Study of Cloud and Precipitation Processes using a Global Cloud Resolving Model

Project Representative

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The objective of this project is to better understand cloud and precipitation processes on the Earth and to improve these processes in climate models by global cloud resolving approach. In FY2010, a 10-day long 3.5-km mesh global simulation of genesis process of Typhoon Fengshen was conducted. The results were analyzed in terms of multi-scale processes of tropical cyclogenesis and validated against the in-situ and satellite observations. A series of sensitivity experiments using 14 km mesh were executed to evaluate global statistics of simulated clouds. Based on the results, physical parameters were tuned to improve reproducibility of the cloud properties in long-term simulations. In order to understand basic mechanisms of tropical atmospheric variabilities with intraseasonal timescale, idealized experiments with aquaplanet setups were also performed. The results suggest the importance of zonal contrast of sea surface temperature forcing.

Keywords: cloud and precipitation processes, global cloud resolving model

1. Introduction

Understanding and adequate modeling of cloud and precipitation processes are key issues to accurate prediction of global climate change. Global cloud resolving simulation is an epoch-making approach which is capable of excluding uncertainty inherent in the "cumulus parameterization", which has long been used in conventional general circulation models (GCMs). Our research team has been developing a global cloud resolving model, Nonhydrostatic ICosahedral Atmospheric Model (NICAM; Satoh et al. 2008[1]) since 2000. In these ten years, a number of numerical experiments have been executed on the Earth Simulator (ES), and physical packages were renewed in FY2009 (Satoh et al. 2010[2]). In this research project, which started in FY2009, we focus on evaluations and improvement of cloud and precipitation processes of the NICAM simulation. In FY2010, we have conducted (1) Global 3.5-km mesh simulation of Typhoon Fengshen (TY0806), (2) sensitivity experiments with a global 14-km mesh model, and (3) aquaplanet experiments. Details are reported in the following sections.

2. Global cloud resolving simulation of Typhoon Fengshen (TY0806)

Prediction of tropical cyclogenesis is a challenging task because of its occurrence under multiple effects of large-scale disturbances, such as intraseasonal variability (ISV), monsoon, and tropical waves (Miura et al. 2007[3]; Fudeyasu et al. 2008[4]; Oouchi et al. 2009[5]; Fudeyasu et al. 2010[6]; Kikuchi et al. 2010[7]; Taniguchi et al. 2010[8]; Yanase et al. 2010[9]). In order to clarify multi-scale processes of cyclogenesis, we have conducted a case study of TY0806 (Fengshen), as an extension of the research work in FY2009, with increasing the horizontal resolution (3.5 km mesh) in this FY. The genesis of Fengshen was successfully observed in the field campaign PALAU2008, and its entire life cycle was also covered by the period of the international observation project Year of Tropical Convection (YOTC). The simulation period was 10 days starting at 00UTC 15 June 2008 (4 days before reaching typhoon intensity).

The 3.5-km mesh simulation well reproduced large-scale wind fields (Fig. 1). The westerlies in the lower troposphere

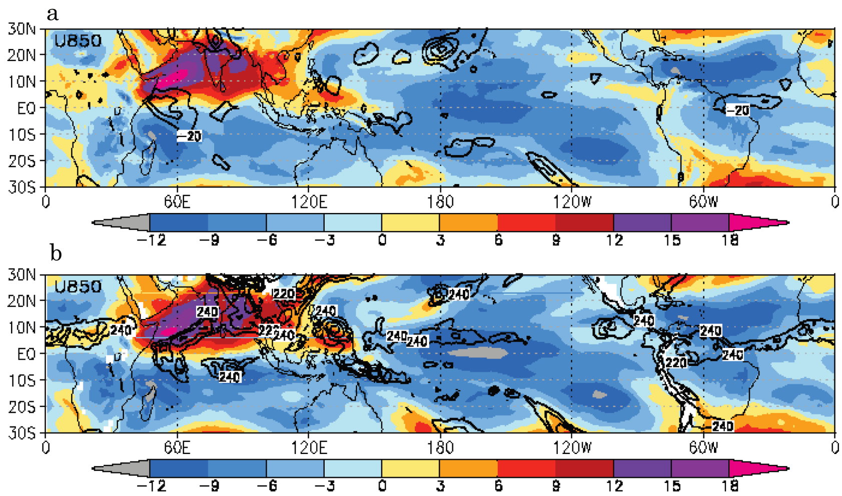

Fig. 1 Zonal wind at 850 hPa (15-21 June 2008 average) in (a) European Center for Medium-Range Weather Forecasts (ECMWF) YOTC operational analysis data and (b) the 3.5-km mesh NICAM simulation.

