博士論文(要約)

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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Abstract: Executive Summary

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 mid-latitude 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.

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Chapter 1

Introduction

1.1 Background and Overview

One of the main advantages of using a Regional Climate Model in implementing dynamic downscaling method is the addition of topography-induced features to the coarse-resolution meteorological products like Reanalyses and Global Climate Model (GCM) outputs. This is primarily important especially for hydrologic impact studies for basin scale and regional applications. Realistic representation of the spatial and temporal distribution of precipitation fields to be used as forcing to hydrologic impact studies is crucial (Skok et al. [2015]). So it is imperative that the Regional Climate Model (RCM) used for dynamic downscaling has appropriately selected physics schemes to be able to reproduce realistic precipitation fields both spatially and temporally.

However, precipitation in RCMs are represented through the sub-grid parameterizations that are typically geographic-dependent, and seasonal-bound (Giorgi and Mearns [1999], Ruiz-Arias et al. [2013]). As such sub-grid parameterization persist as one of the most difficult aspects in atmospheric modelling (García-Díez et al. [2013]). In addition, the correct representation of precipitation in an RCM entails the correct representation of moist convection processes entirely dependent on sub-grid parameterizations in the model. Thus, modeling precipitation and clouds in RCMs still post as one of the most challenging problems in numerical modeling of the atmosphere and remains as one of the main contributors to the uncertainties in persistent biases in the modelled circulation system (Bony et al. [2015], Sherwood et al. [2014]). 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.

Due to the complexities of dealing with sub-grid parameterizations, a lot of studies have been devoted to addressing sensitivities to season-bound application, resolution adequacy, process and geographic application (Warner [2011]). Previous studies done on sensitivity of parameterizations usually deal primarily on the spatio-temporal application issues such as done by Aligo et al. [2009], Kusaka et al. [2010], Bryan et al. [2003], Yu and Lee [2011] and Warner and Hsu [2000]. These studies focus on the resolution aspect requirement and influence of parameterization to the investigated phenomena. On the other hand, studies dealing with parameterization sensitivity and process linkage were focused on the validation aspect relying primarily on the mechanism-based assessment. Example of these studies include on microphysics sensitivity(Bryan and Morrison [2012], Morrison et al. [2009], Khain et al. [2015]). 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 as can be seen in the non-exhaustive list of past studies shown in Table 1.1. One end is multi-physics focus, statistics only evaluation, and seasonal to longer temporal scale as shown by studies like Fernández et al. [2007],Evans et al. [2011], and Mohan and Bhati [2011]. While, the other end is single-physics focus, statistics and process-based evaluation, and event-based application as shown by studies by Van Weverberg et al. [2013],Wang and Seaman [1997], Shin and Hong [2011], and Jin et al. [2010]. 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 application of RCMs by developing a parameterization selection methodology that includes a diagnostic evaluation method focusing on the moist convection process representation in the WRF model. The WRF

Table 1.1: Physics Parameterization Sensitivity Studies (Non-exhaustive)

Authors	Focus of Study	Parameterization Focus
Fernández et al. [2007]	Multi-physics seasonal ensemble performance	CU-MP-BL-RAD
Evans et al. [2011]	Multi-physics seasonal ensemble performance	CU-MP-BL-RAD
Mohan and Bhati [2011]	Heavy rainfall event	CU-MP-BL-RAD-LSM
Jankov et al. [2005]	Warm season mesoscale convective system rainfall	CU-MP-BL
Nasrollahi et al. [2012]	Hurricane simulations	CU-MP
Mercader [2010]	Heavy rainfall event	CU-MP
Han et al. [2008]	Seasonal combination performance	BL-LSM
Van Weverberg et al. [2013]	Seasonal mesoscale convective system rainfall	MP
Wang and Seaman [1997]	Multi-rainfall event	CU
Shin and Hong [2011]	Single day single-column test	BL
Jin et al. [2010]	Seasonal sensitivity to land surface processes	LSM

model is used due to the myriad availability of parameterization schemes necessary for an intercomparison study on physics parameterization for precipitation process representation. The intercomparison study facilitates the analysis of parameterization combination usage as only few studies have been done and rely primarily on statistic based evaluation. This study proposes to include a process-based analysis to the typical statistical evaluation methodology. In addition, the study aims to analyze and assess the applicability and potential transferability of physics parameterizations to different climate regimes. This is done through a mutli-climate regime application focusing on island climatology. The selected study areas are mid-latitude Japan cases, tropical Philippine case, and equatorial tropics Indonesia case.

The numerical design experiment were made to explore individual parameterization sensitivity to precipitation. This has allowed the exploration on the impact of individual parameterization to the precipitation representation. There are a total of four parameterization sensitivity experiments, one each for cumulus convection schemes, boundary layer schemes, microphysics schemes, and radiation schemes.

The land surface model (LSM) parameterization was not included in the sensitivity experiment, but a default NOAH LSM was used in all the sensitivity experiments.

1.2 Research Motivation and Objective

There are two main objectives in the study. First, assess the applicability of the parameterizations for moist convection processes on different climate regimes. The assessment of the applicability tests the individual contribution/impact of the parameterization sensitivity in predicting precipitation in the model. This study deals with four physics parameterizations in the model associated in moist convection processes, which are cumulus convection parameterization, microphysics, planetary boundary layer(including surface layer), and radiation. The study also tries to address the coupling of these parameterization in model's capability of representing precipitation. Three main coupling were investigated, which are cumulus-microphysics(CU-MP) scheme coupling - total precipitation production, cumulus-boundary layer (CU-BL) scheme - vertical motion and turbulent mixing, and cumulus-microphysics-radiation coupling (cloud fraction and energy flux impact). This demonstrates the sensitivity of selecting physics parameterization in the WRF model in representing the spatio-temporal distribution of precipitation. And through the comparison study, the transferability of the parameterization to different climate regimes is explored and investigated. This objective is necessary to understand some aspects in creating a generalized framework on dealing with physics parameterization unification or to further the development of the physics parameterization schemes as primarily discussed by Arakawa and Wu [2013], Arakawa and Jung [2011], and Arakawa [2004].

The second objective is to create an application framework guideline on physics parameterization usage and selection including a preliminary evaluation framework based on the results of the first objective of this study. Through this objective, the application of WRF in downscaling precipitation is expected to improve. This is a subset of the work by Giorgi and Mearns [1999] and Warner [2011] in providing more concrete guidelines in using atmospheric models for meteorological phenomena. This study focuses mainly on model physics parameterization for hydrological applications usage.

1.3 Research Framework

RCM usage for downscaling precipitation or regional climate modeling, and short term forecasting have three main application issues. These issues can be mainly divided into three components such as physics parameterization component, resolution issue components, and domain-dynamics component.

The research framework focuses on the physics parameterizations on the precipitation process representation in RCM. The WRF model was selected and used due to its updated and wide range of parameterization scheme inclusion rooted on its community or shared model ideal. Using WRF model, it enables us to assess the impact of using various schemes of several parameterization components(multi-physics - CU, BL, RAD, MP) and its combinations of paramterization schemes to represent specific precipitation processes. The study addresses applicability improvement of RCM through physics parameterization intercomparison study. The intercomparison study on physics parameterizations focused on modeling precipitation as shown in Figure 1.1. The physics parameterization study used 24-km and seasonal focus to investigate on respective scheme applicability on season and on geographic location for each study areas. The scheme transferability of the schemes were investigated with schemes' inherent limitations based on initial development and implementation. The scheme transferability issue was addressed through a multi-climate regime island climatology application. The study areas selected were midlatitude Japan, tropical Philippines, and equatorial tropical Indonesia.

The inclusion of additional exploration on the resolution issue component and domain-dynamics component were done to enhance the credibility and robustness of the physics parameterization comparison study. Typically, the domain selection and dynamics issue can be further separated into two different components. However in this study, domain selection issue was thought of as mainly dependent on its potential impact on the dynamics of the model. Domain selection was done subjectively in terms of the large-scale processes considered in the study area and based on previous studies done for the respective study areas.

