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

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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 resolving clouds on the whole globe. In the FY2011, three specific themes were pursued as the extension of the FY2010 research: (1) Evaluation of global cloud properties of the 3.5-km mesh Nonhydrostatic Icosahedral Atmospheric Model (NICAM) simulation outputs using a satellite simulator. A sensitivity experiment on cloud microphysical parameters was newly performed for this purpose, (2) Improvement of climatological properties of clouds and precipitation by implementation of a subgrid-scale convection scheme to NICAM. A series of sensitivity experiments showed reduction of the biases in surface precipitation over the Indian Ocean and the South Pacific Convergence Zone (SPCZ), and (3) An idealized experiment with an aquaplanet setup was extended to 160 model days. A slow eastward-propagating mode, resembling the Madden-Julian Oscillation (MJO), was obtained in the experiment. The importance of forcing by Walker circulation to the emergence of this slow mode was found. Preparatory simulations of recently observed prominent MJO events in the field program have also been started.

Keywords: cloud and precipitation processes, global cloud resolving model

1. Introduction

Understanding of cloud and precipitation processes based on latest observational products and numerical simulations are critical to reliable prediction of global climate change. Our research team has been developing a global cloud resolving model, Nonhydrostatic Icosahedral Atmospheric Model (NICAM, Satoh et al. 2008[1]), which is capable of calculating cloud and precipitation processes explicitly on the whole globe. NICAM has been run on the Earth Simulator to produce a number of research products (e.g., Tomita et al. 2005[2]; Iga et al. 2007[3]; Miura et al. 2007[4]; Oouchi et al. 2009[5]; Noda et al. 2010[6]; Yamada et al. 2010[7]). After the renewal of physical packages in the FY2009 (Satoh et al. 2010[8]), evaluations of simulated cloud and precipitation processes in comparison with in-situ observation and satellite data have been promoted in this project (Satoh et al. 2011[9]). In the FY2011, we have extended our research themes on the basis of the FY2010 achievements. In this article, three major topics are reported in the following sections.

2. Evaluation of cloud properties in the global 3.5-km mesh simulation by J-simulator

Evaluation of the aerosol and clouds simulated with general circulation models (GCMs) and cloud resolving models is an important step toward reducing uncertainty associated with climate and weather prediction. One approach for the evaluation is to simulate the data that satellite would observe based on the atmospheric information simulated with the models. This study uses Joint Simulator for Satellite Sensors (J-simulator) that is being developed under Japan Aerospace Exploration Agency (JAXA) EarthCARE satellite project. The global 3.5-km mesh NICAM simulation data (the FY2010 products, Satoh et al. 2011 [9]) was evaluated against satellite data which was obtained from CloudSat 95 GHz radar and CALIPSO lidar.

In the FY2011, the joint Probability density functions (pdfs) of the signals and temperature (Contoured Frequency by tEmperature Diagram, CFED) were constructed with three different cloud masks that use radar, lidar and both of them, from observed and simulated signals (Fig. 1). The use of temperature as a substitute for altitude gives insights on cloud microphysical processes. NICAM tends to have fewer occurrences of clouds defined with radar mask less than −45ºC level, more concentrated reflectivity, and larger reflectivity than observation. On the other hand, the lidar signal indicates more cloud occurrences above −50ºC and two modes existing in T<−40ºC. The portions of the CFEDs are easily related to hydrometeor categories by turning on/off each contribution in J-simulator. Furthermore, the use of radar and lidar signals for a given volume enables us to evaluate the water content and effective radius qualitatively against observation. For example, the water content (effective radius) of snow category was shown less (larger) than the observations.

Based on the assessment of cloud microphysical properties in the NICAM simulation, a global 3.5-km mesh sensitivity experiment was conducted in the FY2011, where the fall speed of cloud ice was decreased to a more realistic value, and autoconversion rate of cloud ice to snow was accelerated based on the sensitivity study using the 14-km mesh NICAM (Satoh et al. 2011[9]). The sensitivity run was initialized in the same way as the control run and integrated for a three-day period. Figure 2 compares the latitude-height sections of zonally averaged ice condensates in the control and sensitivity runs. As expected, mass of ice condensates of all categories are reduced in the sensitivity run. The CFEDs of the sensitivity run were also evaluated. The slower sedimentation and faster snow growth led to less overlapping areas of radar and lidar signals than the control (not shown). Comparison between observed and simulated IR and evaluation of the lidar CFED suggest excessive amount of cloud ice mass mixing ratio at higher altitude than the control case. This can be related to higher amount of cloud ice above 200 hPa in the sensitivity run than the control case (Fig. 2). In a general sense, no obvious difference in water content and effective radius was indicated in terms of the radar-lidar signal diagnosis.

