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Finding the Optimum Resolution, and Microphysics and Cumulus Parameterization Scheme Combinations for Numerical Weather Prediction Models in Northern Thailand: A First Step towards Aerosol and Chemical Weather Forecasting for Northern Thailand

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PoS(ISGC 2016)006

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Weather forecasts dictate our daily activities and allow us to respond properly during extreme weather events. However, weather forecasts are never perfect, but differences with model output and with observations can be minimized. Discrepancies between meteorological observations and weather model outputs are often caused by resolution differences (point vs. grid comparisons) and by the parameterizations used in the model. Atmospheric model parameterization refers to substituting small-scale and complicated atmospheric processes by simplified ones. In order to make weather forecasts more accurate, one can either increase the model resolution or improve the parameterizations used. Increasing model resolution can simulate small-scale atmospheric processes better, but takes a longer simulation time. On the other hand, improving model parameterization schemes involve in-depth measurements, analysis and research on numerous atmospheric processes. However, one can find a combination of existing parameterization schemes that would minimize observation-model differences. It is therefore essential to ask the question, "What model resolution and parameterization scheme combinations at a particular location and at particular seasons produce model output that has the smallest difference with observations simulated at a reasonable amount of time?"

Northern Thailand is a meteorologically active and unstable region especially during the summer and monsoon months (e.g. intense thunderstorms, hail storms, etc). It is also where high concentrations of air pollutants occur during the dry months (e.g. haze). It is therefore essential to have model forecasts close to observations for this region to reduce risk from weather and from air quality degradation. This study aims to find the optimum model resolution and parameterization scheme combinations at particular provinces in northern Thailand with available data during the wet and dry seasons that produces minimum differences with observations.

Nested model simulations were performed using the Weather Research and Forecasting (WRF) model (v. 3.6) ran in the High-Performance Computer (HPC) cluster of the National Astronomical Research Institute of Thailand (NARIT) for northern Thailand (2 km spatial resolution and hourly output), for the whole of Thailand (10 km spatial resolution and hourly output), and for the entire Southeast Asia (50 km spatial resolution and 3-hourly output). Combinations of the WRF Single-Moment 3-class, the WRF Single-Moment 5-class, the Lin et al. (Purdue), the WRF Single-Moment 6-class and the WRF Double-Moment 6-class microphysics parameterization schemes, as well as the Betts-Miller-Janjic, the Kain-Fritsch scheme, the Grell-Freitas (GF) ensemble and the Grell 3D cumulus parameterization schemes were utilized to determine the optimum resolution and parameterization of the model when compared to observations. Measured data came from the Thai Meteorological Department (TMD) weather stations in Chiang Mai, Chiang Rai and Lampang in northern Thailand from December 1-15, 2014 (cool dry season), from May 1-12 (hot dry season) and from August 1-7, 2015 (wet season). Results showed a seasonal dependence on the optimum microphysics and convective parameterization combination scheme. It was also found out that cloud resolving model grid sizes still failed to capture convective process as indicated by the derived optimum resolution for the hot-dry and wet seasons.

International Symposium on Grids and Clouds 2016
13-18 March 2016
Academia Sinica, Taipei, Taiwan

1. Introduction

In numerical weather prediction (NWP), physical laws of motion and conservation of energy that govern the evolution of the atmosphere (the dynamics) can be written into mathematical equations that can be solved numerically. For example,

$$\frac{\Delta A}{\Delta t} = f(A) \tag{1}$$

where $\frac{\Delta A}{\Delta t}$ is the change in a forecast variable, A, at a particular point in space with respect to time, t, and $f(A)$ describes the physical processess that can cause changes in the forecast variable. Values of meteorological variables later in time are calculated by finding their initial values and then adding the physical forcing, $f(A)$, that acts on the variables during the forecast period. This can be mathematically represented as,

$$A^{forecast} = A^{initial} + f(A)\Delta t \tag{2}$$

with the actual equations used are called the primitive equations. These equations dictate the forces or dynamics that give movement to air. It includes thermodynamic changes occurring in the atmosphere calculated from momentum, mass, energy and moisture conservation laws. Equally essential are: processes that occur at scales smaller than the model can resolve; energy, water and momentum exchanges between the atmosphere and other sources such as land, ocean and solar radiation; and cloud and precipitation physics. In NWP, the atmosphere is divided into smaller grid boxes (the size of which is called model resolution) where all these processes are calculated over an area which the model runs called the model domain [1].