This study introduces and proposes an RCM diagnostic evaluation methodology for physics parameterization selection as shown in Figure 1.1. The method utilizes a combination of precipitation products over land from APHRODITE data and over land/ocean from TRMM 3B42, and atmospheric structure products like

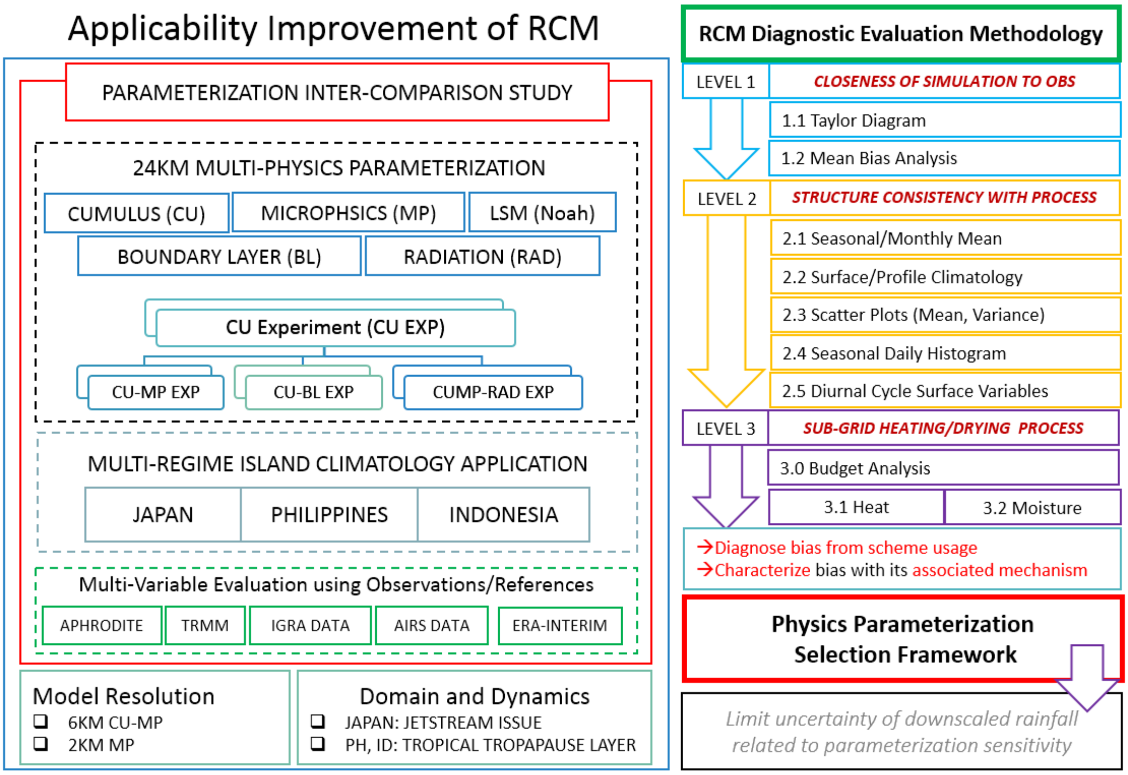


FIGURE 1.1: Research Framework

radiosonde data from IGRA, temperature and humidity satellite data from AIRS, and ERA-Interim variables. A three level diagnostic evaluation methodology to assess simulations and compare the scheme usage in the respective sensitivity experiments and application areas. This three level diagnostic evaluation method allowed bias estimation from scheme usage and understanding of associated mechanism of the bias. Essentially the usage of multi-variable evaluation and three-level evaluation facilitates diagnosis of bias including the processes associated with bias production. 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.

Chapter 2

Research Strategy and Methodology

This chapter deals with more detailed description on the data used and corresponding evaluation method, the numerical design of the sensitivity experiments, rationale of targeted sensitivity approach, and multi-climate regime application basis for this study. This study introduces and proposes an RCM diagnostic evaluation methodology for physics parameterization selection as shown in Figure 2.1.

The method utilizes a combination of precipitation products over land from APHRODITE data and over land/ocean from TRMM 3B42, and atmospheric structure products like radiosonde data from IGRA, temperature and humidity satellite data from AIRS, and ERA-Interim variables. A three level diagnostic evaluation methodology to assess simulations and compare the scheme usage in the respective sensitivity experiments and application areas. 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. Essentially the usage of multi-variable evaluation and three-level evaluation facilitates diagnosis of bias including the processes associated with bias production. The multi-regime application with targeted sensitivity experiments and diagnostic

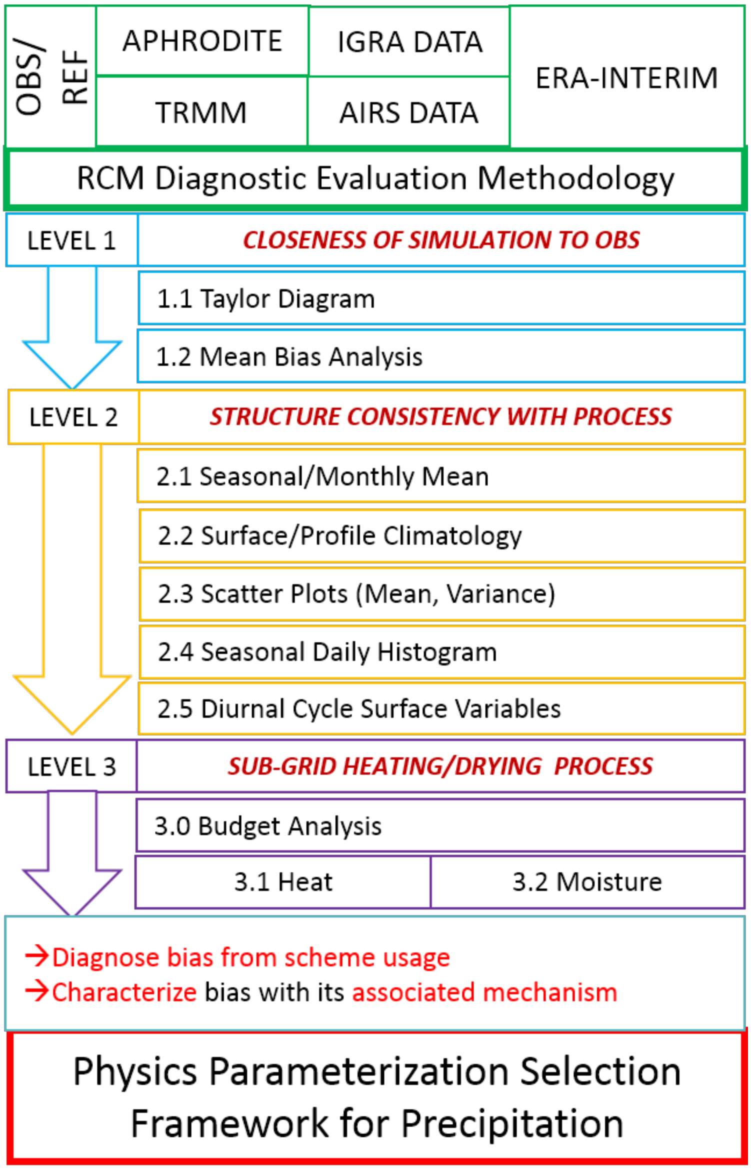


FIGURE 2.1: Diagnostic Evaluation Methodology using combination of precipitation(APHRODITE, TRMM) and vertical atmospheric structure observation/reference(IGRA, AIRS satellite, ERA-Interim)

evaluation method constitute the basis of the development of multi-physics scheme selection framework for precipitation modeling.

2.1 Data Validation and Evaluation Method for the Simulations

The main evaluation methods used in the diagnostic methodology aforementioned were taylor diagram analysis using spatial correlation and simulated standard deviation ratio to the observed, distribution comparison through histogram and box-and-whisker plots, and diagnostic budget profile analysis. These evaluation methods enable us to characterize the impact of scheme usage to the mean precipitation structure, distribution, and associated sub-grid heating/drying processes. Through its implementation, a complete view of the characteristic nature of the schemes and coupled schemes to the precipitation prediction in the model was established. The linkage between the scheme usage to precipitation can be established and demonstrated. Lastly, the budget profiles enable linking of the precipitation bias to the vertical sub-grid heating and drying processes from parameterization schemes usage in the model. This allows a more complete view of the moist convection process simulated by the combination of the parameterization schemes in the WRF model. The data used for the validation and evaluation of the simulation experiments were tabulated in Table 2.1.