broadly prevailed over the Indo monsoon region as a part of monsoon circulation. The westerly extends to the equatorial western Pacific region due to an ISV event, which forms the conditions favorable to tropical cyclogenesis. The mesoscale structure of Fengshen (Fig. 2a, b) and development of upright deep circulation (Fig. 2c, d) are also in good agreement with in-situ observations.

Fengshen is known as the case subject to significant errors in operational track forecasting. In FY2009, impact of turbulent scheme on Fengshen track forecast was investigated by the sensitivity simulations with 14-km mesh (Satoh et al. 2010[2]). It is noteworthy that the 3.5-km mesh simulation better reproduced the typhoon track even with the standard setting of the turbulent mixing. This result suggests potential ability of high-resolution models to improve prediction of structure, development, and track of typhoons.

Validation of the cloud macro structures and microphysical variables in this simulation is currently underway with use of a satellite data simulator called Joint Simulator for Satellite Sensors (J-simulator). J-simulator is being developed under Japan Aerospace Exploration Agency (JAXA) EarthCARE project, which performs a retrieval simulation of active and

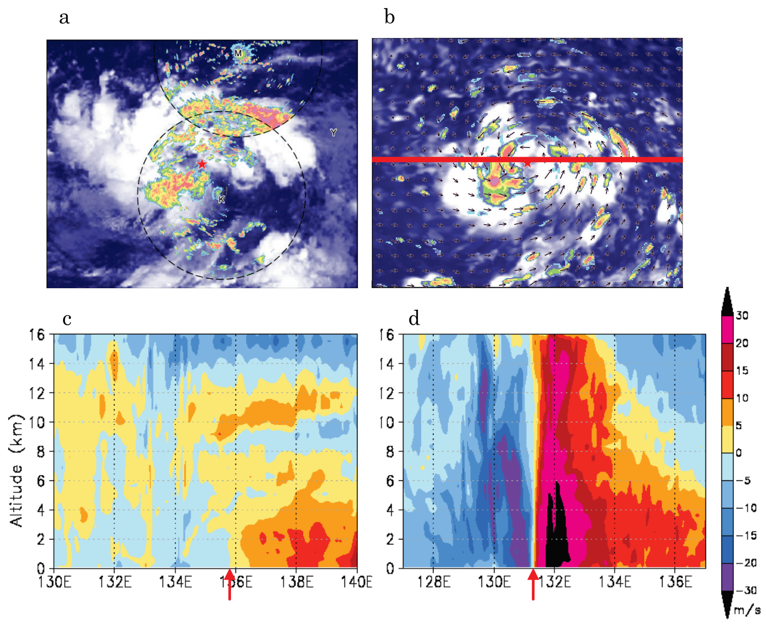

Fig. 2 Horizontal distribution of (a) MTSAT-1R (white) and radar echo (color) and (b) simulated outgoing long-wave radiation (OLR, white) and surface precipitation (color) in the 3.5-km mesh simulation at 00UTC 17 June 2008 (2 days before the typhoon genesis) (courtesy of Dr. Hiroyuki Yamada). Simulated vertical section of meridional wind along 9.5°N (red line in [b]) at (c) 00UTC 17 June and (d) 00UTC 19 June 2008. Red arrows in (c) and (d) indicate the center of the vortex.

passive satellite observations based under the simulated meteorological and cloud microphysical condition (Fig. 3a, 3c, and 3d). Comparison of the simulated and observed infrared brightness temperature indicates that in general the spatial distribution of clouds is well simulated, especially in mid and high latitudes, but the simulated cloud tops tend to be higher in the tropics (or for convective clouds). A preliminary analysis with simulated CloudSAT and CALIPSO signals suggests that the simulated snow tends to be larger than the observation and the cloud ice is optically too thick at the upper level. Use of multiple satellite observation and J-simulator allows us to improve the physical parameterizations including the cloud microphysical parameterization comprehensively. Global satellite observation provides valuable information not only to the retrievals of physical quantities relevant to aerosol and clouds but also to the validation of these simulated by numerical models.