NWP models are usually driven by coarse spatial resolution (e.g. 1^o x 1^o) global climate models that are unable to resolve sub-grid scale features (i.e. clouds, topography, etc.). In order to perform regional and local impact studies, downscaling has to be performed. One form is dynamical downscaling, where output from the coarse resolution model is used to drive a higher spatial resolution model. One such model which can perform dynamical downscaling is the Weather Research and Forecasting (WRF) model. This is used in this study.

1.1 Model Parameterizations

However, even when dynamical downscaling is performed, there are still small-scale atmospheric processes that NWP models cannot resolve. The model must therefore account for the aggregate effects of these small-scale processes. This is called parameterization. Figure 1 shows some of the physical processes that are typically parameterized by models. NWP models for the tropics are quite sensitive to two typical parameterization schemes [2]. These are the cumulus parameterizations and the microphysics parameterizations. Model output sensitivity tests on these two parameterization schemes are therefore necessary before making operational products.

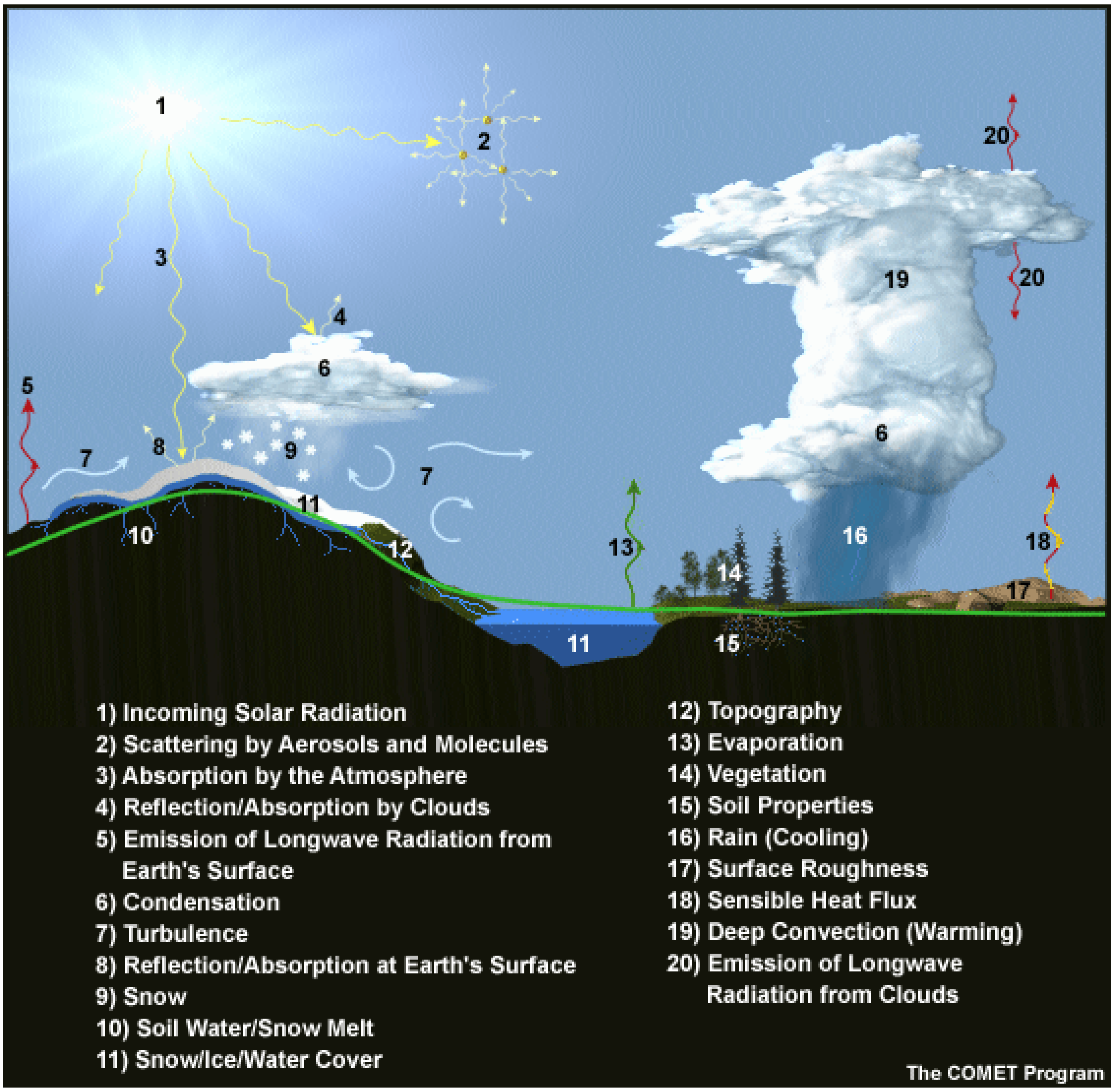

Figure 1. Some of the atmospheric processes parameterized by NWP models.