Table 2.1: Data used for Simulations and Validation

Data Name	Type and Purpose
ERA-Interim	BC for simulations, Reference for Budget Profiles
APHRODITE Precipitation and 2-meter Air Temperature	Surface Variable Validation
TRMM 3B42 Precipitation	Validation for Precipitation over Sea
AIRS Air Temperature and Humidity Profiles	Vertical Structure Validation for Moisture and Temperature
Radiosonde data from IGRA	Additional Vertical Structure Validation for Wind and Temperature

Table 2.2: Data Period and Resolution used for Simulations and Validation

Data Name	Period	Resolution
ERA-Interim	31May2005 to 01Jun2006	0.75-degree, 6-hourly
APHRODITE Precipitation	31May2005 to 01Jun2006	0.25-degree, daily
APHRODITE 2-meter Air Temperature	31May2005 to 01Jun2006	0.25-degree, daily
TRMM 3B42 Precipitation Data	01June2005 to 31May2006	0.25-degree, 3-hourly
AIRS Air Temperature and Humidity Profiles	01June2005 to 31May2006	1-degree, 12-hourly
Radiosonde data from IGRA	June2005 to May2006	1-degree, Monthly

2.1.1 Taylor Diagram and PCC-SDR Comparison Plots

Taylor diagram is a unique type of graph that allows us to incorporate spatial correlation scores, root-mean-squared-errors, and standard deviation comparison from a reference data. Alternatively, PCC versus SDR plots were used to analyze performance using spatial correlation(pattern correlation coefficient or PCC) on the y-axis and standard deviation ratio of simulated versus observed. The usage of spatial correlation coefficient allows assessment of spatial distribution fidelity of simulated mean precipitation to observed, while SDR can be used to assess ability of the simulation to capture precipitation variability of the observed and gives idea on the bias characteristic(over/underestimation tendency). These two plots enables to assess the fidelity of the simulated variables to the observed variables such as precipitation and 2-m air temperature. The taylor diagram gives a compact view of the schemes statistical performance in terms of the mean spatial distribution, variability of the reference compared to simulated variables, and normalized magnitude errors from the simulations. However PCC-SDR plots are used as alternative to taylor diagram to improve clarity and ease of interpretation with the simulations' capability to capture mean spatial distribution of precipitation including its variability.

2.1.2 Histogram and Boxplot Analysis

It is highly important to characterize the distribution aside from the mean structure of the variables considered. Histogram analysis allows to see the frequency and magnitude distribution of the variable considered. Box and whisker plot analysis allows us to characterize the density of the distribution according to the median, and upper and lower quantile range of the distribution. This allows more insight to the characteristic distribution of the variables considered.

2.1.3 Budget Profile Analysis

The heat and budget profile analysis entails the usage of the equations below. Large-scale heat and water budget analysis to compute the residual heating(Q1) and drying(Q2) in the vertical atmosphere. These residual heating and drying profiles are equated to the unresolved processes as a contribution of physics parameterizations. In this way, the unresolved processes can be diagnosed as a contribution of physics parameterization. This allows us to connect the physics parameterization to contribution of unresolved heating and drying process in the model. It allows to connect individual schemes by considering specific processes associated to it but a more systemic perspective in its usage and coupling with other schemes to produce such vertical structures. Its fidelity to the ERA-Interim as a reference profiles allows evaluation of the capability of the combination to correctly simulate the unresolved process in the model.

$$\frac{d\theta}{dt} = -\overrightarrow{v} \cdot \nabla\theta - \omega\frac{\partial\theta}{\partial p} + \frac{1}{c_p}[\frac{p_0}{p}]^{(\frac{R}{c_p})}Q_1 \tag{2.1}$$

$$\frac{dq}{dt} = -\overrightarrow{v} \cdot \nabla q - \omega\frac{\partial q}{\partial p} - \frac{1}{L}Q_2 \tag{2.2}$$

where θ is potential temperature, q is water vapor mixing ratio, $\overrightarrow{v}$ is the wind velocity, ω is vertical velocity, p is pressure, p_0 is pressure, R is universal gas constant, c_p is heat capacity, L is latent heat of vaporization, Q_1 is apparent heating, and Q_2 is apparent moisture sink or apparent drying

2.1.4 Contribution of Parameterizations to Unresolved Heating/Drying Processes

This diagnostic evaluation methodology was introduced by Yanai et al. [1973], where the unresolved convection process was diagnosed using the residuals of large-scale heat and water budget analysis as introduced in Chapter 1. Originally, Yanai et al. [1973] and other succeeding studies used this diagnostic method to analyze contribution of cumulus convection to the apparent heating and drying profiles for the moist convection process understanding. This study, however, use this bulk diagnostic method not only to validate the contribution of cumulus convection parameterization schemes but also the relative contribution of the other components to the apparent heat and drying budget profiles. Each of the parameterization contributes to the apparent heating and drying profiles. This section illustrates the contribution of each parameterization to the heating contribution from unresolved process. It primarily comes from the cumulus convection scheme heating but is also modulated by the other three schemes by their relative influence on the other components of the moist convection process. In the profiles, only the seasonal domain-time mean was used in the analysis. ERA-Interim data was used as a reference in the vertical budget profile results in the absence of more appropriate observations, that might be affected or biased by the usage cumulus convection scheme used in generating the reanalysis data. Using heat and water budget equations (2.1) and (2.2), the residuals of the budget equations known as apparent heating Q_1 and apparent moisture sink or drying Q_2 in K/day. Apparent heating and drying are equivalent to the subgrid or unresolved heating and drying processes such as shown below.

$$\Pi = [\frac{p_0}{p}]^{(\frac{R}{c_p})} \tag{2.3}$$

$$Q_1 = \frac{L}{c_p \Pi}(c - e) - \frac{\overline{\partial \omega\prime \theta\prime}}{\partial p} + \frac{1}{\Pi} Q_R \tag{2.4}$$

$$Q_2 = -(c - e) - \frac{\overline{\partial \omega\prime q\prime}}{\partial p} \tag{2.5}$$

where θ is potential temperature, q is water vapor mixing ratio, $\overrightarrow{v}$ is the wind velocity, ω is vertical velocity, p is pressure, p_0 is pressure, R is universal gas constant, c_p is heat capacity, L is latent heat of vaporization, Q_R is radiative heating, Q_1 is apparent heating, and Q_2 is apparent moisture sink or apparent drying.

The unresolved heating process include net condensation, vertical heat transport, and radiative heating. While unresolved moisture sink or drying process include net condensation and vertical moisture transport. Each of the paramterizations contribute to the unresolved heating and drying process. The heating and drying process in the atmospheric column is primarily controlled by the cumulus convection parameterizations as it can directly contribute to the net condensation and vertical heat-moisture transport. It also affects the radiative heating as a consequence of convective cloud formation. Meanwhile, boundary layer parameterization contributes directly to the vertical heat and moisture transport as it controls the surface process and turbulent eddies above the boundary layer. It can also impact net condensation and radiative forcing as a tertiary contributor as it facilitates the formation of low boundary layer clouds. On the other hand, microphysics parameterization contributes primarily to the net condensation part and impacts radiative heating as a consequence of cloud formation. Lastly, radiation physics parameterization contributes primarily to the radiative heating component of apparent heating but also impacts the net condensation part as it influences the evolution of microphysical properties of clouds. The usage of each parameterization component is bound to contribute to the apparent heating and drying profile. This comparison and relative contribution comparison from each parameterization component facilitates a systemic view rather than individual contribution. This type of evaluation method allows assessment of important processes that need the strong coupling of sub-grid schemes in representing focused or desired process. In this case, coupling of scheme was used to provide a systemic view of the schemes in representing relevant processes associated with precipitation process, representation in the model and resulting precipitation prediction capability.

The following discussion used the bulk diagnostic equations for apparent heating and drying profiles to analyze the impact of usage of specific parameterization component and its coupling usage to other parameterization component. The parameterization coupling centers on the usage of cumulus convection parameterization and its coupling to different parameterization components to represent specific parts of the moist convection process. The coupling tackled are CU-BL for convective initiation environment and efficient transport of heat and moisture from surface to the vertical atmospheric column, CU-MP coupling for the total precipitation representation and cloud formation as a consequence, CUMP-RAD for the microphysical radiative impacts that affects cloud evolution and precipitation formation, and lastly CUBL-surface-Noah LSM for specific presentation of surface processes necessary for convection.

2.2 Numerical Design Framework

The RCM used in this study was the WRF model version 3.4.1 and 3.5.1 (only for CU-BL experiment) with default settings shown in Table 2.3. It is a non-hydrostatic, terrain-following vertical coordinate RCM4). 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. There area a total of four main parameterization sensitivity experiment as follows: schemes used for the schemes used in Cumulus sensitivity experiment (CU Exp) shown in Table 2.4; Cumulus-Microphysics sensitivity experiment (CU-MP Exp) shown in Table 2.5; and schemes for cumulus-microphysics-radiation sensitivity experiment (CUMP-RAD Exp) as shown in Table 2.6; and schemes used in Cumulus-Boundary Layer experiment(CU-BL Exp) shown in 2.7 .

