論文の内容の要旨

Thesis Summary

論文題目(Title of Dissertation)
Improvement of Regional Climate Model Applicability using Precipitation Structure Scheme Linkage with Focus on Multi-Physics Parameterizations (物理的パラメタリゼーションの複合に着目した降水形態スキームの連携による地域気候モデルの適応範囲の改良)

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本文 (Body)

The distribution of precipitation fields from Regional Climate Models (RCMs) to be used as forcing to hydrologic impact studies is crucial, especially in the advent of climate change issue. So, it is imperative that the RCM used for dynamic downscaling has appropriately selected physics parameterizations schemes to be able to reproduce realistic precipitation fields.

The appropriate representation of precipitation in an RCM entails the correct representation of the cloud formation and evolution. Small-scale or complex processes associated to cloud and precipitation processes are represented in RCMs through simplified representations called sub-grid parameterizations (parameterizations, which includes cumulus convection (CU), microphysics (MP), radiation (RAD), planetary boundary layer (BL), and land surface models (LSM). Each of these parameterizations has different implementations called schemes that can vary in complexity and applications. A lot of parameterization scheme sensitivity studies have been done to address the intrinsic application dependency of the schemes leading to two main spectrum of analysis. One end is multi-physics focus, statistics only evaluation, and seasonal to longer temporal scale. While, the other end is single-physics focus, statistics and process-based evaluation, and event-based application. Few studies have investigated multi-physics focus, statistic and process-based evaluation for seasonal application. Scheme applicability have been the focused on the past studies to specific regional area and none has tried to address scheme transferability to different regional areas with distinct climate regimes.

This study aims to improve the application of RCMs by developing a parameterization selection methodology for precipitation with multi-physics (CU, BL, MP, RAD) focus that includes a process-based diagnostic evaluation method. The WRF model was as used as default RCM due to the multi-physics option availability necessary for an intercomparison study on parameterization for precipitation process representation. Through an intercomparison study for each study area, scheme applicability was assessed and analyzed. In addition, multi-climate regime application focusing on island climatology using targeted sensitivity approach addressed the issue of scheme transferability to different climate regimes. The selected study areas were mid-latitude Japan cases, tropical Philippine case, and equatorial tropics Indonesia case.

Multi-regime application was done initially for Japan and successively for Philippines and Indonesia. Japan was selected as initial study area due to its midlatitude climate regime with distinct seasonal variation for precipitation and island climatology. Philippines and Indonesia were consequently selected due to their island climatology but with different climate regimes defined mainly by latitudinal location. Targeted sensitivity approach was used for the sensitivity experiment focusing on the processes associated to rainfall production in the model. The sensitivity experiment was initially done for cumulus convection (CU) schemes due to its control on convection trigger and cloud dynamics. Then, two main sensitivity scheme combination experiments were done focusing on the cloud formation and evolution process through CU-MP and CU-MP-RAD scheme coupling, and focusing on convection-environment interaction through CU-BL scheme coupling. The LSM parameterization was not included in the sensitivity experiment, but a default Noah LSM was used in all the sensitivity experiments. Simulation period for all the cases was set from 1 June 2005 to 31 May 2006, excluding a 1-month spin-up period. One-way nesting was employed for the simulations. No data assimilation or nudging technique was used. The simulations were hindcast simulation experiments, where global reanalysis data (ERA-Interim including SST) were used as initial and boundary conditions. A three level diagnostic evaluation methodology to assess simulations in the sensitivity experiments was used using a combination of precipitation observations (APHRODITE, TRMM) and vertical structure observations/ reference (IGRA, AIRS satellite, ERA-Interim). First level dealt with statistical assessment for fidelity of the simulations to observations. Second level dealt with assessment of simulated structure consistency to process through histogram comparison, variable seasonal and diurnal cycles, profile cross-sections, and scatterplots. Lastly, third level dealt with diagnosing the contribution of scheme usage to sub-grid heating and drying processes in the simulations using residual heat and water budget analysis. This three level diagnostic evaluation method allowed bias estimation from scheme usage and understanding of associated mechanism of the bias. The multi-regime application with targeted sensitivity experiments and diagnostic evaluation method constitute the basis of the development of multi-physics scheme selection framework for precipitation modeling.