1.1.1 Microphysics Parameterization Schemes

Microphysics refers to the amount, type, processes (e.g. phase changes) and interaction between different condensates or hydrometeors (e.g. water vapor, cloud, rain, etc.). One of the pioneering researches on microphysics in NWP was conducted by Kessler in the 1950's wherein distributions of water vapor, cloud, rain and snow were studied in relation to air circulation. The microphysics processes implemented by this scheme are the following: the production, fall and evaporation of rain; the accretion and autoconversion (collision-coalescence) of cloud water; and the production of cloud water from condensation [3].

Some of the microphysics schemes used by models are the following (illustrated in Figure 2):

WRF Single-Moment 3-class, WSM3 (**mp3**)

This microphysics parameterization is based on Hong, Juang and Zhao in 1998 and revisions done by Hong, Dudhia and Chen in 2004. Similar to the scheme presented by Kessler, this scheme also uses three categories of hydrometeors, namely water vapor, cloud water/ice, and rain/snow. Cloud water and cloud ice, as well as rain and snow, are distinguished by temperature, with cloud ice and snow existing when the temperature is less than or equal to freezing point [4,5]. This is also a *single-moment* scheme, meaning that only the total mixing ratios of the condensates are modeled.

WRF Single-Moment 5-class, WSM5 (**mp4**)

This scheme is similar to *WSM3*, except that cloud water and cloud ice, as well as rain and snow, are in different categories. It allows the existence of supercooled water and the gradual melting of snow to rain as it travels towards the surface (mixed phase processes).

Lin et al. (Purdue) (**mp2**)

This microphysics scheme utilizes six categories of hydrometeors. These are water vapor, cloud water, cloud ice, rain, snow and graupel (also called soft hail, snow pellets or grail). The production terms are based on Lin et al. (1983) [6] and Rutledge and Hobbs (1984) [7] with modifications including saturation adjustment, in reference to the work of Tao in 1989 [8], and ice sedimentation. The scheme is taken from the Purdue cloud model as discussed in Chen and Sun [9].

WRF Single-Moment 6-class, WSM6 (**mp6**)

This scheme is similar to *WSM5*, with the inclusion of graupel as another modeled variable [10].

WRF Double-Moment 6-class, WDM6 (**mp16**)

This is a *double-moment* scheme version of *WSM6*. *Double-moment* includes the modeling of the number concentration of the condensates.

1.1.2 Convective or Cumulus Parameterization Schemes

Convective or cumulus parameterization pertains to mass-flux type schemes which consider updrafts and compensating subsidence as well as downdrafts, vertical momentum transports, entrainment and detrainment. It also reduces thermodynamic instability to prevent unrealistic convection by redistributing temperature and moisture throughout a grid column. One of the first convective schemes is the one developed by Kuo in 1975. It is a simple cumulus parameterization scheme by simulating the ascent of an air parcel by adjusting temperature and moisture profiles toward moist adiabatic [11].