The direct comparison of cloud microphysical outputs, such as mass mixing ratio and effective radius, between the control and the sensitivity run gives further supporting information. In conclusion, the forward approach with J-simulator is effective to

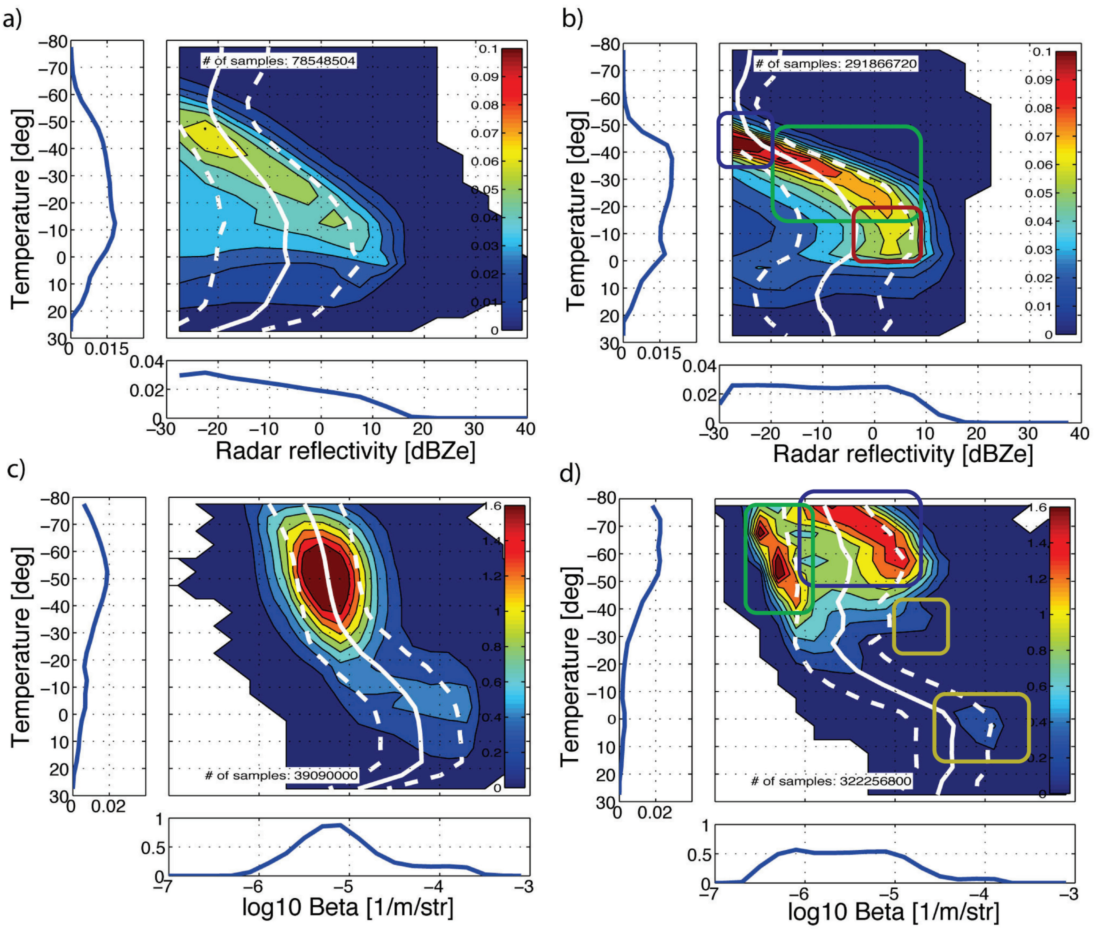

Fig. 1 CFED for 94 GHz radar reflectivity with C1 and 532 nm lidar backscattering with C2. a) and c) are the observation; b) and d) the NICAM simulation. The colorfill shows 100 times of the joint pdf. The white solid curves are the mean, and white broken lines are the mean plus or minus the standard deviation. The marginal pdfs in terms of radar reflectivity and temperature are shown in the bottom and left panel, respectively. The blue, green, red, and yellow round rectangles show the major contributions from cloud ice, snow, graupel, and cloud droplets, respectively. (courtesy of Dr. Tempei Hashino).

evaluate the NICAM simulation.

3. Toward the reduction of precipitation biases in high-resolution simulations

Small-scale convection can hardly be resolved at a horizontal grid size larger than the order of 1 km, although it plays an important role for vertical transport of heat, moisture, and momentum in the tropics. We introduced a cumulus parameterization scheme (Chikira scheme, Chikira and Sugiyama 2010[10]), aiming at a better representation of the effects of such subgrid-scale convection along with improving model climatology (e.g., the spatial characteristics) of precipitation in a few kilometer mesh NICAM.