The initial sensitivity experiment was focused on the impact of CU scheme due to its control of the trigger of convection and cloud dynamics influencing the distribution of precipitation. Initial study area was Japan since most parameterization schemes were developed in midlatitude applications. Default schemes were chosen initially for Japan based on previous studies that have shown good capability in simulating seasonal precipitation. The default schemes chosen were Kain-Fritsch for CU, MYNN 2.5 for BL, WSM6 for MP, RRTMG for RAD, and Noah LSM. Different types of convection schemes were used such as low-level control that uses moisture-instability-lift convective initiation (KF and Tiedtke), deep-level control schemes that uses large-scale forcing to initiate convection (Betts-Miller-Janjic or BMJ, New Simplified Arakawa-Schubert or AS), and ensemble type schemes that utilizes both deep-level and low-level control convective initiation and uses ensemble feedback for precipitation (Grell-Devenyi or GD, Grell-3d or GR, Grell-Freitas or GF). Performance evaluation using pattern correlation coefficient (PCC) and standard deviation ratios (SDR) were used. It showed seasonal clustering during DJF and MAM seasons due to dominance of large-scale forcing on the precipitation mechanism during the season. While, large variation during JJA and SON seasons indicate the dominance of sub-grid processes in the precipitation mechanism. For individual schemes, distinct characteristic performance were seen for KF scheme with highest SDR for all season, and GR scheme with highest PCC and close to SDR=1.0 for all season. Using mean bias analysis, it was found out that KF scheme has a distinct mean overestimation bias during JJA season. The mean overestimation tendency was also seen in the seasonal histogram comparison, where the mean overestimation was due to the frequency overestimation in the 8mm/day to 40mm/day precipitation and frequency underestimation for 0 to 8mm/day precipitation. Furthermore using heat and moisture budget analysis, the frequency overestimation were shown to correspond with lower tropospheric drying overestimation seen for KF scheme. In comparison, GR scheme had less overestimation tendencies as shown by the mean bias analysis, histogram comparison, and budget profiles such that it indicated good PCC and SDR results consistently. The CU experiment was also done for Philippine and Indonesian cases to assess scheme transferability. The PCC-SDR comparison plots showed 0.5 SDR variations for Japan while 3.0 SDR for Philippines and 3.6 SDR for Indonesia indicating the high sensitivity of precipitation to selection of CU scheme over the tropics as compared to midlatitude. Climate regime type dictate the CU scheme selection sensitivity to precipitation modeling in terms of dominance of large-scale forcing on precipitation mechanism and latitudinal location. Dominance of large-scale forcing and latitudinal location on CU scheme sensitivity was seen during DJF season in Japan, partial dominance of large-scale forcing in the subtropical DJF season over Philippines, and small-scale forcing dominance in tropical DJF case in Indonesia. On the other hand, hot humid climate regime as shown by JJA seasons for Japan and all seasons for Philippines and Indonesia showed large sensitivity of CU scheme usage to simulating precipitation indicating the importance of proper scheme selection. Focusing on the specific scheme transferability, KF scheme was found to have overestimation problems in hot humid climate type as indicated by the mean bias analysis for Philippines and Indonesia. Furthermore, it was confirmed that the overestimation tendency was also seen in the histogram comparison and budget profile analysis similar to Japan case previously mentioned. On the other hand, GR scheme showed better performance over Philippines but overestimates like KF scheme over Indonesia. But, GR scheme showed peculiar drying profile structure for Philippines and Indonesia not seen in ERA-Interim reference profile that might be due to ensemble feedback implementation of the scheme. Lastly, Tiedtke scheme showed comparable results with other schemes for the three study areas in the PCC and SDR scores. But, it showed best similarity with reference over DJF heating/drying profile structure due to its organized cluster convection inclusion in the scheme with less precipitation overestimation over Indonesia.