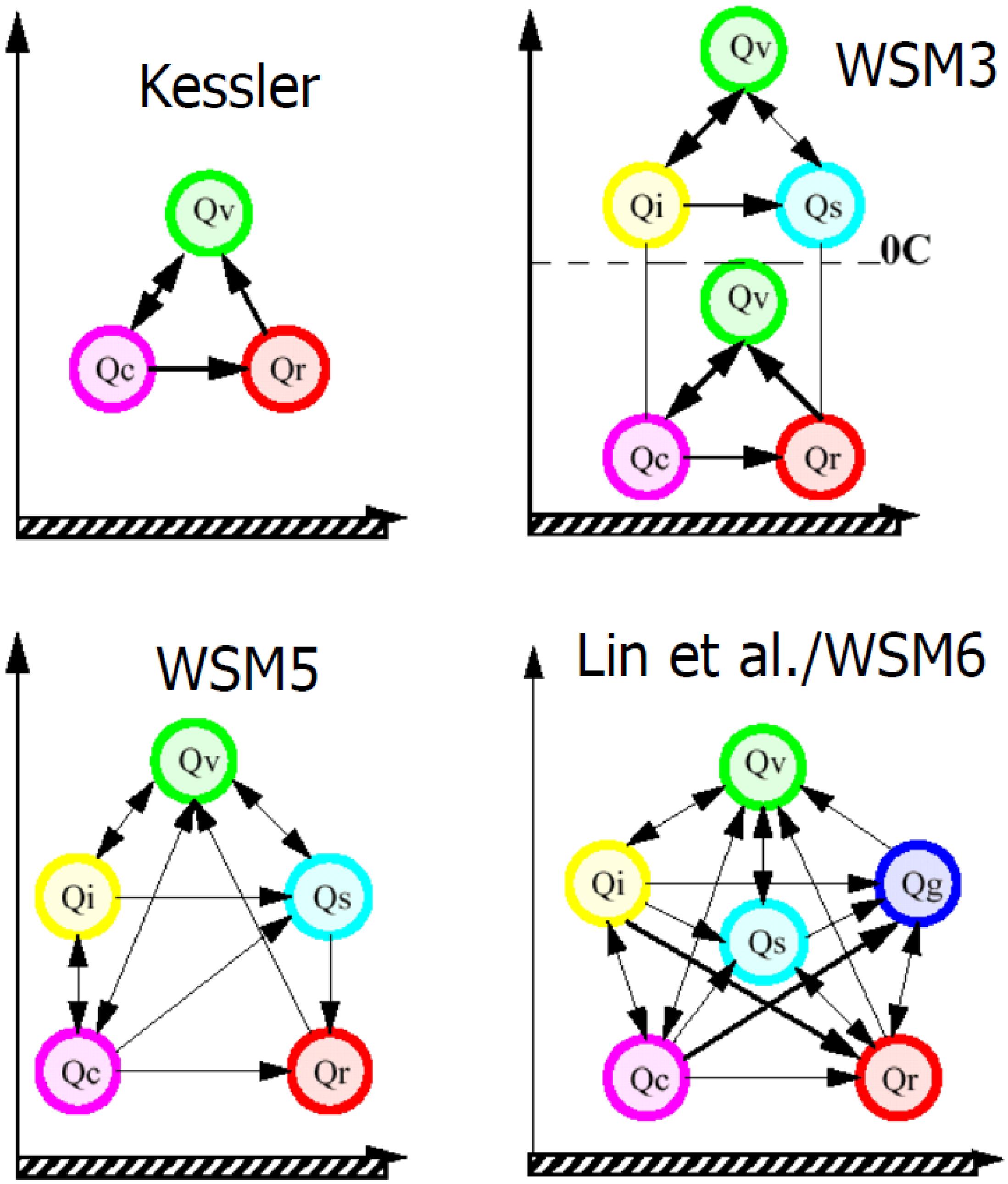

Figure 2. Microphysics Parameterization Schemes. Mixing ratios Q_v (water vapor), Q_c (cloud water), Q_i (cloud ice), Q_r (rain), Q_s (snow) and Q_g (graupel) are modeled (Image courtesy of Jimy Dudhia).

Some of the convective or cumulus parameterizations used by models are the following:

Betts-Miller-Janjic, BMJ (**cu2**)

This convective scheme is more complex than the Kuo scheme. It adjusts the profiles toward a pre-determined, post-convective reference profile derived from climatology [12, 13]. Janjic in 1990, 1994 and 2000 made modifications to this scheme by introducing "cloud efficiency" in determining target profiles of heat and moisture [14, 15, 16].

Arakawa-Schubert, AS (**cu4**)

This scheme includes the effects of moisture detrainment from convective clouds, warming from environmental subsidence, and convective stabilization in balance with the large-scale destabilization rate [17].

Kain-Fritsch, KF (**cu1**)

This cumulus parameterization scheme redistributes mass in the grid column such that the convective available potential energy (CAPE) is consumed [18, 19, 20].

Grell-Freitas, GF (**cu3**)

This scheme is based on a stochastic approach originally implemented by Grell and Devenyi in 2002 [21]. Two approaches were tested on resolutions ranging from 20 km to 5 km. One approach is based on spreading subsidence to neighboring grid points, the other one on a recently introduced method by Arakawa et al. in 2011 [22] in unifying multiscale modeling of the atmosphere [23].

