Simulation and Verification of Tropical Deep Convective Clouds using Eddy-Permitting Regional Atmospheric Models III

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The objective of this project is to develop an eddy-permitting regional atmospheric model, which can simulate turbulent motion with deep moist convection. We develop a regional model called diamond NICAM, whose simulation domain consists of one diamond (two triangles in an icosahedron for the whole globe). In this fiscal year, we performed a series of one-month simulations to validate the regional NICAM. The diurnal cycle of the simulation by the diamond NICAM shows same characteristics as the one of the original global NICAM and other simulations. We also performed large-eddy simulation of stratocumulus clouds in order to determine the responses of typical marine stratocumulus cloud to perturbed boundary layer states. The results show that the most important factors controlling the boundary layer cloud behavior are the amplitude of gaps in vapor and temperature across a boundary layer top.

Keywords: LES, regional atmospheric model, NICAM, cloud resolving model, boundary layer clouds

1. Introduction

Deep convection in tropics is one of the most important heat sources for the planetary-scale atmospheric circulation. Although the convection system occurs in synchronization with a diurnal cycle, the diurnal cycle, i.e., intensity and space distribution of deep convection, is not well simulated in most of GCMs. Therefore, it is an important task to understand the dynamical aspects of such deep convective systems in relation with the diurnal cycle and local circulation. The purpose of this project is as follows;

- to develop an eddy-permitting regional atmospheric model, which can simulate turbulent motion with deep moist convection, by the use of a grid resolution on the order of a hundred meters, in order to represent explicitly the cloud-scale processes,
- to perform several Large-Eddy Simulation (LES)s for tropical convection using this model, and to improve the model by comparing the results with observation and performing some sensitivity studies, and
- to investigate the generation and maintenance mechanism of convective systems based on the simulated data, which can be fundamental for improving cumulus parameterization schemes used in larger-scale atmospheric models including GCMs.

In order to develop the eddy-permitting regional atmospheric model efficiently, we adopted a model using similar dynamical and physical frameworks to those of a global cloud-resolving model called NICAM (Nonhydrostatic ICosahedral Atmospheric Model, Satoh et al., 2008[1]). Based on NICAM, we have developed two kinds of models. One is a regional model called a diamond NICAM, whose simulation domain consists of one diamond (two triangles in an icosahedron), although the original NICAM global domain consists of ten diamonds (twenty triangles). The results of some test experiments are shown in section 2. Although the diamond NICAM can be used for a very small region, because the model is based on a spherical-coordinate it cannot be used for the case of cyclic boundary conditions, which is often adopted in small-scale numerical simulation study for convection. Therefore, another model called a plain-coordinate NICAM is also developed which can be used for the case of cyclic boundary conditions. Some results of simulating boundary layer clouds relating to such boundary conditions are shown in section 3.

2. Diamond NICAM for regional climate simulations

This regional atmospheric model is developed for conducting realistic regional climate simulations, targeted onto a certain limited area. Stretched horizontal grid version of a regional model based on the global cloud-resolving model, NICAM, had developed and used by Tomita (2008) [2] and Satoh et al. (2010) [3]. In these simulations, inhomogeneity of horizontal grid sizes causes inconsistency of physical parameterizations such as cumulus convection. The simulation domain of the newly developed regional model (hereafter diamond NICAM) consists of one diamond (two triangles in an icosahedron), although the original NICAM global domain consists of ten diamonds (twenty triangles). We modified the original NICAM to enable the limited area simulation with minimum modification of source code.

In this fiscal year, we performed a series of one-month simulations to validate the regional NICAM. We performed three numerical simulations, i.e., (1) stretched grid global simulation without nudging, (2) stretched grid global simulation with nudging, and (3) diamond NICAM simulation. The initial and nudging data used are the simulation results of Glevel-9 global NICAM performed in Yamada et al. 2010 [4].