After establishing KF scheme overestimation problem, additional sensitivity experiment was done focusing on the CU-MP-RAD coupling and CU-BL coupling experiment to investigate impact of scheme coupling to default CU scheme's precipitation bias tendencies. CU-MP-RAD coupling sensitivity experiment was divided into two parts, CU-MP coupling for total precipitation representation and CU-MP-RAD for cloud radiative impacts. This sensitivity experiment was designed to investigate the influence of coupling the CU scheme with MP and RAD schemes. First, CU-MP EXP was done using single-moment schemes (WSM6, WSM5, WSM3, Lin et al, SBU YLin, and NSSL) and double-moment schemes (WDM6, Morrison, Thompson). KF scheme was used as a default scheme for Japan and Philippines and Tiedtke for Indonesia case. PCC-SDR results and other evaluation methods showed no significant differences between MP schemes. Essentially, coupling MP scheme with CU scheme modulates intensity of precipitation and heating/drying profile structures but cannot solve the bias tendency of default CU scheme, KF. Then, CUMP-RAD coupling was done to investigate the influence of radiation scheme usage to precipitation. Default CUMP scheme were selected (KF-WSM6 for Japan and Philippines, Tiedtke-WSM6 for Indonesia) and coupled with four different radiation schemes such as RRTMG, RRTM-Dudhia, Goddard, and Fu-Liou-Gu. PCC-SDR results showed no significant improvement but variations were largest over Indonesia indicating higher influence of cloud in radiative energy partitioning over the tropics. In summary of CU-MP-RAD experiment, precipitation biases from CU scheme usage cannot be solved by coupling with MP and RAD schemes, however, influences the intensity of precipitation and heating/drying profile structures by modulating the total rainfall partitioning and cloud radiative effects.

CU-BL sensitivity experiment was done to investigate the influence of BL scheme coupling to CU scheme in representing convective environment and its impact to precipitation. Three main types of BL schemes were used, which are local TKE types (MYJ, MYNN 2.5, MYNN3, BouLac), local TKE mass-flux types (QNSE, UW, Grenier-Bretherton-McCaa) and non-local mixing type (TEMF, ACM2, YSU) coupled with KF scheme for Japan and GF scheme for Indonesia and Philippines. KF scheme was used as default to investigate its overestimation problem, while GF scheme was selected due to scale-aware convective fraction treatment for better land surface heterogeneity treatment. Using PCC-SDR results, variation of BL scheme usage introduced mainly on the SDR scores due to its control on the diurnal cycle of surface processes influencing precipitation variability. Usage of non-local type BL scheme showed largest overestimation in mean bias analysis, histogram comparison, and budget profile analysis. In contrast, usage of local type BL schemes showed least overestimation in all the evaluation method. Local mass-flux BL types showed intermediate response between local and non-local mixing types. Coupling with BL schemes modulate intensity of precipitation and heating/drying profile structures that is similar to MP and RAD tendency but with greater influence in magnitude.

The proposed selection methodology centers on the CU scheme as it controls the spatio-temporal distribution of precipitation as defined by the climate regime. It controls convection trigger and cloud dynamics so it dominantly influences simulated precipitation. Consequently, coupling with BL scheme is proposed to be next consideration due to its influence on the significant magnitude modulation in the precipitation and associated vertical structures by controlling convection-environment interaction processes. Lastly, MP and RAD coupling consideration since it controls the cloud formation and evolution through rainfall partitioning by MP schemes and cloud radiative impacts through RAD schemes with moderate modulation of precipitation intensity and heating/drying structures as compared to BL coupling. This selection prioritization is based on the magnitude influence of the scheme coupling to simulated precipitation. Coupling parameterization evaluation is important as it provides an evaluation of scheme combination usage.

In summary, the linkage of parameterization to precipitation and the impact of coupling parameterization schemes in the RCMs was demonstrated in the study. This study proposes a scheme selection methodology to analyze multi-physics scheme combination usage in representing seasonal precipitation. Also, it proposes an accompanying evaluation methodology in characterizing biases and associated mechanism that contributes to improvement of RCM application studies for hydrologic purposes and contributes to parameterization development physics unification.