Grell-3D, G3 (**cu5**)

This cumulus scheme is based on Grell and Devenyi [21] and Grell and Freitas [23] but includes cloud and ice detrainment.

1.2 Related Studies in the Southeast Asian Domain

Chotamonsak et al. in 2012 [24], evaluated the WRF model for regional climate applications over Thailand, focusing on simulated precipitation using various convective parameterization schemes available in WRF. In his study, boundary conditions were obtained from the NCEP/NCAR reanalysis data utilized for simulations at the 60-km model resolution parent domain encompassing Southeast Asia and some portions of India and China. A nested domain with 20-km model resolution was used for Thailand. Four convective parameterization schemes (*BMJ*, *Grell-Devenyi*, *improved Grell-Devenyi* and *KF*) were utilized in the study for the year 2005. Sensitivity to analysis nudging, which pertains to relaxing the model towards the boundary conditions, was also performed in this study. Results were evaluated against station rain data from the Thai Meteorological Department and gridded precipitation data from the Climatic Research Unit of the University of East Anglia. In general, the simulations with analysis nudging and *BMJ* cumulus parameterization yielded the smallest bias relative to observations.

Also in 2014, Raktham et al. [25] assessed the WRF model's ability to simulate major weather phenomena such as dry conditions, tropical cyclones and monsoonal flows over East and Southeast Asia. *KF* and *BMJ* cumulus parameterizations as well as *Lin et al. (Purdue)*, *WSM3,* *WSM6* and *Thompson* microphysics schemes were used to assess the parameterization sensitivity. Sensitivity to the placement of the boundary conditions was also assessed. The simulations utilized a 36-km model resolution with 51 vertical levels. Results showed that dry conditions showed little sensitivity to configuration combinations, while the tropical cyclone cases showed high sensitivity to convective parameterizations and low sensitivity to microphysics schemes. Monsoonal flows, on the other hand, showed significant sensitivity to the placement of the boundary conditions.

2. Methodology

2.1. Model Domain, Spatial and Temporal Resolution, and Temporal Coverage

The Weather Research and Forecasting model (version 3.6) was ran on the high performance computing (HPC) cluster of the National Astronomical Research Institute of Thailand (NARIT). The HPC has a total of 5 compute nodes with 16 cores each totaling to 80 cores reaching a maximum speed of 2.26 teraflops. Message passing interface (MPI) was the protocol used to run WRF in parallel computing mode. In this work, it was found that the optimum number of cores was 8 and this configuration was used for simulations in the model domain as shown in Figure 3.