In the first place, we conducted a test simulation using the same parameter setting as in the latest version of Model for Interdisciplinary Research on Climate (MIROC) (Fig. 3). The inclusion of the parameterization reduces excessive precipitation over the Indian Ocean. The parameterization acts

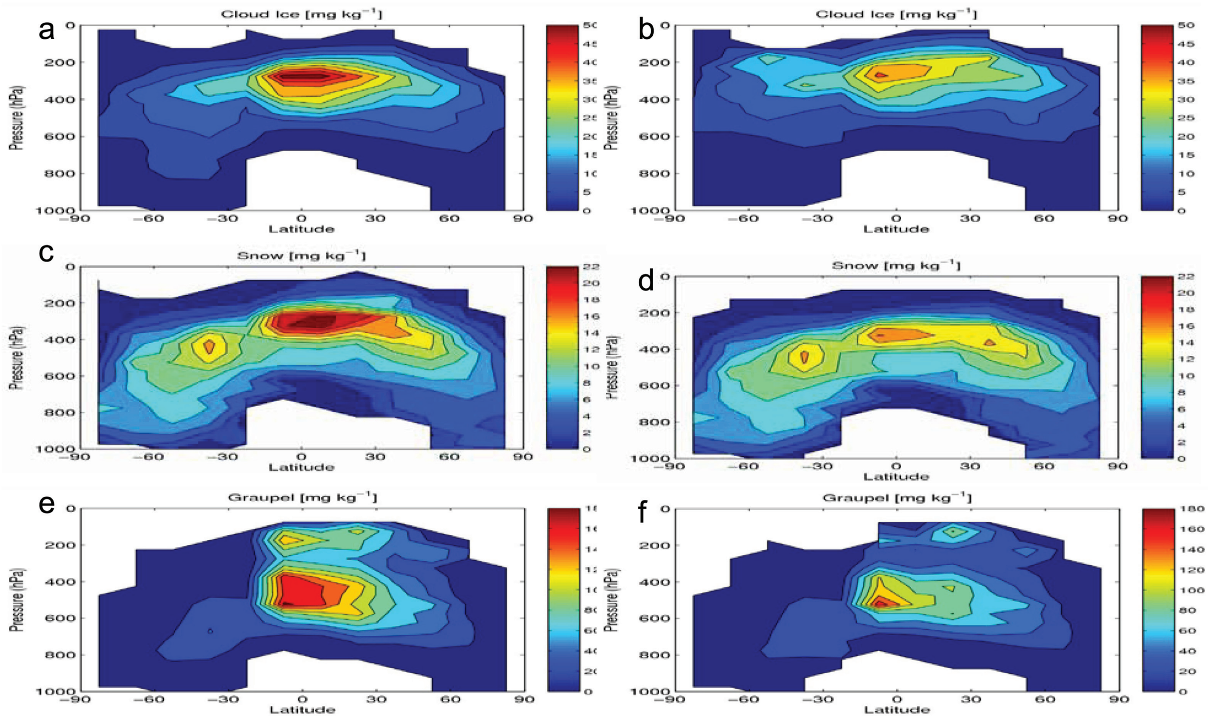

Fig. 2 Latitude-height sections of zonally averaged (a) (b) cloud ice, (c) (d) snow, (e) (f) graupel content (10^{-6} kg kg^{-1}) for the control run (left panels) and the sensitivity run (right panels) of the global 3.5-km mesh NICAM simulation outputs. The grid points with condensates exceeding 0.2 x 10^{-6} kg kg^{-1} are considered. (courtesy of Dr. Tempei Hashino).