TABLE 2.3: Default WRF Model Settings in Hindcast Simulations

Vertical coordinate	28 eta levels
Horizontal resolution	24km
Number of Grids per Domain	112Hx91V -JP
	100Hx100V -PH
	250Hx100V -ID
Land Surface Model	Noah LSM
Boundary Conditions	ERA-Interim incl. SST

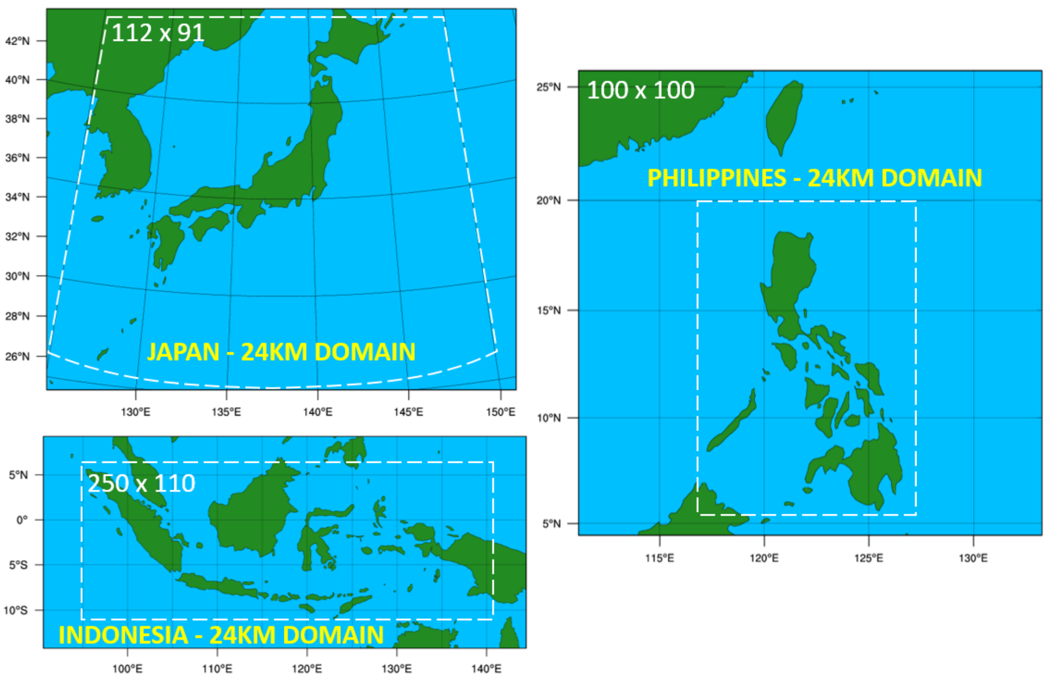


FIGURE 2.2: 24-km simulation domains and analysis domains(indicated by white dashed lines) for respective study areas

2.3 Targeted Sensitivity Approach

The sensitivity experiment focuses on establishing the linkage between the parameterization scheme coupling to the precipitation process in the WRF model. Targeted sensitivity approach was used for the sensitivity experiment by focusing on the processes associated to rainfall production in the model as shown in Figure ?. 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. CU-MP coupling was investigated for total rainfall representation in WRF model, while CUMP-RAD coupling was investigated for cloud radiative impacts. These two scheme coupling constitute the cloud formation and evolution process in the WRF model. On the other hand, CU-BL coupling was used to investigate the influence of surface processes to the initiation of convection by CU schemes. By the analysis of the sensitivities of scheme coupling usage to associated processes in the precipitation representation in the model, bias resulting from scheme usage can associated to a specific mechanism of the over/underestimation of specific variables.

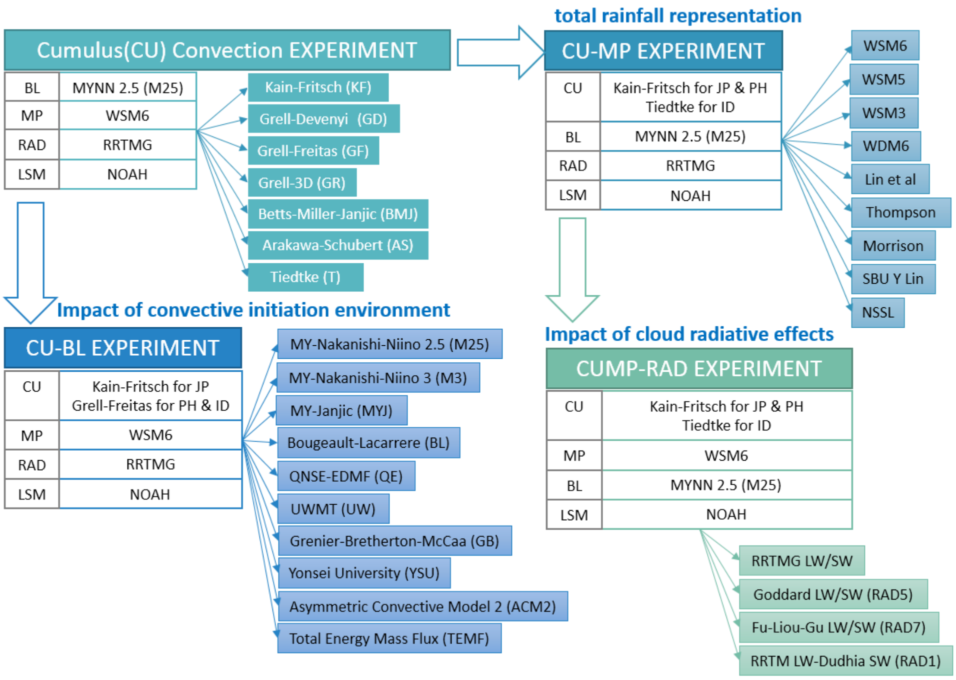


FIGURE 2.3: Targeted Sensitivity Approach for Precipitation Processes - Scheme Coupling Linkage

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. Table 2.4 shows the different types of convection schemes used. The schemes used were low-level control type 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).

TABLE 2.4: Cumulus Sensitivity Experiment (CU Exp) - *Note: Default are JP Cases, Case Name(P) - PH cases, and Case Name(I) - ID cases

Case Name*	Cumulus Scheme
WK	Kain-Fritsch (KF)
WB	Betts-Miller-Janjic (BMJ)
WA	Arakawa-Schubert (AS)
WT	Tiedtke (T)
WGD	Grell-Devenyi (GD)
WGR	Grell-3D (GR)
WGF	Grell-Freitas (GF)

Then, investigation of coupling CU with MP and RAD schemes were done and the schemes used shown in Tables 2.5 and 2.6. While, the schemes used for CU-BL sensitivity experiment were shown in Table 2.7.

2.4 Multi-climate Regime Application

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

Table 2.5: CU-MP Sensitivity Experiment (CUMP Exp) - *Note: Default are JP Cases, Case Name(P) - PH cases, and Case Name(I) - ID cases

Case Name*	Microphysics Scheme
WK	WSM6
LK	Lin et al. scheme
TK	Thompson
WDK	WDM6
W3K	WSM3
W5K	WSM5
FK	Ferrier et al.
SK	SBU Y. Lin
NK	NSSL 2-moment
MK	Morrison et. al
default CU	KF for JP and PH, Tiedtke for ID

Table 2.6: CUMP-RAD Sensitivity Experiment (CUMP-RAD Exp) - *Note: Default are JP Cases, Case Name(P) - PH cases, and Case Name(I) - ID cases

Case Name*	SW-LW rad schem
Default	RRTMG SW - RRTMG LW
RAD1	Dudhia SW - RRTM LW
RAD4	Goddard SW - Goddard LW
RAD7	FLG SW - FLG LW
default CU-MP	KF-WSM6 for JP and PH, Tiedtke-WSM6 for ID

island climatology but with different climate regimes defined mainly by latitudinal location. The domains of application areas are shown in Figures 2.4 and 2.2. The application areas selected are all island archipelagos with different climate regime due to latitudinal location, but are affected by the Asian Monsoon. The selected study areas are Japan, Philippines, Indonesia. The physics parameterization experiment does not include land surface model (LSM) parameterizations as it includes more complex processes such as biogeochemical processes and varied complexity of the schemes. The NOAH LSM was used as a default scheme for LSM, which was demonstrated to work adequately by previous studies by Kawase et al. [2013], Kusaka et al. [2005], Kusaka et al. [2012] for Japan, Bagtasa [2012], Spencer et al. [2012] for Philippines, and for Indonesia(Evan et al. [2013],De Haan and Kanamitsu [2008]). The application areas were selected with sea surface temperature(SST) dominant impact on the seasonal precipitation mechanisms in the study areas such that less impact to study areas' precipitation mechanism by land surface processes in monthly and seasonal scale.