3. Model tuning for future cloud-resolving simulations

Some physical processes of NICAM are tuned aiming at improving the global radiative budgets to agree with satellite observations. Figure 4 shows an example of sensitivity in terms of a parameter (b kg kg^{-1} s^{-1}), changing from 0.02-0.04. The sensitivity test is conducted using a global 14-km mesh model with an integration period during 1 April 2004 and 10 April 2004. This parameter means a time scale with respect to an autoconversion process from cloud ice to cloud snow species. (Note that these are the results explored in the final phase of this FY, and hence do not show remarkable differences depending on b.) The zonal means of outgoing longwave radiation (Fig. 4a) show that errors of global means for b=0.02, 0.03, and 0.04 (kg kg^{-1} s^{-1}) is -1.5, 3.5, and 6.4 W m^{-2}, respectively, yielding that the case with b=0.02 (kg kg^{-1} s^{-1}) provides the most reasonable result in the present analysis. The parameter does not have a significant impact on the budget of outgoing shortwave radiation (Fig. 4b).

Figure 5 compares global distributions of leveled cloud amounts with satellite data. The global-mean of the high cloud amount is comparable to the satellite observation, due to the parameter tuning described above. The global characteristics of mid and low cloud amounts also agree well with the observation. For regional comparison, one can observe areas with much larger values in the high cloud amount especially over SPCZ, which are not appeared in the observation; presumably this