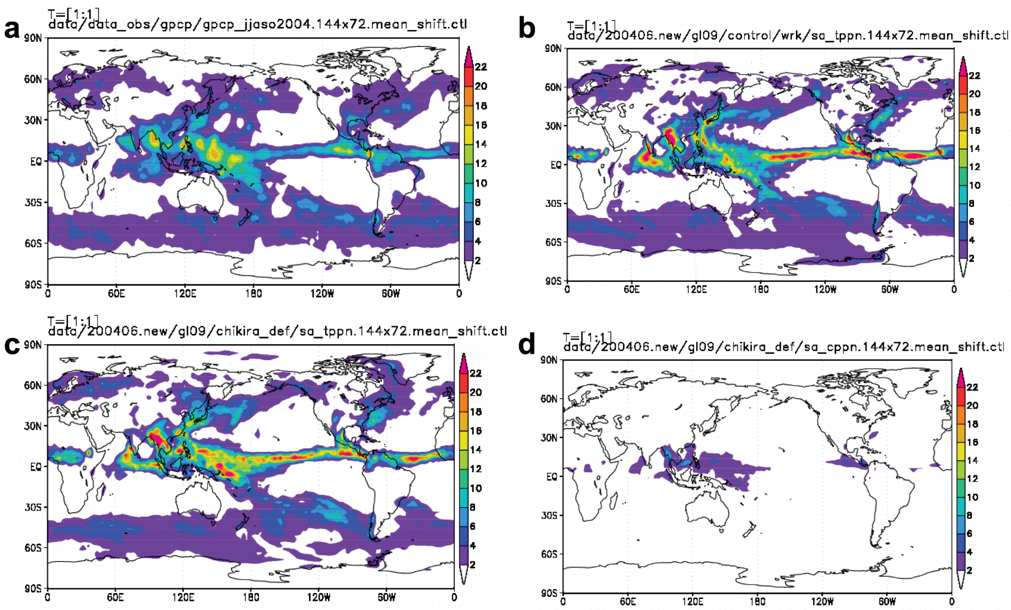

Fig. 3 Comparison of surface precipitation (mm dy^{-1}) of (a) GPCP data and (b)-(d) 14-km mesh NICAM simulations during June 2004. (b) shows the total amount of surface precipitation without the Chikira scheme. (c) and (d) show the total amount of surface precipitation and the contribution by the Chikira scheme , respectively.

to produce surface precipitation especially over the western and eastern parts of the Pacific Ocean in the tropics, although their amplitudes are much smaller than the total surface precipitation.

We also conducted a set of sensitivity experiments regarding unknown parameters of the scheme. The parameters chosen are the ones determining the vertical distribution of subgrid-scale in-cloud vertical velocity (***a*** and Cε of Eq. 4 in Chikira and Sugiyama 2010[10]). The changes of the parameters within a realistic fluctuation range affect the detailed changes of surface precipitation such as its intensity over the SPCZ (Fig. 4). Subsequent sensitivity studies about possible parameters to further reduce the model precipitation biases have been continuing.

4. Aquaplanet experiments

Over the tropics, two types of precipitation systems (PSs), super clusters (SCs) and Madden-Julian Oscillation (MJO), are frequently observed, having similar symmetric structures about the equator but different eastward-propagating (EP) speeds. In this project, a series of aquaplanet experiments has been conducted to gain insight into these basic regimes of organized clouds and precipitation in the tropics.

Yoshizaki et al. (2012a[11]), focusing on the reasons why these PSs exist, examined the dependence of the longitudinal variations of sea surface temperature (SST) using NICAM with an aquaplanet setups (Fig. 5). Here, a component, A, is written as $\langle A \rangle$ when it is longitudinally averaged, and as A_b when it is temporally averaged. Then, the Hadley circulation (HC) is defined as $\langle A_b \rangle$, and the Walker circulation (WC) as $A_b - \langle A_b \rangle$. In a longitudinally uniform-SST case, only SC-like fast-EP PSs appeared (Fig. 5a). When the longitudinal variation of the SST was increased (Fig. 5c), on the other hand, a stationary WC emerged and MJO-like slowly EP PSs occurred on the western part of a high-SST area. It is expected in the real atmosphere