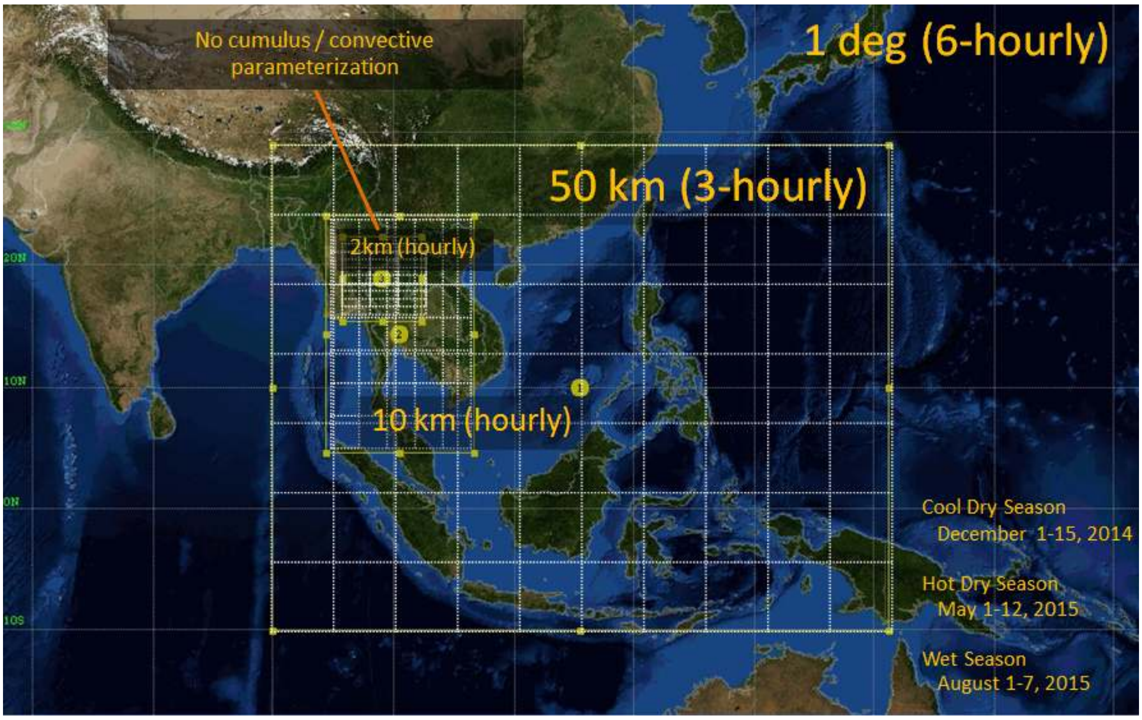

Figure 3. The model domain, spatial and temporal resolution and the temporal coverage used in this study.

The lateral boundary conditions, which include some parts of India, East Asia and Australia were taken from the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data (http://rda.ucar.edu/datasets/ds083.2/index.html#!description). The FNL data are on a 1 degree x 1 degree grid prepared operationally every 6-hours. The parent domain is situated in most of Southeast Asia having a 50-km model resolution with output every 3 hours. The second inner domain is placed over Thailand including some surrounding regions having a grid size of 10 km with hourly model output. The innermost domain is focused over northern Thailand with a resolution of 2-km and having model output every hour. Since the innermost domain has a convection resolving grid size (less than approximately 5 km), no cumulus parameterization scheme was used for this region.

Northern Thailand has three official seasons encompassing approximately four months each. However, due to the limitations in memory of the NARIT HPC and due to the observations available from the Thai Meteorological Department (TMD), only representative days at particular months and at a specific year were chosen for each season. The cool dry season, which officially begins in November and runs through February, was simulated from December 1-15, 2014. The hot dry season, which ranges from March to June, was modeled from May 1-12, 2015. The wet season, which runs from July to October, was processed from August 1-7, 2015. These dates were also chosen based on the average temperature and precipitation of that year.

2.2 Parameterizations

The microphysics (**mp**) and convective (**cu**) parameterization combinations used in the sensitivity study are summarized in Table 1. **mp3cu1** are the default WRF parameterizations and **mp2cu2** provided the smallest bias when compared to observations in Thailand [23] and in Southeast Asia [24].

Table 1. Parameterization combinations used.

	Microphysics				
Cumulus	WRF Single-Moment 3-class, WSM3 (mp3)	WRF Single-Moment 5-class, WSM5 (mp4)	Lin et al. (Purdue) (mp2)	WRF Single-Moment 6-class, WSM6 (mp6)	WRF Double-Moment 6-class, WDM6 (mp16)
Betts-Miller-Janjic, BMJ (cu2)			X		
Kain-Fritsch, KF (cu1)	X	X	X	X	X
Grell-Freitas, GF (cu3)		X	X	X	X
Grell-3D, G3 (cu5)		X	X	X	X

2.3 Validation Sites and Performance Metrics

The location of the validation sites are illustrated in Figure 4.

Figure 4. Validation sites from the top 3 cities (in terms of population) in northern Thailand.

Summarized in Table 2 are the metrics used to assess the performance of the model after comparing with the observations. Temperature, pressure and relative humidity were the only meteorological parameters used in calculating for the metrics during the cool-dry and hot-dry seasons since there was no rain data during this period. Precipitation data was added during the wet season. Wind speed and wind direction were excluded in the calculation of the metrics since the wind observations were located inside the urban canopy. However, the model configuration used did not include urban surface physics.

Table 2. Performance Metrics

Metric	Equation	Meteorological Parameter Used, y (y_o = observed; y_m = modeled)
%Bias	$\frac{\sum(y_m - y_o)}{\sum y_o}$	temperature, pressure, humidity, rain (only during wet season)
Mean Absolute Error, %MAE	$\frac{\sum\lvert y_m - y_o\rvert}{\sum y_o}$	
Root-Mean-Square Error, %RMS	$\frac{\sqrt{\frac{\sum(y_m - y_o)^2}{N}}}{\sum y_o}$	
Correlation Coefficient, R	Pearson product-moment	

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3. Results and Discussion

3.1 Optimum Microphysics and Convective Parameterization Scheme

After the model ran using the different parameterization combinations, the performance metrics were averaged for the different meteorological parameters and validation sites to come up with just one value for each metric for each microphysics and convective parameterization combination. Shown in Figure 5 are the performance metrics during the cool-dry season for the 2-km model grid resolution averaged for all validation sites.