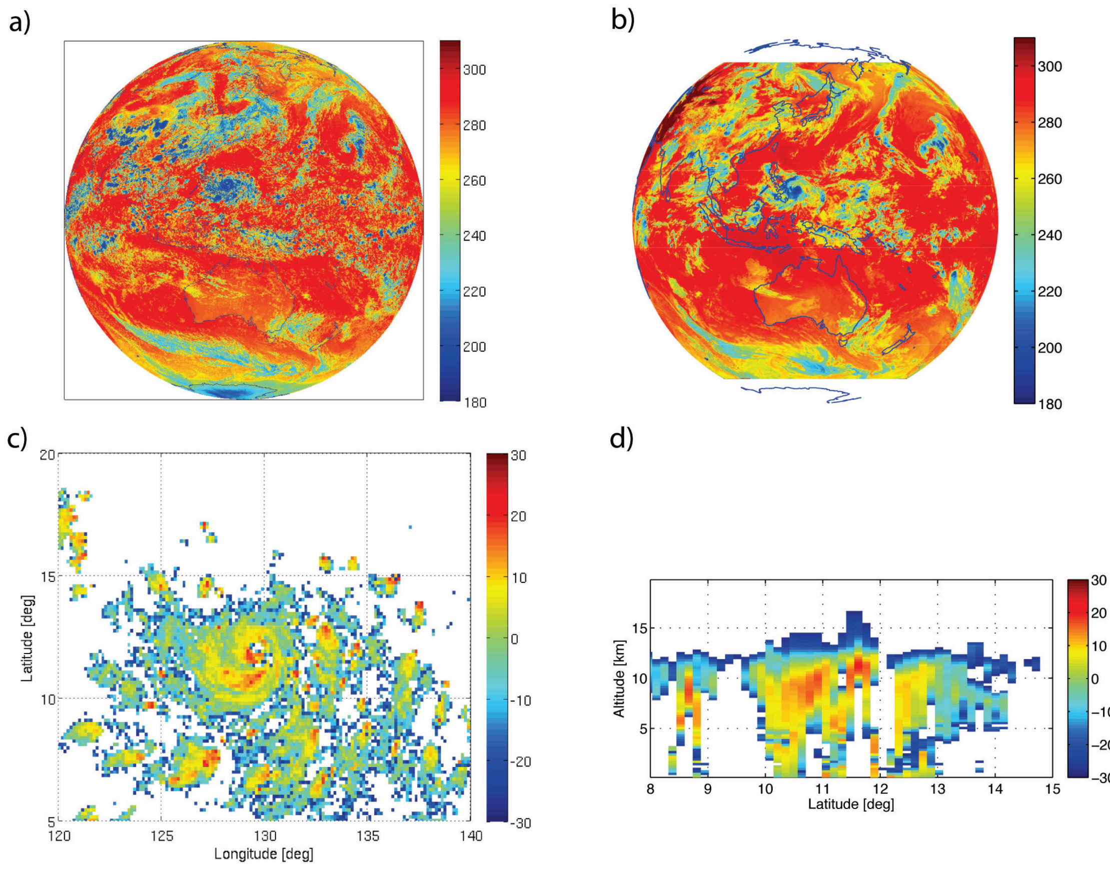

Fig. 3 Example of satellite observation simulated with J-simulator from the 3.5-km mesh NICAM simulation including Typhoon Fengshen at 12UTC 19 June 2008. (a) simulated infrared 10.8 μm, (b) observed infrared 10.8 μm by MTSAT (MRI, Japan; Chiba University, CEReS) and globlally-merged IR (CPC, NOAA), (c) simulated 94 GHz radar reflectivity at altitude of 10 km focused on Typhoon Fengshen, and (d) vertical cross section of the radar reflectivity (the eye is located at 12°N) (courtesy of Tempei Hashino).

difference is a noteworthy point to care about behavior of adjacent cloud systems in future NICAM experiments.

4. Aquaplanet experiments

Previous studies using NICAM with an aquaplanet setup (Tomita et al. 2005[10]; Nasuno et al. 2007[11]), where zonally uniform sea surface temperature (SST) was given, showed spontaneous generation of fast propagating disturbances similar to the super clusters (SCs) which moves at about 15 m s^{-1} (fast mode). Miura et al. (2007)[3], on the other hand, simulated a Madden-Julian Oscillation (MJO)-like slow propagating disturbance as well as SCs-like ones, which moves at 5-6 m s^{-1} and 18 m s^{-1}, respectively, with the realistic orography and SST distributions in NICAM.

To confirm what forced the MJO-like disturbances, experimental studies are performed with longitudinal wave-number one variation (with amplitude ΔT) added to a zonally uniform SST distribution. Figure 6 shows longitude-time sections of outgoing long-wave radiation (OLR) at (a) ΔT=0 K, (b) ΔT=2.25 K, and (c) ΔT=4.5 K with 14-km mesh NICAM. In Fig. 6a, the fast propagating SCs-like disturbances moving at about 15 m s^{-1} are obtained similarly to the previous aquaplanet case with 3.5 km and 7 km mesh sizes (Tomita et al. 2005 [10]). In Fig. 6b, in addition to fast propagating disturbances in the low SST area, quasi-steady disturbances appear in the high SST area, as a response to the Walker circulation. In Fig. 6c, quasi-steady disturbances become intense and slowly propagating disturbances appear. The slow propagating ones can be thought of as MJO-like, although their speeds vary among the cases.

The atmosphere in Fig. 6a seems to balance the destabilizing

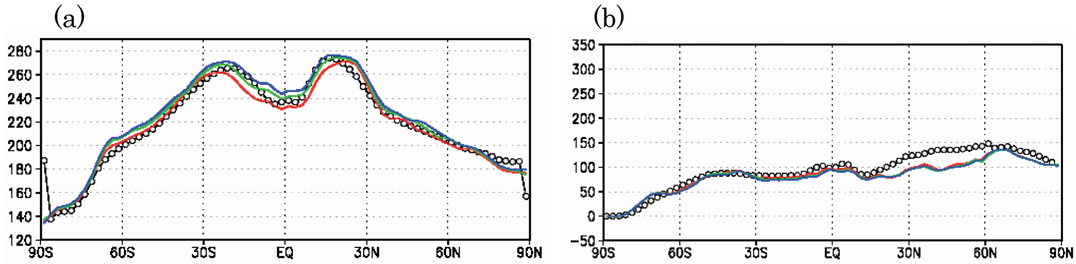

Fig. 4 Radiative budget for zonal means of (a) outgoing longwave radiation, and (b) outgoing shortwave radiation (W m^{-2}). The black line with circle shows the data of a satellite observation. The lines of red, green, and blue lines show the result of cases with b=0.02, 0.03, and 0.04 (kg kg^{-1} s^{-1}), respectively.