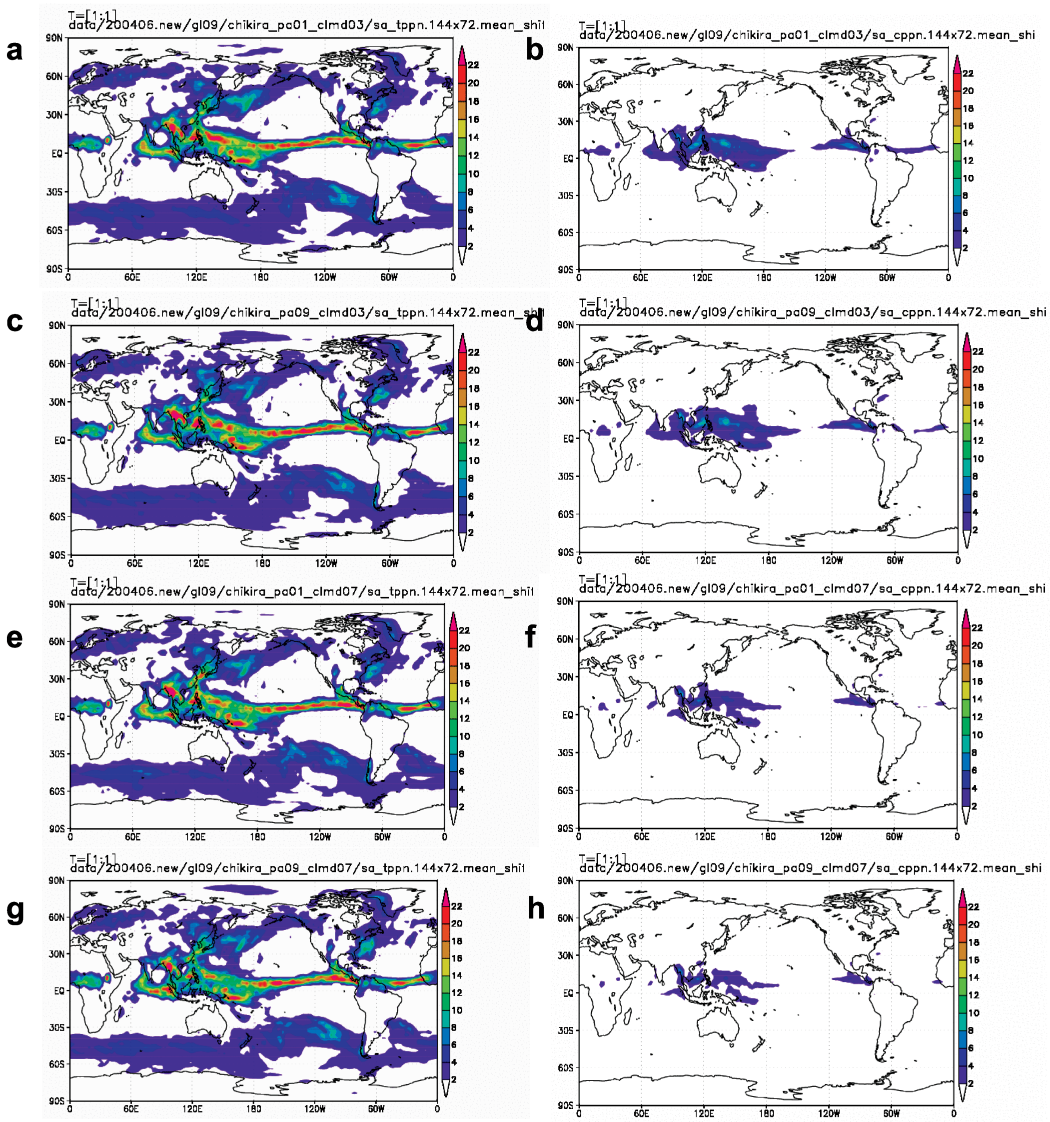

Fig. 4 Sensitivity of parameters (a and C_ε) in the Chikira scheme to surface precipitation (mm dy^{-1}) during June 2004 using the 14-km mesh NICAM. (a) and (b) are the total amount of surface precipitation and the contribution by the Chikira scheme, respectively, using a=0.1 and C_ε=0.3. (c) and (d) are the same as (a) and (b), except using a=0.9 and C_ε=0.3. (e) and (f) are the same as (a) and (b), except using a=0.1 and C_ε=0.7. (g) and (h) are the same as (a) and (b), except using a=0.9 and C_ε=0.7.

that two different types of EP PSs can simultaneously exist due to complex surface conditions: 1) SCs as free PSs and 2) MJOs as forced PSs. Here, free (forced) PSs mean convection, which is uncontrolled (controlled) by the longitudinal variation of the SST. Owing to the WC (Fig. 6), combined with the HC, the MJO was generated and decayed locally, and westward-propagating PSs were dominantly observed in the subsidence areas of the WC.