Table 2.7: CU-BL Sensitivity Experiment (CU-BL Exp) - *Note: Default are JP Cases, Case Name(P) - PH cases, and Case Name(I) - ID cases

Case Name*	PBL Scheme	Surface
M25	MYNN 2.5	MYNN
M3	MYNN 3	MYNN
MYJ	MYJ	ETA
GB	Grenier-Bretherton-McCaa	MM5
UW	Univ of Washington MT	MM5
BL	Bougeault-Lacarrere	MM5
QNSE	QNSE-EDMF	QNSE
YSU	YonseiUniv	MM5
TEMF	TEMF	TEMF
ACM2	ACM2	Pleim
default CU	KF for JP, GF for PH and ID	
WRF version	GF scheme was introduced in WRF 3.5.1	

Figure 2.4: Respective Domain of Study Areas

The mid-latitude Japan case has two principal sources of intense rainfall production over Japan. These are the East Asian (EA) summer monsoon during the warm season from June to November, and the EA winter monsoon during the cold season from December to May. In the warm season, intense rainfall production is due mainly to the Baui front in the months of June to July and tropical cyclones from August to September. The tropical Philippine case, on the other hand, mainly experiences Southwest (SW) Monsoon from June to November and Northeast (NE) Monsoon from December to May. Heavy rainfall events are mainly due to the monsoons and average occurrence of 20 tropical cyclones a year mostly occurring from June to November.Also, it is affected by occurrence of ITCZ and ENSO. Lastly, the equatorial tropical Indonesian case located between 10 °North to 15 °South latitude, which experiences almost opposite of the Philippine case seasonality. Indonesian rainfall is monsoonal characteristic influenced by IOD, ENSO and MJO. There are two main phases of monsoon annually, which are wet phase from November to March coinciding with ITCZ and dry phase from May to September due to the dry southwesterly wind from Australian continent.

Chapter 3

Cumulus Convection Scheme Impact to Precipitation Prediction

This section will be included in a publication for submission to Journal of Geophysical Research.

Chapter 4

Representation of Total Rainfall and Cloud Radiative effects through CU-MP-RAD Coupling

This section will be included in a publication for submission to Journal of Geophysical Research.

Chapter 5

Representation of Convection-Environment Interaction through CU-BL coupling

This section will be included in a publication for submission to Journal of Geophysical Research.

Chapter 6

Development of Scheme Selection for Precipitation Modelling

Some parts of this section will be included in a publication for submission to Journal of Geophysical Research. Most parts of Section 6.1 and parts of Section 6.2 detailing Japan and Philippine cases were published in Journal of Japan Society of Civil Engineering.

6.1 Seasonal Precipitation and 2-m Air Temperature Validation for the Sensitivity Experiments

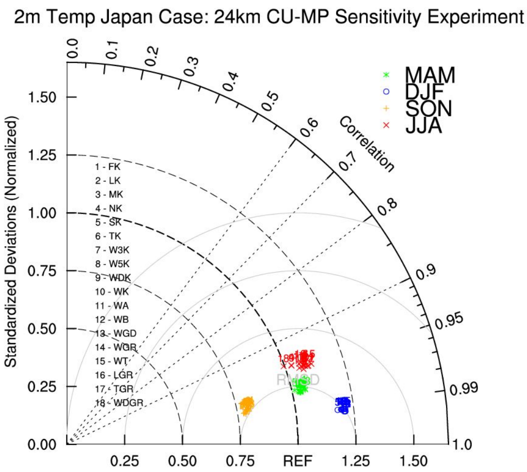
This section comprises the summary of the results and relevant discussions for the validation of seasonal precipitation and 2-meter air temperature in the 24km simulation cases for Japan, Philippines, and Indonesia against APHRODITE data. It outlines initially the results of the 24-km resolution simulations for the three study areas in capturing the seasonal precipitation and 2-meter air temperature. Next, it outlines the relative impact of each parameterization to the prediction of precipitation. It details the connection of the scheme usage to precipitation through mean bias analysis, taylor diagram analysis, histograms, and other related variable plots relevant to the scheme. This also illustrates the need of multiple diagnostic evaluation techniques to be used to characterize the scheme usage's impact related to precipitation prediction. The discussion characterized the impact through evaluating not just the mean structure but also including the distribution associated with it.

6.1.1 2-meter Air Temperature

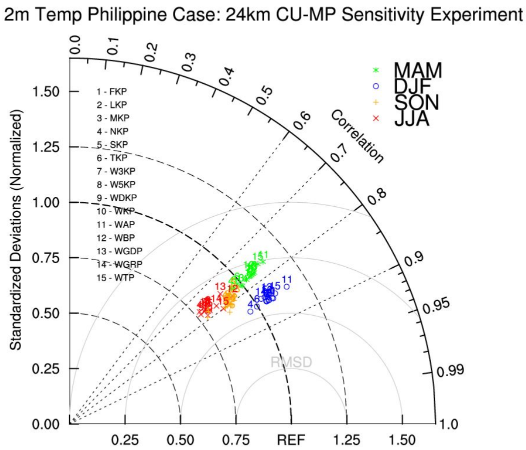
The results of 2-m Air Temperature validation for the three application areas for the sensitivity experiment shows a considerable good skill as shown by Figure 6.1. The Japan midlatitude case (Figure 6.1(a)) show high spatial correlation greater than 0.90 with normalized RMSD less than 0.50. On the other hand, Philippine case (Figure 6.1(b)) show good spatial correlation grater than 0.70 with less than 0.75 RMSD(CU-MP EXP).

6.1.1.1 Japan Midlatitude Case

The simulations for the sensitivity experiments show that the model can simulate the seasonal 2-m air temperature with high skill. However, there is a distinct seasonal clustering for the case simulations considered. This is evident for both all sensitivity experiments as can be seen from the clustering of similar colors defined as different season shown in Figures 6.1(a) and 6.1(a). Seasonality of the results show that it can capture the range of variability for boreal summer and spring while underestimated for the boreal autumn and overestimated for boreal winter. If we consider the season as the transition from preceding and succeeding season, we can think of the seasons as transitions for either cooling or warming. With that in mind, it seems that model can capture the observation variability during the warming transition associated with summer and spring, while either under/overestimation is seen during the cooling transition associated with autumn/winter. The 2-m temperature variability is overestimated when transition is from warming while underestimating when there is successive cooling transition from preceding season to current season and current season to succeeding season as summarized in Table 6.1.



(a) JP CASE: CU-MP Experiment



(b) PH CASE CU-MP Experiment

Figure 6.1: Seasonal 2-meter Air Temperature Validation using APHRODITE

Table 6.1: JP CASE: Seasonal 2-m Air Temperature Validation

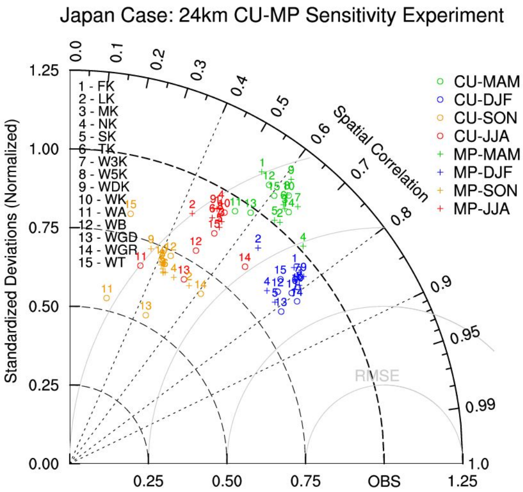
Season	Preceding	Succeeding	Remarks
Summer (JJA)	warming	cooling	good skill but higher rmse
Autumn (SON)	cooling	cooling	underestimated
Winter (DJF)	cooling	warming	slightly overestimated
Spring (MAM)	warming	warming	good skill but higher rmse

6.1.1.2 Philippine Tropical Case

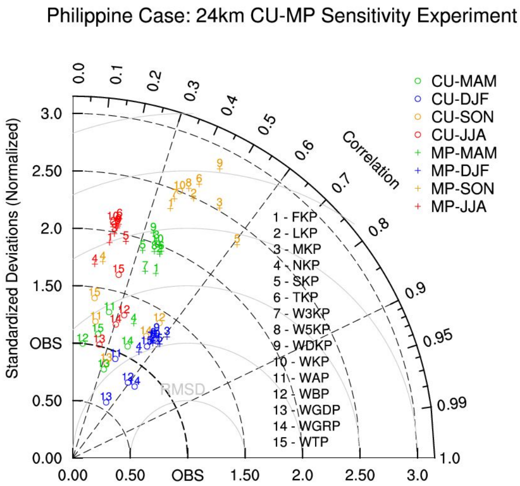
Philippine tropical case results show that the model has a good skill in capturing the 2-meter air temperature variability throughout the two main dominant seasons, SouthWest summer monsoon season (June-July-August(JJA), September-October-November(SON)) and North East winter monsoon season (December-January-February (DJF), March-April-May (MAM)). The DJF season shows highest skill in spatial correlation(>0.8) and RMSD(<0.75). MAM, JJA, and SON seasons shows almost similar spatial correlation and RMSD, but with the slight underestimation in variability for JJA and slight overestimation in MAM variability. The results show seasonal clustering of cases for CU-MP Experiment. In Figure 6.1(b), the scheme seasonal clustering were found to be the SW monsoon season(JJA and SON) as defined by circular clustering while NE monsoon season(DJF and MAM)clustering as shown by an elongated clustering. The distinct clustering as shown by the previous figures were more pronounced when comparing DJF season with the other seasons. DJF season in the Philippines is typically the coolest season of the year as dominated by the Northeast winds coming from Siberia. This distinct climate feature governing the season and its variability seems to be the reason on the seasonal clustering shown.