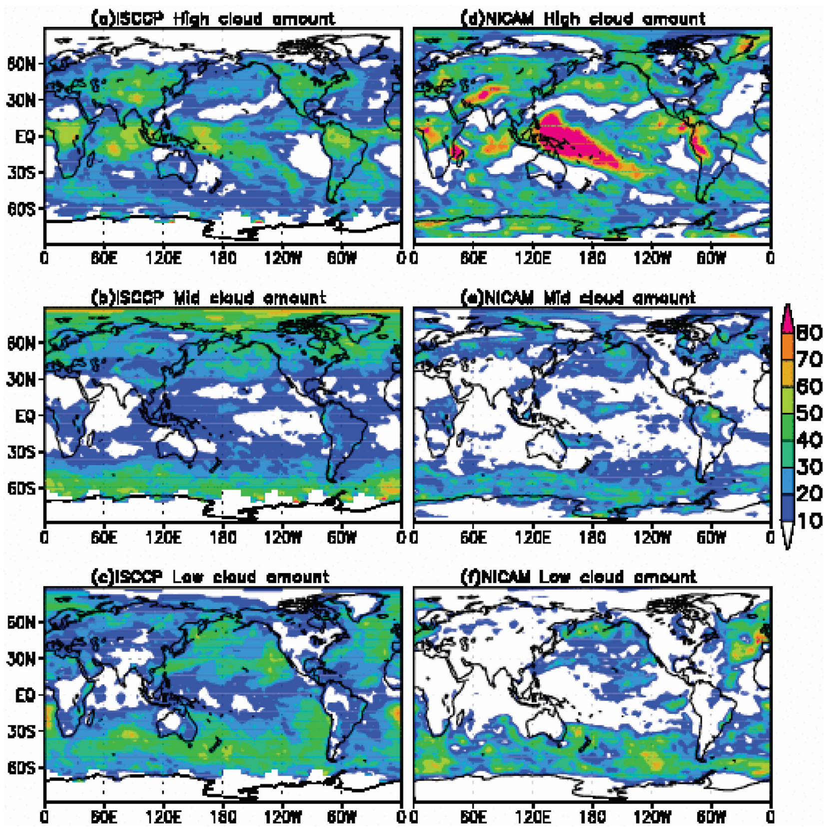

Fig. 5 Comparison of the observed (left) and modeled (right) cloud amounts. From top to bottom, high, mid and low cloud amounts are shown, respectively.

