423のシミュレーションを行なった。これによりアイウォールやスパイラルバンドの形成とそれに伴う強風や豪雨の形成過程を調べた。また、AFESの計算結果にCReSSをネスティングし、西太平洋上における台風発生時の台風に伴う降水システムの形成実験を行なった。近畿地方に大洪水をもたらした台風T0423のシミュレーションでは、T0423の北東側に強い降水域が形成され、近畿地方には発達した積乱雲で構成された降雨帯がかかり、豪雨がもたらされていることがシミュレーションされている。

3.3. 降雪システム

冬季の寒気吹き出しが起こったとき、日本海上には筋状雲や渦状擾乱など多くの降雪システムが形成される。日本海全領域を覆い、水平解像度1kmで積乱雲を解像してシミュレーションを行い、日本海上に発生する縦モードと横モードの筋状雲や収束帯上の帯状雲のシミュレーションを行い、実際の現象に非常によく似たものを再現した。また北米の五大湖とカナダ東岸のラブラドル海の降雪システムについて、カナダの研究者と協力してシミュレーション実験を行った。五大湖上とその周辺域に発生する筋状雲についてのシミュレーションを500 mの水平解像度で行ない、衛星画像に見られるような実際の現象に非常に近いものを再現した。またラブラドル海のものについては、海氷をカナダ東岸沿いに配置し、筋状雲の実験を行い、海氷野の海氷密度の減少するところからも雲が発生することを示した。

キーワード：階層構造，雲解像モデルCReSS，梅雨前線，集中豪雨，台風，降雪システム