6.1.2 Precipitation

The results summary show that 24-km resolution simulations for cumulus convection schemes, microphysics scheme, boundary layer schemes are shown in Figure 6.2 for the Japan, Philippines, and Indonesia. Spring season simulation cases captures the rainfall variability well. Winter and summer season simulations, on the other hand, captures almost 75% of rainfall variability. Lastly, autumn season simulations show the least seasonal skill. Almost all captures approximately 75% variability with some exceptions for the AS scheme and GD schemes showing only 50% of the observed variability. Warm (cold) season cases has lower (higher) spatial correlation and smaller (larger) normalized RMSD as summarized in Fig 6.2.



(a) JP CASE: CU-MP Experiment



(b) PH CASE CU-MP Experiment

FIGURE 6.2: Seasonal Precipitation Validation using APHRODITE

6.1.2.1 Japan Midlatitude Case

Results summary show a distinct seasonality in the ability of the model in capturing the precipitation variability. Seasonal variability of precipitation is captured by the simulations for summer, spring, and winter season with some slight differences. For autumn season precipitation, only 75% of the variability is captured. Winter season shows the highest skill in spatial correlation and RMSE values. Spring, summer, and Japan has two main sources of heavy precipitation, which are during summer season due to Baui front and extratropical cyclones and during winter season due to the orographic precipitation on the Japan Sea side of the archipelago.

The cold season dominated by large-scale synoptic features can be resolved by the resolution explaining the better performance compared to the warm season. Warm season precipitation mechanism is mostly dominated by mesoscale convection system and frontal systems of the mesoscale-β with 20km-200km features that cannot be fully resolved Warm season includes the baui front from June to July and typhoons from August to September. Baui precipitation bands are multi-scale clouds encompassing large-scale to mesoscale-γ features like large cumulus clouds of the order 2km-20km(Ninomiya [2007]). The multi-scale structure of the baui front cannot be fully captured by the resolution (Ninomiya [2007]). For typhoon precipitation bands, these are highly dependent on the accuracy of the typhoon path. Locational errors of typhoon path can greatly contribute to the worse performance of warm season. In addition, monthly mean biases were calculated and found that warm season biases were typically larger due to larger total precipitation amount. The biases were normalized by dividing the mean bias with the monthly mean.

6.1.2.2 Philippine Tropical Case

Rainfall variability mainly affected by the orographic lifting during monsoon seasons and tropical cyclone occurrences. However, individual convective clouds and isolated thunderstorms also play a major part in the rainfall variability in the region, which cannot be resolved by the 24-km resolution used in this study. As shown in Fig. 5, Standard deviation of precipitation show largest for the wet season (JJA, SON) compared to the dry season (DJF, MAM). The rainfall variability were captured well by the simulations for Dec-Jan-Feb (DJF), satisfactorily for Mar-Apr-May (MAM) and Jun-Jul-Aug (JJA), and for Sep-Oct-Nov (SON) seasons. Figure 6.2(a) clearly shows that larger variation can be seen from the usage of cumulus scheme, which is consistent in all seasons. This is evident due to the clustering of MP Exp sensitivity cases with similar Kain-Fritsch scheme used. The DJF season shows the least variation among the CU-MP schemes due to the dominating Northeast monsoon 850hPa level cold winds originating from Siberia blowing over Japan and Pacific Ocean to the eastern coast of the Philippine islands. Due to the transition of weakening Northeast monsoon winds to strengthening Southwest monsoon winds, the sensitivity for MAM season shows intermediate skill performance for JJA and DJF season. The JJA season skill, however, clearly is due to the unresolved smaller scale features of orographic precipitation, individual large cumulus clouds, and locational errors for tropical cyclone path. The locational errors from tropical cyclone precipitation is clearly evident during the SON season as can be seen from the largest spread of both standard deviation, RMSD, and spatial correlation. The SON season is dominated by the rainfall from tropical cyclones due to its weakening SW monsoon and transition from SW monsoon winds to the relatively colder and drier Northeast monsoon winds. Plotting the monthly biases as shown in Fig. 6 results of sensitivity experiment show wide (narrow) variation among the cumulus (microphysics) schemes for simulating precipitation as shown by the orange (blue) shade lines in Fig. 6, which are consistent with the results of Taylor diagram in Fig. 5.

6.2 Domain-Dynamics Issue

Domain and dynamics play a huge role in simulating the regional climate properly. Some issues were documented in the 24-km simulations for respective domain areas for Japan, Philippines, and Indonesia. For Japan case, an anomalous negative precipitation bias (Figure 6.3) during months of October, November, and December accompanied by positive 2-meter temperature biases (Figure 6.4. The related biases were due to the propagation of the jet stream along the domain area from October to December as illustrated in Figure 6.5 where impedance of the propagation of the jet stream through the domain boundary and into the domain as indicated by the lower wind speed in the simulations as compared with the ERA-Interim data. However, since the focus of the study is on seasonal rather the monthly scale, the results for JJA season and DJF seasons still remains robust even with the jetstream domain propagation problem in the simulations. However, SON seasonal precipitation results might be greatly affected by the aforementioned domain problem so the robustness of the trends on the physics parameterization sensitivity on this season is deemed unreliable.

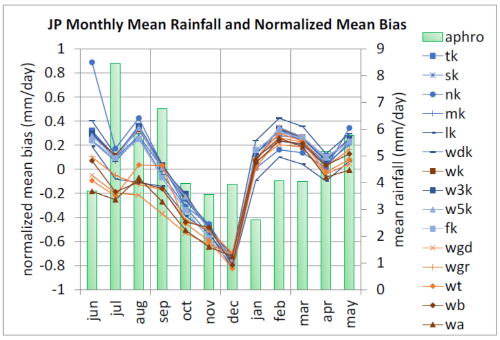


FIGURE 6.3: Monthly Mean Bias Analysis for Seasonal Precipitation using 0.25-degree averaged daily APHRODITE product over Japan

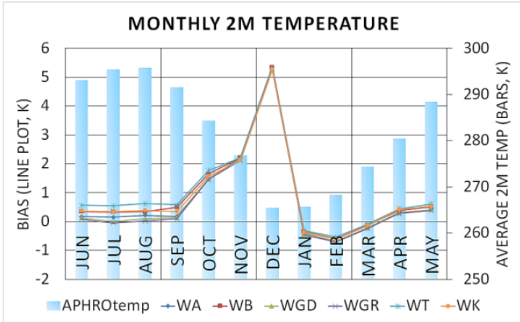


FIGURE 6.4: Monthly Mean Bias Analysis for 2-meter Air Temperature using 0.25-degree daily APHRODITE product over Japan

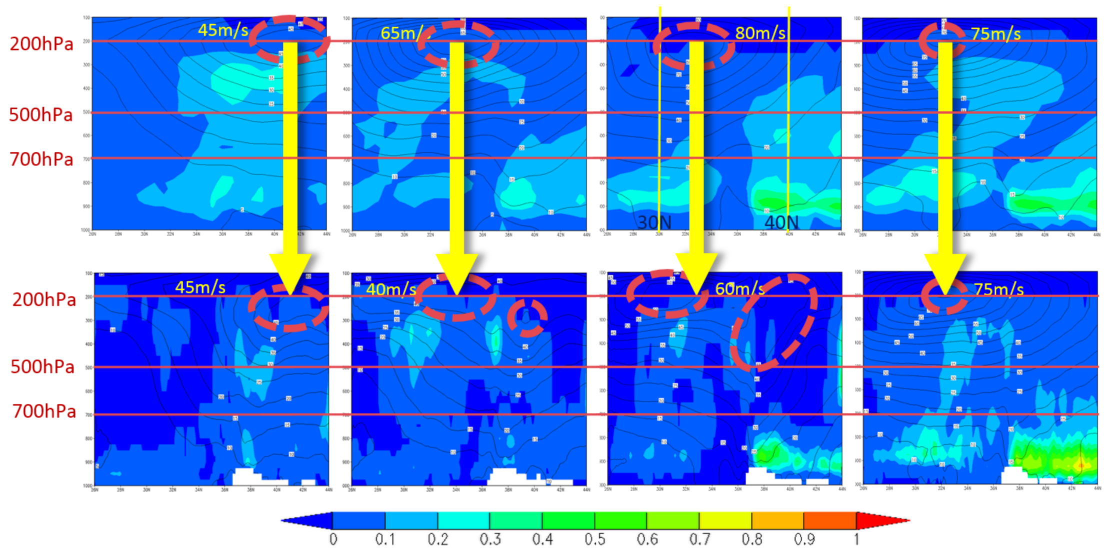


FIGURE 6.5: Comparison of 140 longitude cross-section profile of Monthly Mean Cloud Fraction(rainbow color) and Wind Speed(Black contours) from October 2005 to January 2006 for ERA-Interim (top) and WSM6-KF case(bottom)