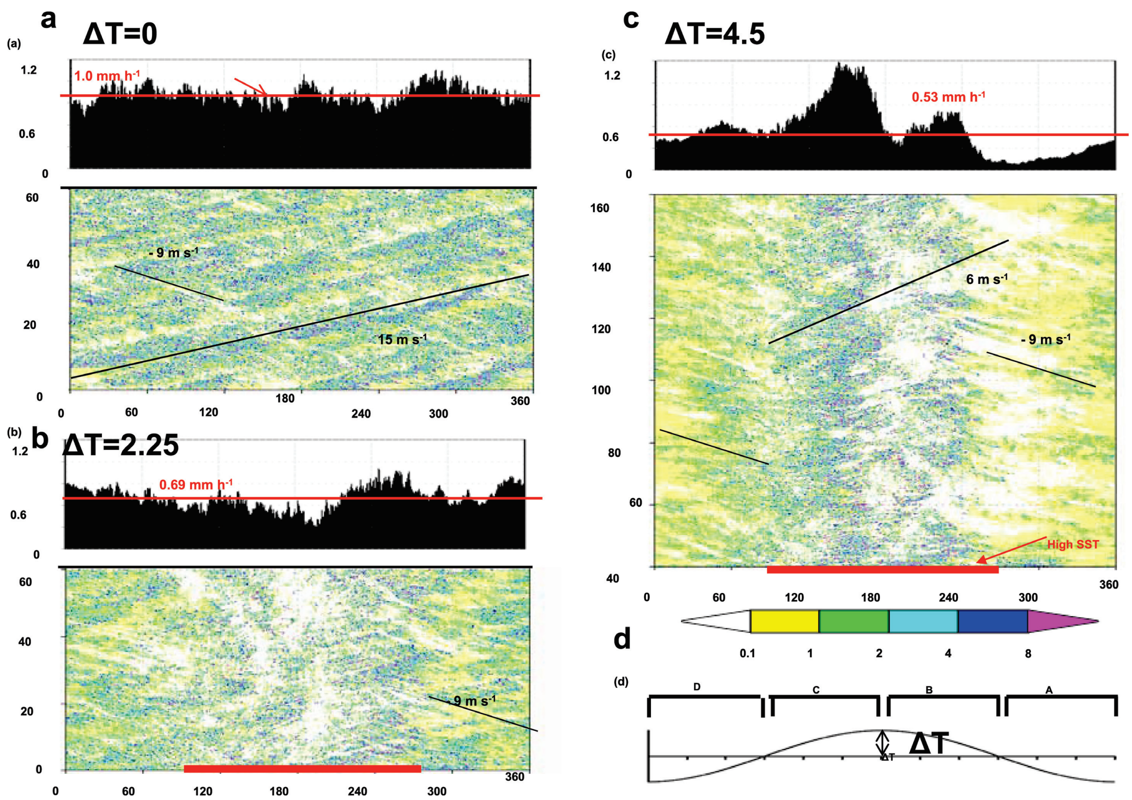

Fig. 5 Time-mean distributions and longitude−time sections of surface precipitation (mm h^{-1}) averaged between 3°S and 3°N for (a) $\Delta T = 0$, (b) $\Delta T = 2.25$, and (c) $\Delta T = 4.5$ cases. (d) Zonal distribution of the SST variation. The figure is adopted from Fig. 2 of Yoshizaki et al. 2012a.

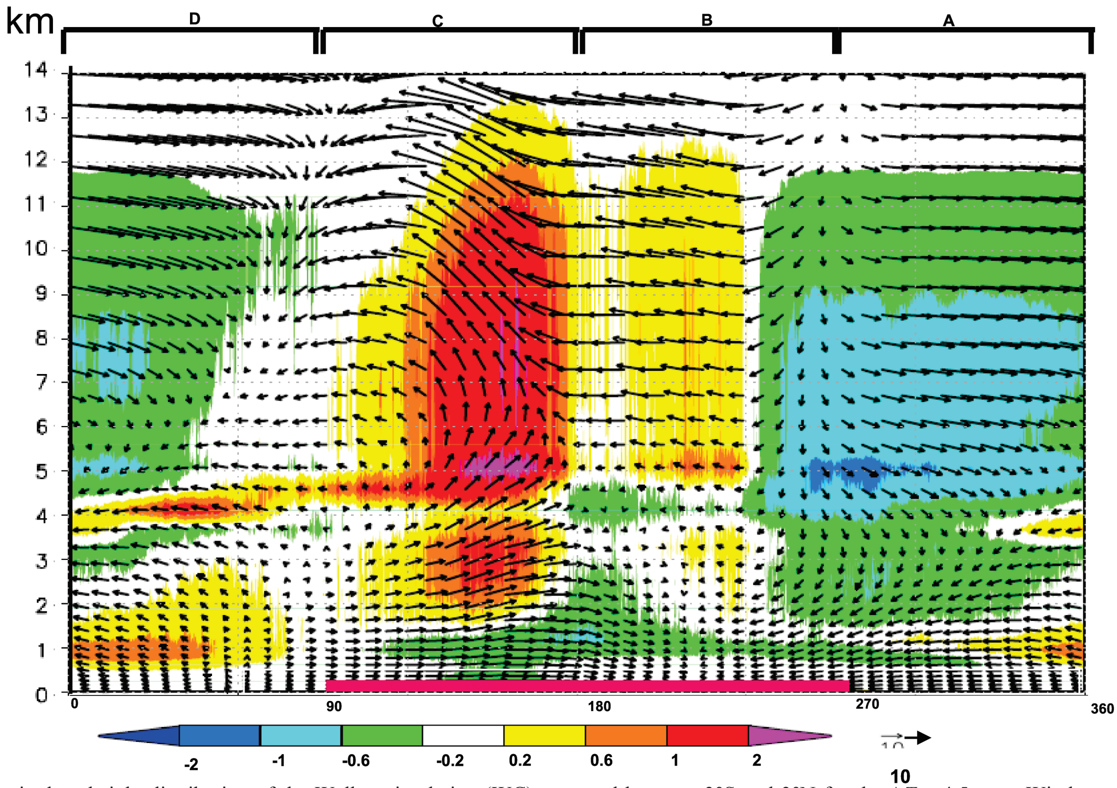

Fig. 6 Longitude − height distribution of the Walker circulation (WC) averaged between 3°S and 3°N for the $\Delta T = 4.5$ case. Wind vectors and a color bar denote (u, 400w) and diabatic heating, respectively. A red line between 90°−270° longitude denotes the high-SST area. The figure is adopted from Fig. 5b of Yoshizaki et al. 2012a.