Figure 1 shows domains of numerical simulations. Figure 1(a) is grid location for stretched grid global simulation (simulations 1 and 2) as one of the control experiments. Figure 1(b) shows grid location of numerical simulation by diamond NICAM (simulation 3). Duration of the simulations is from 00Z 2 June 2004 to 00Z 1 July 2004. We validate the simulations with global Glevel-9 NICAM simulation (Yamada et al., 2010)[4]. Difference of the experiment setting between (simulation 2) and (simulation 3) is only numerical domain. The results of (simulation 2) and (simulation 3) should be same if the diamond NICAM works correctly.

Figure 2 shows one-month averaged 6-hourly precipitation for each simulation. The figure shows the simulated diurnal cycle of precipitation over a large island. i.e., the precipitation is weak from 06 to 17 LST over the island, and in the nighttime, the maximum appears over the northwestern ocean and the band from northeast to south west of the island along the mountain ranges. This diurnal cycle of precipitation well agrees to the one observed, which is not well simulated by a usual global model with coarse grid interval (Hara et al. 2009)[5]. The diurnal cycle of the simulation by the diamond NICAM in (d) shows same characteristics as the one of the original global NICAM and other simulations.

3. Large-eddy simulations of stratocumulus cloud

Marine stratocumulus clouds are one of the most important climatic elements, especially with respect to their influence on the Earth's radiative budget through their high solar albedo and significant coverage. Consequently, a realistic representation of stratocumulus clouds in global climate models (GCMs) is required for an accurate prediction of future climate change. However, at present, such boundary-layer (BL) clouds are poorly represented in GCMs and their low-accuracy prediction prevents a better understanding of future climate change. The reason for this difficulty arises not only from the complexity associated with modeling BL processes, but also from model biases, such as in the predicted thermodynamic and dynamic structure in and around the BL used to generate clouds within their BL scheme. It remains unclear which of these biases within the large-scale conditions are crucial to the accurate reproduction of BL clouds. To develop a better understanding of the effects of variations in the simulated large-scale conditions, we use large-eddy simulations to evaluate the effects of the fluctuation based on the latest GCM ensemble data on the prediction of a Californian stratocumulus under perturbed environments.

The case chosen was initially conducted in the DYCOMS-II model intercomparison study (Ackerman et al., 2009[6]; herein, A09). The horizontal and vertical grid lengths were 50 and 5 m, respectively, following A09. The domain size was 6.5 × 6.5 km^2 horizontally, and 1.5 km vertically. In this study, the setting of the control experiment (herein, CTL) from the A09 was modified in two aspects. First, for simplicity, the wind velocity at the initial state was modified to (u, v) = (8.0 m s^{-1}, 0 m s^{-1}) over the domain to examine the sensitivity of wind and the associated vertical shear. The wind velocity of 8.0 m s^{-1} corresponds to the approximate average of the initial wind

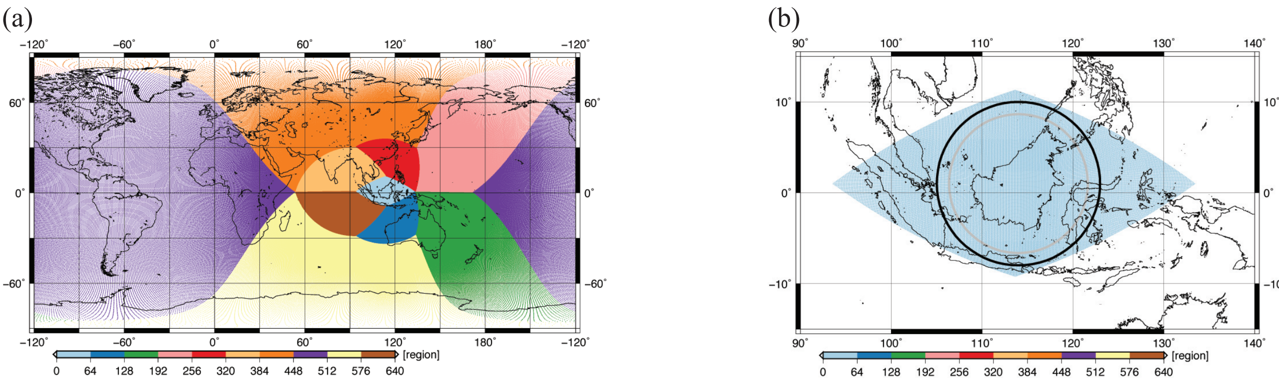

Fig. 1 Domains of numerical simulations of (a) grid location of stretched grid global NICAM, and (b) grid location of diamond NICAM.