Chapter 7

Conclusion

7.1 Summary of Results

Prediction of cloud and precipitation still pose as one of the most challenging aspect of atmospheric modeling. This is due to the nature of the subgrid processes parameterized in atmospheric models. Large amount of the uncertainty from regional climate models come from sub-grid parameterizations. This is due to the complexity of the feedback and interaction between physics parameterizations. Understanding the subgrid processes for predicting precipitation and the usage of applicable schemes for specific season or events are invaluable in the selection of appropriate parameterization for representing the moist convection process and precipitation in the model. Thus, the study aimed to improve RCM application for modeling precipitation for hydrologic applications through the development of a scheme selection methodology with a multi-physics(CU, BL, MP, RAD) focus and coupling of schemes based on a parameterization scheme intercomparison study. The scheme intercomparison study was implemented using a targeted sensitivity experiment approach on multi-climate regime application and evaluated by a proposed RCM diagnostic evaluation methodology to address scheme applicability dependent on climate-regime and geographic location and scheme transferability on different climate-regime types. The targeted sensitivity approach focused on cumulus scheme usage impact to precipitation modeling and assessed the coupling of the CU scheme to different parameterizations such as microphysics, radiation, and boundary layer scheme. The coupling of CU scheme with different parameterizations were analyzed based on the process that these coupled scheme combination represent in the precipitation process representation in the model. The CU-MP coupling was identified to represent total precipitation production in the model. CUMP-RAD coupling was identified to represent the cloud radiative impacts to precipitation modeling. And lastly, CU-BL coupling was identified to represent the impact of surface boundary layer processes to simulated precipitation. This scheme coupling combination sensitivity approach allows the linkage of scheme usage impact to the simulated precipitation. In addition, the applicability of the schemes were analysed by the usage of the proposed diagnostic evaluation for each season for each study area. The application from midlatitude Japan study area to tropical Philippine case and to equatorial tropical Indonesian case allows assessment of transferability of schemes to different climate regime types.

Initial sensitivity experiment was done for the cumulus convection scheme based on the literature survey(significant studies by Krishnamurti et al. [1980], Wang and Seaman [1997], Liang et al. [2004], Zhu and Liang [2007], etc.)that indicate high sensitivity of modelled precipitation to cumulus schemes. Results of the CU Exp showed the influence of cumulus scheme to the spatial mean distribution of precipitation, seasonal histogram, and associated apparent heating and drying profile magnitude and structure. The results showed a direct link between the biases from the vertical profile with the precipitation biases. The study further established the dominance and central importance of CU scheme in moist convection representation in RCM particularly through the inclusion of budget profile analysis in connecting the scheme usage to precipitation biases with biases from vertical apparent heating and drying profiles. It connected the precipitation biases with its associated vertical profile biases due to the CU scheme usage. Specific scheme sensitivity to simulating precipitation was observed through the multi-climate regime application for KF, GR, GF, and Tiedtke scheme with default schemes for microphysics, radiation, boundary layer, and LSM parameterizations. KF scheme showed overestimation bias due to relative humidity sensitivity of the scheme during hot humid climate regime during JJA season in Japan, and all seasons for tropical cases in Philippines and Indonesia. The overestimation was seen on the mean spatial distribution, seasonal histogram, and heating/drying budget profiles consistently. GR scheme, however, showed less overestimation than other schemes and highest spatial correlation during all seasons in Japan and during winter monsoon season in the Philippines(DJF, MAM). In purely tropical Indonesian case, GR scheme showed similar overestimation tendency with KF scheme. This characteristic of GR scheme is due to the ensemble type weighting function used for estimating precipitation in the model. The original application and evaluation was done in a midlatitude application where the weighting function of the convective trigger ensemble was calibrated. This shows potential of the GR scheme in terms of transferability issue by providing different weighting function of the ensemble average calibrated based on the climate-regime and latitudinal location of the study area. The transferability of this scheme is highly dependent on the weighting function used in the ensemble of convective triggers. This also showed that default weighting function GR scheme has greater weight on KF scheme convective trigger. But, a concern was seen on the peculiar drying profile seen from GR scheme over Philippines and Indonesia that might also be due to the ensemble weighting function in the mean feedback of the scheme. This is also a concern for the other ensemble schemes such as GD and GF schemes. GF scheme has an added complexity due to inclusion of scale-aware fraction for vertical eddy fluxes. Lastly, Tiedtke scheme showed comparable results for seasonal precipitation for all study areas. But, Tiedtke schemes' significant applicability was seen from consistent precipitation and heating/drying profile structure due to organized cluster convection implementation only in Indonesia case.

The coupling of CU scheme with microphysics, radiation, and boundary layers chemes through CU-MP-RAD Exp and CU-BL coupling. The results showed that coupling with BL, MP, and RAD schemes modulate the intensity of the precipitation distribution, seasonal histogram, and sub-grid heating/drying processes. Coupling with boundary layer schemes showed the greatest variability among the schemes in modulating the intensity of precipitation due to its control on the convective initiation environment in facilitating the surface processes and turbulent mixing. In contrast, microphysics scheme also modulate the intensity of precipitation but more importantly, contribution of the scheme to cloud formation influence the modulation of the precipitation and budget profiles. The intensity modulation of radiation scheme was comparable with the microphysics scheme. The radiation schemes mainly vary on the lower boundary layer cloud top and upper-troposphere level where high clouds are located. Due to this, a coupled scheme combination system was explored such as CUBL coupling for convective initiation environment, CU-MP for total precipitation representation, and CUMP-RAD for microphysical radiative impacts. This targeted sensivity experiment linked the usage of parameterization scheme to precipitation representation in the model and diagnose the associated precipitation distribution and vertical sub-grid heating/drying processes.

Based on the CU Exp results, default CU scheme in CU-MP-RAD coupling used was KF scheme for Japan and Philippines and Tiedtke for Indonesia. The default CU scheme was selected due to investigation of CU-MP and successively CU-MP-RAD coupling can alleviate default CU scheme's bias tendency. In summary, coupling of MP schemes with CU and RAD schemes cannot solve the bias tendency of default CU scheme used but modulated precipitation, histogram, and vertical heating/drying processes. No significant differences were seen in coupling CU-MP schemes except with microphysics schemes with ice transition treatment such as SBU YLin, Morrison and NSSL schemes. Similarly, no significant results were seen in coupling radiation with default CUMP cases.

For CU-BL coupling, the default CU scheme were KF for Japan and GF for Philippines and Indonesia. KF was used as default in Japan to investigate coupling can solve bias tendency of CU scheme. GF scheme was used for better land heterogeneity treatment for Philippines and Indonesia. The results show that precipitation and sub-grid heating/drying structure were mainly dependent on the default CU scheme used. Precipitataion variability was mainly affected by the CU-BL coupling results. In general, coupling with non-local mixing BL schemes showed largest overestimation while local TKE mixing BL schemes showed least overestimation. GF default scheme was initially applied and evaluated with a local TKE Mellor-Yamada BL scheme, thus, showing least overestimation tendencies. Additional surface perturbation were added on the scheme was included in the scheme to alleviate typical problem of local TKE BL schemes' mixing underestimation during convective boundary layer conditions in the diurnal cycle. Exclusion of this additional perturbation should be done when GF scheme is coupled with non-local mixing type BL scheme as well as for local TKE mass flux BL schemes.

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.

7.2 Recommendations

The study demonstrated the linkage of scheme usage to precipitation process representation in RCMs in both individual component and coupled component perspective. It is necessary to have both evaluation perspective to enable the assessment of the parameterization interaction and feedback in the precipitation process representation in the model. 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.

There were other issues that this study partially addressed to support the robustness of the results of the parameterization sensitivity intercomparison study. These issues were usage of ERA-Interim as reference profiles for the budget profile analysis, resolution issue, and domain-dynamics issue. These issues were addressed by the following paragraphs.

1. The ERA-Interim data was used as reference to the heat and moisture budget analysis due to unavailability observation for budget residuals. The reanalysis was the best guess of gridded vertical atmosphere data closest to observation so it was used, however, it still has some limitations. Due to the inherent limitations of the reanalysis as a complete substitute for the evaluation. Additional evaluation using observed data was needed to assess the vertical structure of the simulations. In this study, AIRS satellite data and IGRA radionsonde profiles to validate the atmospheric structure of the simulations.