Yoshizaki et al. (2012b[12]) also studied PSs in coarse resolution simulations. An EP property of the PSs appeared even with the horizontal resolution as coarse as 112 km, so long as the vertical stratification was kept conditionally unstable. The appearance or disappearance of the EP property is explained by comparing mesoscale (100 km) and large-scale (1,000 km) PSs, a non-precipitation system (NPS), and a precipitation system simulated by a dry model (DP) with positive-only wave Conditional Instability of the Second Kind (CISK) heating. By assuming that the height and the updraft intensity of convection are common in these systems, the turnover times of representative convections were estimated. Compared with the time scale of the equatorial beta (T_β), where its effect essentially works and the distinct EP property appears, the turnover times of the large-scale PS and DP were longer than T_β, producing the EP property, whereas those of the NPS and mesoscale PSs were shorter, inducing no EP property. These results are consistent with previous studies based on observations and numerical experiments (Nakazawa 1988[13]; Nasuno et al. 2007[14]).

5. Summary

The goal of this research project is to evaluate cloud and precipitation processes in the global cloud resolving model NICAM and to improve the physical processes in the model. The key issues are: (1) evaluation of the high-resolution simulation results using in-situ and satellite observations, (2) improvement of the model physics in perspective of reliable future climate prediction, and (3) basic understanding of multi-scale mechanisms of organized clouds and precipitation in the tropics. In the FY2011 we investigated these subjects.

The cloud microphysical properties of the global 3.5-km simulation outputs were evaluated in close comparison with satellite data using the J-simulator, which have been developed in the JAXA EarthCARE project (to be launched in 2014). The evaluation by a new analysis method, CFEDs, revealed several conspicuous biases of ice species in NICAM simulation. Sensitivity experiments showed that the total mass of ice condensates can be controlled by properly setting fall speed and autoconversion rate of ice clouds, but cloud microphysical properties (e.g., effective radius) were generally unaltered. The usefulness of this kind of analysis in evaluating the simulation results is confirmed. Improvement of climatological properties of clouds and precipitation is also indispensable to next generation GCMs. The importance of shallow clouds and boundary layer processes, which cannot be resolved by a few kilometer mesh sizes, is increasingly recognized. With this perspective, a subgrid-scale convection scheme (Chikira and Sugiyama 2010[10]) was implemented to NICAM. A series of sensitivity experiments indicated reduction of the biases over the Indian Ocean and SPCZ. Further investigation is in progress. The understanding of basic modes of convective organization in the tropics helps us interpret the simulated clouds and precipitations. The results from a series of aquaplanet experiments revealed the importance of zonal circulation in the equatorial region (Walker circulation), which is forced by zonal variation of SST (and by land mass distribution in the real atmosphere), to the emergence of slow eastward propagating mode of convection. This mode resembles MJO, and is distinctly different from another typical type of tropical convective disturbance; the fast eastward-propagating 'free' mode.

We have also started a new research subject, namely, understanding of cloud and precipitation in the recently observed MJO events. Preparatory simulations of prominent MJO events which occurred during a field campaign CINDY2011 / DYNAMO (intensive observation period: October 2011 - January 2012) and those during the YOTC period (October 2009 - January 2010 events) have been in progress. This theme will be pursued in the FY2012.

CINDY2011: Cooperative Indian Ocean experiment on intreaseaonal variability in the year 2011 (http://www.jamstec.go.jp/iorgc/cindy/index_e.html)
DYNAMO: Dynamics of the Madden-Julian Oscillation (http://www.eol.ucar.edu/projects/dynamo/)
YOTC: Year of Tropical Convection (http://www.ucar.edu/yotc/index.html)

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References

[1] Satoh, M. T. Matsuno, H. Tomita, H. Miura, T. Nasuno, and S.-I. Iga, "Nonhydrostatic Icosahedral Atmospheric Model (NICAM) for global cloud resolving simulations," J. Comput. Phys., doi:10.1016/j.jcp. 2007.02.006, the special issue on Predicting Weather, Climate and Extreme events. 2008.

[2] Tomita, H., H. Miura, S.-I. Iga, T. Nasuno, and M. Satoh, "A global cloud-resolving simulation: Preliminary results from an aqua planet experiment," Geophy. Res. Lett., 32, L08805, doi:10.1029/2005GL022459, 2005.