velocity in A09. The geostrophic wind was set to 8.0 m s^{-1} over the entire domain during the simulation with a Coriolis parameter of 7.62 × 10^{-5} s^{-1} (A09). Second, the surface fluxes were computed based on Monin–Obukhov's similarity theory (Kondo, 1975)[7] to examine cloud behavior under different stability conditions near the surface. In addition, the definition of the height of the BL top, z_i, was modified from that in A09 to the average of heights where the vertical gap in the total water mixing ratio, $q_t = q_v + q_l$, was at a maximum in each column.

To determine the extent of any differences caused by the slight modification of CTL from A09, we also conducted an experiment that followed A09 for reference (herein, ORG). We examined the responses of simulated clouds by assigning possible errors in GCMs to each factor of the BL states. We

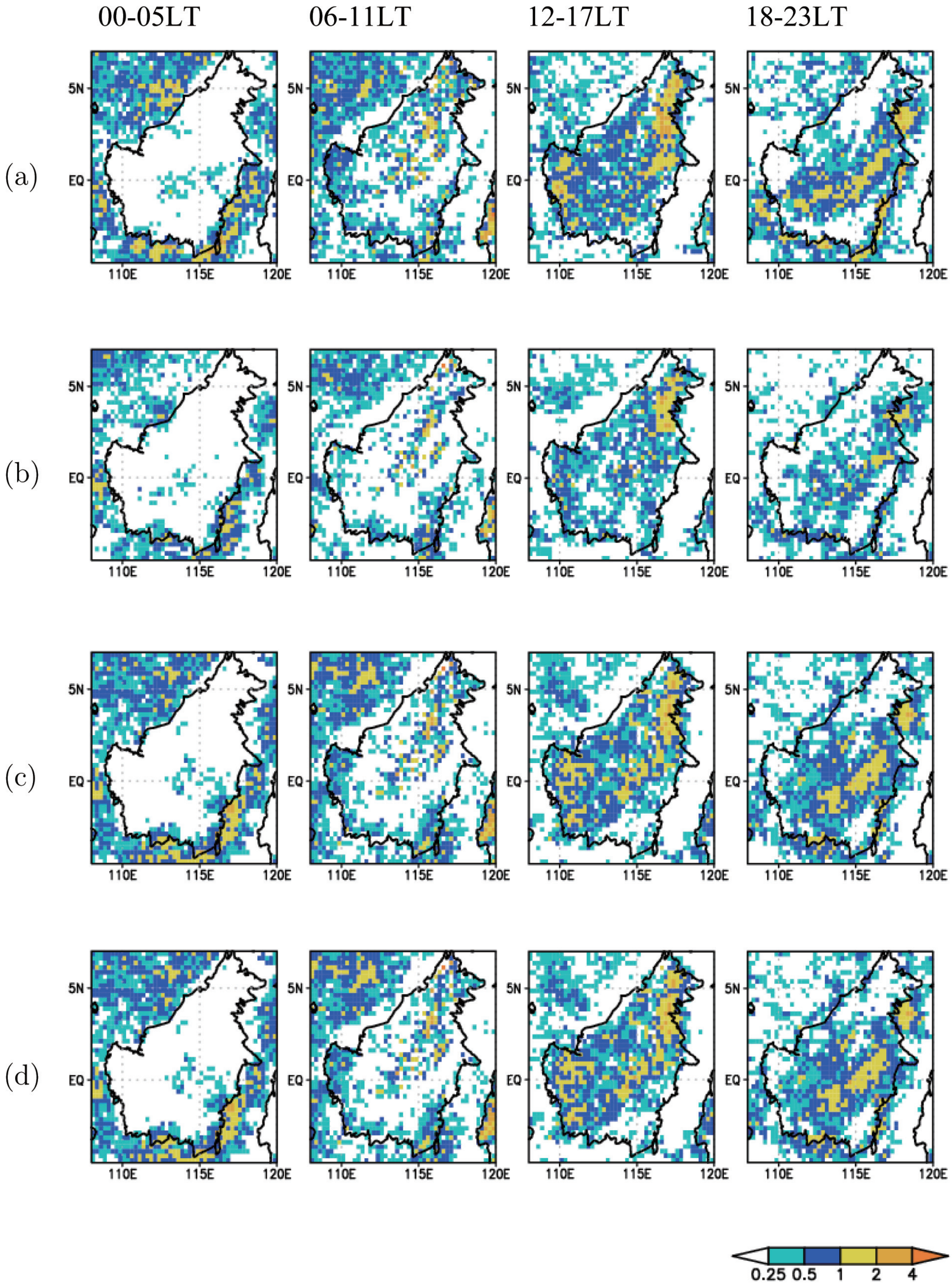

Fig. 2 One-month averaged diurnal cycle of precipitation by (a) global NICAM simulation, (b) stretched grid global simulation without nudging, (c) stretched grid global simulation with nudging, and (d) diamond NICAM simulation. From left to right 00-05LT, 06-11LT, 12-17LT, 18-23LT.

first considered six factors as possible major elements affecting the behavior of stratocumulus cloud: gaps in vapor and in temperature across z_i, the strength of wind velocity (and its vertical shear near z_i), the strength of subsidence, and surface sensible and latent heat fluxes (SHF and LHF, respectively). For these experiments, we examined cases in which low-resolution models, including GCMs, predict each component with a 20% bias. This threshold was selected based on the variance of the large-scale environment over regions of Californian (USA) stratocumulus clouds in the current GCMs within the present climate simulations of CMIP5 (Coupled Model Intercomparison Project Phase 5). Time integration was performed for six hours for these experiments, and averages for the last two hours were analyzed.