   The AIRS data evaluation to understand the bias to energy-water coupling in the simulations through analysis of moisture-temperature coupling of the seasonal state supplementing the heat and moisture budget analysis. As such, air temperature, relative humidity, and specific humidity on five pressure levels (850hPa, 700hPa, 500hPa, 300hPa, 200hPa) were used to evaluate the atmospheric structure of the simulations. Due to this evaluation, some characteristic issues were seen for Japan, Philippines, and Indonesia. For Japan, the lower tropospheric warm wet bias coupled with upper tropospheric cold dry bias during months of October, November, and December. This was found to be consistent with the negative precipitation bias and warm 2-meter air temperature bias. This found to be due to the propagation of jetstream along the boundary into the domain. For Philippine and Indonesia case, it was found to have upper tropospheric bias with cold dry wet bias related to the representation of the Tropical Tropopause Layer through upper tropospheric cloud formation and cloud radiative effects. This might be a systemative error in modeling the tropical atmospheric structure by WRF model. But, more confirmation and additional analysis is needed to confirm.

Additionally, IGRA radiosonde comparison was done to assess the vertical temperature and wind profile of the simulations. It was found that the simulations were able to capture the seasonal atmospheric profile for JJA and DJF season quite well. This supports the credibility of the simulated atmospheric structure have been evaluated against radiosonde data.

2. The resolution issue for the simulations were treated in this study in 5 using the 24km-6km one-way nesting study on cumulus(CU)-microphysics(MP) usage at 6km resolution Kanto case. This was necessary in addressing an aspect that is highly regarded in modeling precipitation. High resolution precipitation is highly desirable in impact assessment studies and the utility and value of this study should be clarified in terms of its applicability when higher resolution is required. The usage of higher resolution of 6km introduced more variability in Precipitation as expected which was an advantage of 6km model usage. However, the usage of higher resolution such as 6km does not guarantee added skill on the precipitation simulation as the biases in the 24km model outer domain primarily passed to the inner nested 6km domain. Due to this, the inherent biases from the 24kmouter domain cannot be addressed and solved by using one-way nested 6km domain. Furthermore, it was explored if usage of explicit cumulus convection and parameterized convection in 6km can augment the problems of the 24km model. However, results show that 24km domain biases were directly passed to the 6km nested domain and usage of explicit cumulus convection does not solve the biases.

The skill performance advantage exhibited by usage of explicit cumulus convection was due to some degree of underestimation in the under 16mm/day threshold in the lower spectrum of seasonal histogram but overestimated frequency of extreme precipitation. This masked the general overestimation bias characteristic of the outer 24km domain of high frequency overestimation in the middle range of the respective seasonal histogram. Also, the usage of Grell-Freitas scheme was investigated in addressing the 6km gray resolution issue but results show that it cannot augment the inherent problems seen on the traditional cumulus schemes withour scale-awareness inclusion. It seems that in the precipitation simulation that it can fully address the problem but may show some potential in dealing with the gray scale issue. However as of the moment, the results on the 6km higher resolution modelling suggest that the outer domain biases primarily determine the capability of the inner-nested domain. Thus, complete analysis of the outer domains for one-way nesting higher resolution modelling needs to be fully assessed in terms of bias sources and associated mechanism of the biases. The issue of gray-scale is still unresolved and further investigations are needed. Analysis of surface variables and CU-BL-LSM coupling should be further investigated.

3. Domain-Dynamics issue investigation was done in 5 to further establish the validity and limitations of this study. The issues were briefly discussed and sources of the issues were investigated. Respective issues were seen on the domains as follows:

   Japan – OND Jetstream climatology and associated precipitation

   Philippines and Indonesia – Tropical Easterly Jet @100hPa, Tropical Tropopause Layer impact on the atmospheric circulation and associated precipitation

   However, the results on JJA and DJF seasons for all the study areas remain robust and does not invalidate the trends and conclusions of the physics parameterization sensitivity study. But, careful consideration should be done next time to avoid such issues presented in this study. Outstanding issue regarding the tropical tropopause layer representation through upper tropospheric cloud formation and cloud-radiative impacts may indicate some systematic bias coming from the model that had not been directly linked towards its impact on the precipitation prediction. This should be addressed in a different study. Another aspect might be related to momentum conversion impact of cumulus convection parameterizations in causing gravity-wave like propagation in the tropical domain. This aspect has not only been addressed by few studies that need to be updated in terms of the new updates on the current physics parameterization development. This ties the thermodynamic control of the physics parameterization to the its direct impact on the dynamics in the system.

4. Additional investigation of surface fluxes and boundary layer processes was done for more objective assessment on the selection of boundary layer scheme and other parameterization related. The formation of low boundary layer cloud that have been pointed out as one of the main sources of model climate sensitivity is due to the differences in the lower tropospheric mixing that can prove to be vital in using RCMs in downscaling for climate change impact assessment usage (Sherwood et al. [2014]). It was shown that the simulations were able to capture the diurnal cycle of the surface processes and variables. The surface variables were seen to be consistent in its variation on the associated diurnal variation of the surface processes. In general, non-local types tend to provide more vigorous mixing in the boundary layer inducing a more conducive convective environment for convective initiation such that it predisposes the cumulus convection scheme used to be triggered frequently resulting to overestimated precipitation. This characteristic behaviour is opposite for the local TKE type boundary layer schemes.

7.3 Scientific Contribution

The study addressed issues on physics parameterization scheme link with precipitation prediction and apparent heating-drying structure. It directly illustrated how this scheme linkage with precipitation and vertical structures increases our ability to assess the relative impact of scheme usage. It also allowed to see the typical tendency of the parameterization components and tested the applicability of the schemes on different climate regime types. These allows the exploration and discussion of scheme transferability regardless of season and geographic location. It basically showed the current status of the sub-grid parameterization components and their associated scheme implementations. The characterization of bias and distribution for precipitation and the relevant heating-drying vertical structure allows complete overview on the impact of scheme usage. This allows further development on specific aspects for parameterization developers and also further establishes the need for unification of the sub-grid processes. The usage of coupled scheme ideal and systemic approach perspective tries to supplement potential for gradual unification of specific parameterization components for specific relevant processes of interest.

This study shows how domain-time heat and water budget profiles can be used as bulk diagnostic tool for the analyzing the contribution of the parameterization schemes in the vertical structure of the atmosphere as integral component in a system rather than an independent component. It gives a platform for the discussion of parameterization feedback as a result of interaction to represent a specific process of interest. It outlines the basis for potentially objectively assessing the selection of appropriate parameterization scheme in both statistical evaluation and process-based evaluation allowing non-sporadic statistical measure advantage out of pure chance. The consistency between the statistical measures and process-based evaluation techniques is indispensable as illustrated in the study for furthering process-based understanding of sub-grid processes in monthly and seasonal temporal scale.

Lastly, it developed a selection methodology for physics parameterization for precipitation prediction modelling through process-based analysis basing it on the thermodynamic control of parameterizations in moist convection process. This is highly invaluable for regional climate modelling studies, short-term forecasting, and process studies. Although the specific applications will definitely require more specific evaluation procedure, this study provides the basic evaluation methodology needed for assessing appropriately selected physics parameterization schemes. But, it also supplements additional variable comparison for each component or each coupled scheme as seen relevant and subject to data observation availability.

Appendix A

Additional Figures

This section will be included in a publication for submission to Journal of Geophysical Research.

Appendix B

Radiation Experiment Validation

This section will be included in a publication for submission to Journal of Geophysical Research.

Appendix C

Evaluation of Air Temperature and Relative Humidity Using AIRS satellite data for BL, MP, and RAD schemes

This section will be included in a publication for submission to Journal of Geophysical Research.

Appendix D

Evaluation of Air Temperature and Wind Speed Profiles Using IGRA data for BL, MP, and RAD schemes

This section will be included in a publication for submission to Journal of Geophysical Research.

Appendix E

Japan Case: Histogram Comparison Using APHRODITE

This section will be included in a publication for submission to Journal of Geophysical Research.

Appendix F

Japan Case: Histogram Comparison Using TRMM

This section will be included in a publication for submission to Journal of Geophysical Research.

Appendix G

Philippines Case: Histogram Comparison Using APHRODITE

This section will be included in a publication for submission to Journal of Geophysical Research.

Appendix H

Philippines Case: Histogram Comparison Using TRMM

This section will be included in a publication for submission to Journal of Geophysical Research.

Appendix I

Indonesia Case: Histogram Comparison Using APHRODITE

This section will be included in a publication for submission to Journal of Geophysical Research.

Appendix J

Indonesia Case: Histogram Comparison Using TRMM

This section will be included in a publication for submission to Journal of Geophysical Research.

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