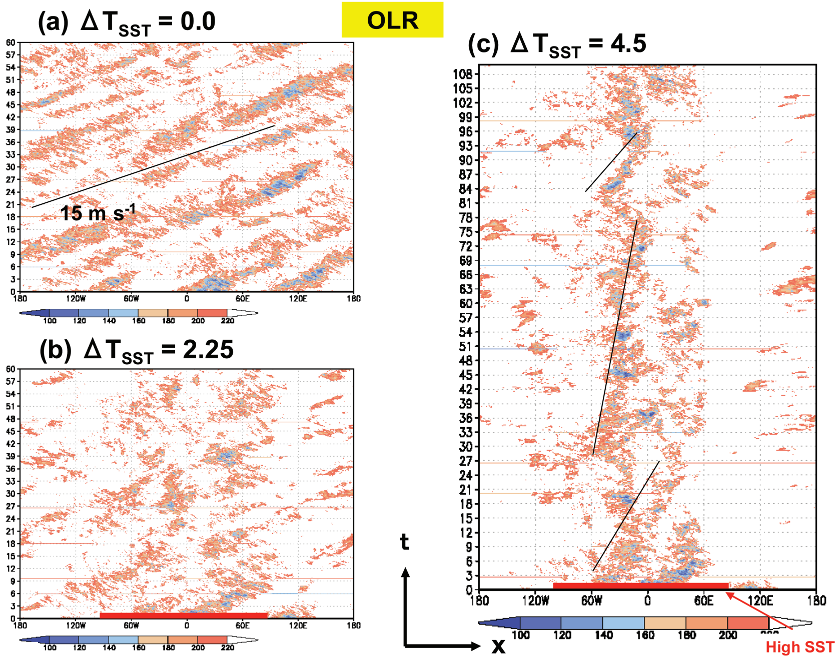

Fig. 6 Longitude-time sections of OLR at the top of atmosphere at (a) ΔT=0 K, (b) ΔT=2.25 K, and (c) ΔT=4.5 K with 14 km mesh. The maximum value of SST is located at the longitude 0 degree.

factors of SST and radiative cooling and the neutralizing factor of convection in the longitudinal direction. Then the SCs-like convection may be called '*free mode*' in this quasi-equilibrium atmosphere. Meanwhile, under the atmosphere where the Walker circulation is forced, the MJO-like slow propagating convection is called '*forced mode*'.

Additional works are needed to study impacts of land and orography as well as ocean and to confirm characteristic features of SCs and MJO quantitatively.

5. Summary

The major aim of this research project is the evaluation and improvement of cloud and precipitation processes in the global cloud resolving model, NICAM. The key issues are: (1) evaluation of the high-resolution simulation results using in-situ and satellite observations and (2) improvement of the model physics in perspective of accurate future climate prediction. Basic understanding of multi-scale mechanisms ranging from day to seasonal scales is also very important. In FY2010, the second year of this project, we proceeded in these directions by three kinds of simulation cases using NICAM with the physical packages renewed in FY2009.

The simulation setup of the short-term (10-day) case study with the highest horizontal resolution (3.5 km) is based on the 14-km mesh runs which had been executed in FY2009. The 3.5-km mesh simulation successfully reproduced the synoptic scale disturbances relevant to the genesis of Fengshen, as well as the internal mesoscale processes in good agreement with in-situ observations (PALAU2008). The simulation results also suggest the potential impact of the high resolution on typhoon track forecasting. Global statistics of cloud microphysical properties were evaluated using the satellite simulator "J-simulator" for the 3.5-km mesh run and by comparison with ISCCP data for the 14-km mesh sensitivity simulations of boreal spring to summer season in 2004. The results suggest that the model needs improvements in production and conversion process of ice clouds, while the global distribution of clouds was relatively well reproduced. Based on systematic investigation in comparison with previous studies (Noda et al. 2010[12]; Yamada et al. 2010[13]) the parameter values of autoconversion rate of cloud ice to cloud snow were tuned for long-term simulations planned in FY2011. Aquaplanet experiments were motivated to understand different behavior of large-scale cloud disturbances in the previous simulations using NICAM (Tomita et al. 2005[10]; Miura et al. 2007[3]). It was found that large-scale slow moving convective variability analogues to MJO emerged with zonally perturbed distribution of SST with 4.5 K amplitude, forced by the Walker circulation. Further investigations are continuing in FY2011.

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全球雲解像モデルを用いた雲降水プロセス研究

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本プロジェクトは地球上の雲降水プロセスの理解を深め、全球雲システム解像モデルでのこれらのプロセスを改善することを目的としている。今年度は台風 Fengshen の発生プロセスに焦点を置いた、全球で 3.5km の水平格子を用いた 10 日間の実験を実施した。その計算結果を熱帯低気圧発生のマルチスケールに注目して解析し、現地観測や衛星観測と比較することによって評価した。また水平 14km 格子を用いた感度実験ではシミュレートされた雲の全球規模で統計的に評価した。本結果に基づいて長期間のシミュレーションにおける再現性を向上させるためにパラメーターを調整した。一方で季節内程度の時間スケールを持った熱帯の大気－海洋変動の基本的なメカニズムを理解するために、理想化された水惑星実験も実施した。その結果は海面温度の東西コントラストの重要性を示していた。

キーワード : 雲降水プロセス , 全球雲解像モデル