Figure 3 compares the liquid water path (LWP) in CTL with the sensitivity experiments. First, we will consider the difference between CTL and ORG. The LWP in CTL shows the result similar to that in ORG, although the former is smaller by ~3% compared with ORG. A possible major reason for this slight difference is increased entrainment of overlying dry air in CTL during an earlier stage of the simulation. In fact, z_i in CTL is slightly higher than that in ORG (not shown). Thus, we conclude that the slight modification of CTL from ORG does not cause significant issues in the behavior of the typical stratocumulus cloud (DYCOMS-II).

Comparing CTL with the other experiments, there are two major factors that change LWP: gaps in vapor and temperature across z_i. For the temperature gap, the result is consistent with previous findings that the temperature stratification of the lower atmosphere strongly controls BL clouds (Wood and Bretherton, 2006)[8]. In addition, our results indicate that, in predicting LWP, the error of the gap in vapor in the GCMs causes a greater error than the gap in temperature, if the predicted percentages of both errors are similar.

The importance of the other factors investigated was of a similar magnitude in all cases, but this was less than the impact of the vapor and temperature gaps across z_i. For the strength of wind velocity, a stronger (weaker) initial wind velocity leads to more (fewer) LWP. The magnitude of the LWP change is more pronounced when wind velocity is increased. The decrease (increase) of the subsidence strength results in the increase (decrease) of LWP. Changes in LHF and SHF also affect the prediction of LWP. LWP increases when SHF increases. The decrease in SHF does not alter LWP greatly in this case. The decrease (increase) in LHF results in the increase (decrease) of LWP.