[3] Iga, S.-I., H. Tomita, Y. Tsushima, and M. Satoh, "Climatology of a nonhydrostatic global model with explicit cloud processes," Geophys. Res. Lett., 34, L22814, doi:10.1029/2007GL031048, 2007.

[4] Miura, H., M. Satoh, T. Nasuno, A. T. Noda, and K. Oouchi, "A Madden-Julian Oscillation event realistically simulated by a global cloud-resolving model," Science, 318, 1763-1765, 2007.

[5] Oouchi, K., A. T. Noda, M. Satoh, H. Miura, H. Tomita,

T. Nasuno, and S.-I. Iga, “A simulated preconditioning of typhoon genesis controlled by a boreal summer Madden-Julian Oscillation event in a global cloud-system-resolving model,” SOLA, 5, 65-68, doi:10.2151/sola.2009-017. 2009.

[6] Noda, A. T., K. Oouchi, M. Satoh, H. Tomita, S.-I. Iga, and Y. Tsushima, “Importance of the subgrid-scale turbulent moist process: Cloud distribution in global cloud-resolving simulations,” Atmos. Res., 96, 208-217, doi: 10.1016/j.atmosres.2009, 2010.

[7] Yamada, Y., K. Oouchi, M. Satoh, H. Tomita, and W. Yanase, “Projection of changes in tropical cyclone activity and cloud height due to greenhouse warming: Global cloud-system-resolving approach,” Geophy. Res. Lett., 37, doi:10.1029/2010GL042518, 2010.

[8] Satoh, M., H. Tomita, T. Nasuno, A. T. Noda, S.-I. Iga, H. Miura, K. Oouchi, H. Taniguchi, Y. Yamada, W. Yanase, C. Kodama, M. Hara, Y. Wakazuki, K. Yasunaga, and T. Seiki, “Study of cloud and precipitation processes using a global cloud-system resolving model,” Annual Report of the Earth Simulator Center, April 2009-March 2010, 49-53, 2010.

[9] Satoh, M., H. Tomita, T. Nasuno, A. T. Noda, S.-I. Iga, H. Miura, K. Oouchi, H. Taniguchi, Y. Yamada, W. Yanase, C. Kodama, M. Hara, Y. Wakazuki, K. Yasunaga, T. Seiki, and M. Yoshizaki, “Study of cloud and precipitation processes using a global cloud-system resolving model,” Annual Report of the Earth Simulator Center, April 2010-March 2011, 43-49, 2011.

[10] Chikira, M. and M. Sugiyama, “A Cumulus Parameterization with State-Dependent Entrainment Rate. Part I: Description and Sensitivity to Temperature and Humidity Profiles,” J. Atmos. Sci, 67, 2171-2193, 2010.

[11] Yoshizaki, M., K. Yasunaga, S.-I. Iga, M. Satoh, T. Nasuno, A. T. Noda, and H. Tomita, “Why do super clusters and Madden Julian Oscillation exist over the equatorial region?” SOLA, 8, 33-36, doi:10.2151/sola.2012-009, 2012a.

[12] Yoshizaki, M., S.-I. Iga, and M. Satoh, “Eastward propagating property of large-scale precipitation systems simulated in the coarse-resolution NICAM and an explanation of its formation,” SOLA, 8, 21-24, doi:10.2151/sola.2012-006, 2012b.

[13] Nakazawa, T., “Tropical super clusters within intraseasonal variations over the western Pacific,” J. Meteor. Soc. Japan, 66, 823–839, 1988.

[14] Nasuno, T., H. Tomita, S.-I. Iga, H. Miura, and M. Satoh, “Multiscale organization of convection simulated with explicit cloud processes on an aquaplanet,” J. Atmos. Sci., 64, 1902-1921, 2007.

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する。今年度は以下の 3 つの課題を実施した。(1) 全球雲解像モデル NICAM を用いた 3.5 km 格子計算における雲微物理特性について衛星シミュレータを用いた評価を行った。この目的のため、雲微物理パラメタに関する感度実験も新たに行った。(2) 雲降水の気候学的特性を改善するため NICAM にサブグリッド対流スキームを導入し、感度計算を行った。その結果、インド洋や南太平洋収束帯の地表降水において改善が見られた。(3) 水惑星数値実験を 160 日まで延長し、マッデン・ジュリアン振動 (MJO) に類似する遅い東進速度をもつ対流モードを得た。この遅いモードの発現におけるウォーカー循環の重要性が分かった。近年の観測プロジェクト期間中に発生した MJO 事例を対象とする予備計算も開始した。

キーワード:雲降水プロセス, 全球雲解像モデル