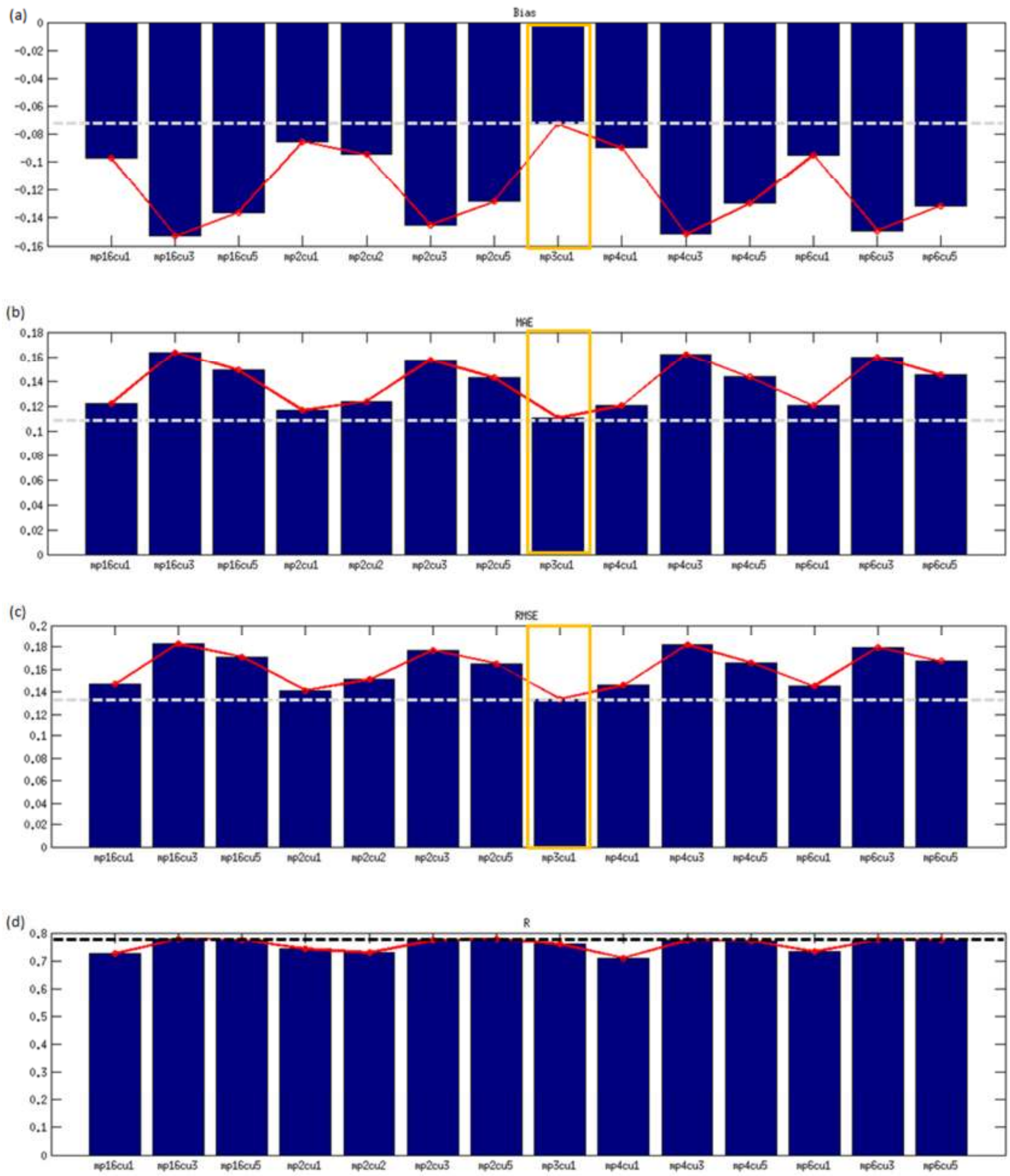

Figure 5. Performance metrics for the cool-dry season for the different microphysics and convective/cumulus pararmeterization schemes at 2-km model grid resolution averaged for all validation sites: (a) % Bias; (b) % Mean Absolute Error, %MAE; (c) % Root-Mean-Square Error, %RMS; and (d) Correlation Coefficient, R.