The results indicate the relative importance of each component, and the most important factors controlling cloud behavior are the amplitude of jumps in vapor and temperature across a BL top. The given variations in wind velocity and its vertical shear, large-scale subsidence, and surface heat fluxes have a lesser effect. This suggests that to reduce model biases predicted in GCMs, greater attention should be paid to the stratification structure across the BL top. The details of this study are written in Noda et al (2014)[9].

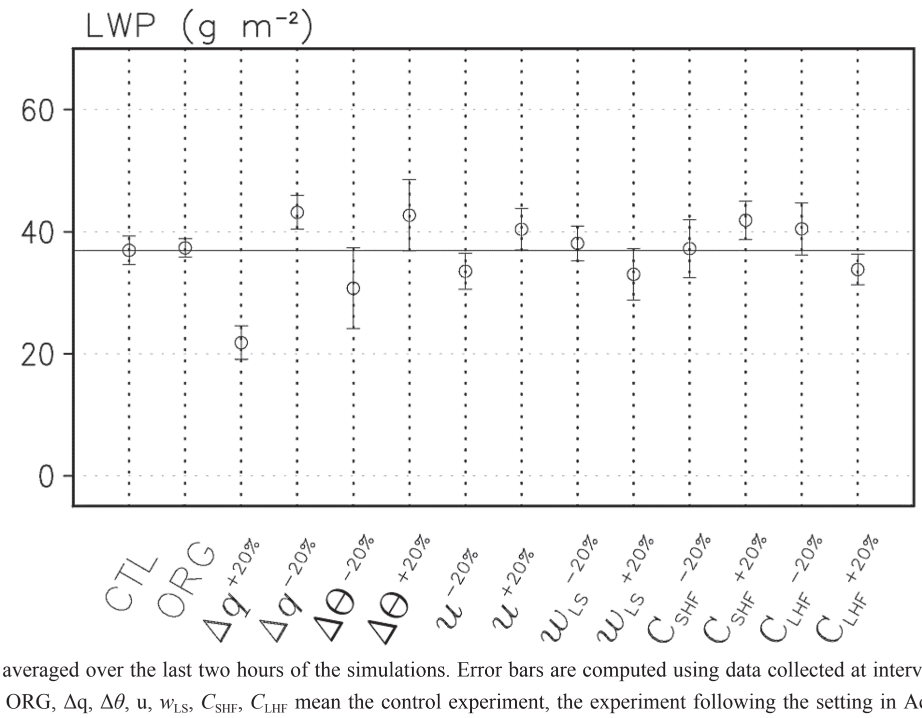

Fig. 3 LWP (g m^{-2}) averaged over the last two hours of the simulations. Error bars are computed using data collected at intervals of 60 s during this period. CTL, ORG, Δq, $\Delta\theta$, u, w_{LS}, C_{SHF}, C_{LHF} mean the control experiment, the experiment following the setting in Ackerman et al. (2009), experiments changing vapor and liquid water potential temperature across inversion, BL mean wind velocity, subsidence, sensible and latent heat fluxes from the surface. Subscripts of "+20%" ("-20%") mean the results in which each quantity is increased (decreased) by 20%. The horizontal line shows the value of CTL.

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渦解像可能な領域大気モデルを用いた深い対流のシミュレーションとその検証（その３）

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本プロジェクトの目的は、十分に細かい格子を用い、深い湿潤対流を解像できるモデルを開発することである。効率的な開発のため、全球雲解像モデル（NICAM、Nonhydrostatic ICosahedral Atmospheric Model）と共通の力学／物理フレームワークを用いた２つの NICAM モデルを開発した。領域版 NICAM は全球版 NICAM の一部を用いるもので、今年度は、その有効性の確認のため１か月再現実験を行った。領域版 NICAM によって再現された日変化の様子は、全球 NICAM などの結果とよく一致した。一方、周期境界条件のケースとして、境界層にできる雲の外部条件の変動に対する応答を調べた。その結果、境界層雲の振る舞いには、境界層上部の温度と湿度のジャンプが大きな影響を持つことがわかった。

キーワード : LES, 領域大気モデル, NICAM, 雲解像モデル, 境界層雲