It can be seen in Figure 5 that for the **cool-dry season**, the **mp3cu1** (see Table 1) parameterization combination had 3 out of 4 performance metrics (bias, MAE and RMS) as optimum. For the **hot-dry season** and the **wet season** (not shown), the **mp2cu2** and the **mp16cu5** parameterizations were optimum, respectively.

3.2 Optimal Model Grid Resolution

For the **cool-dry season**, the **2 km** resolution was optimum (4 out of 4 performance metrics) as shown in Figure 6 for the **mp3cu1** microphysics and convective parameterization combination.

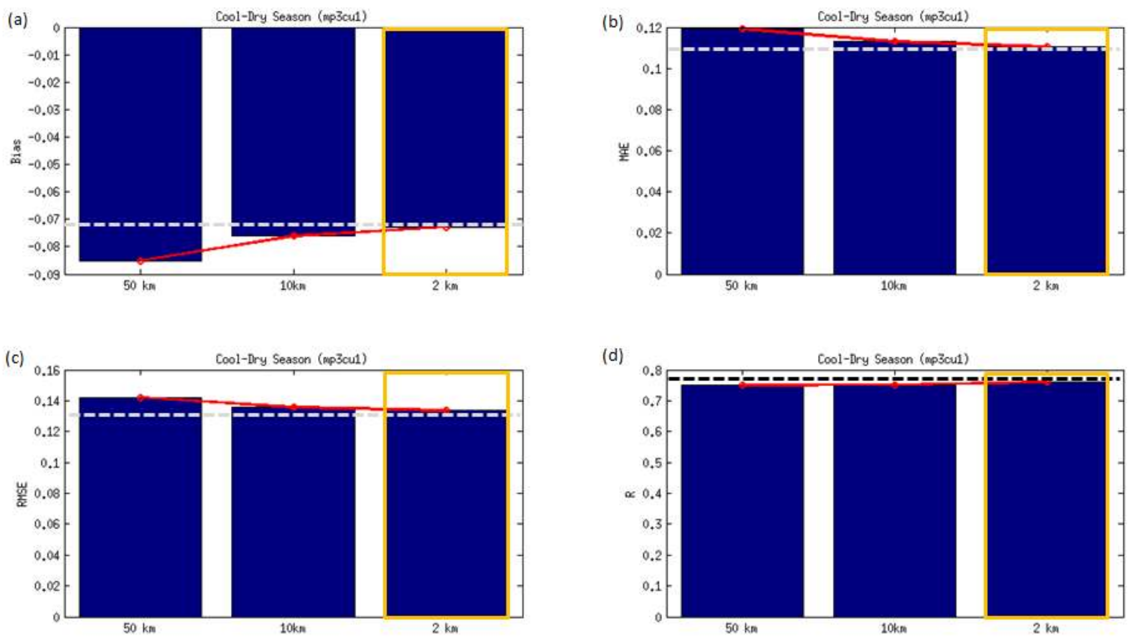

Figure 6. Performance metrics for the cool-dry season for different model grid resolutions (50 km, 10 km and 2 km) using the mp3cu1 scheme averaged over all validation sites: (a) % Bias; (b) % Mean Absolute Error, %MAE; (c) % Root-Mean-Square Error, %RMS; and (d) Correlation Coefficient, R.

Figure 7 and Figure 8 show the difference between the 2-km and the 50-km grid resolution time-series and correlation, respectively, of temperature, surface pressure and relative humidity for the cool-dry season at the Chiang Mai TMD station. It can be seen that the 2-km model resolution had more metrics that were closer to the observed values (temperature: bias, MAE, RMSE, R; pressure: bias, MAE, RMSE; 7 metrics) as compared to the 50-km grid resolution (pressure: R; relative humidity: bias, MAE, RMSE, R; 5 metrics).

However, for the **wet season**, the **50-km** resolution was optimum (4 out of 4 performance metrics) as shown in Figure 9 for the **mp16cu**5 microphysics and convective parameterization combination.

Figure 10 and Figure 11 show the difference between the 2-km and the 50-km grid resolution time-series and correlation, respectively, of temperature, surface pressure, relative humidity and rain for the wet season at the Lampang TMD station. It can be seen that 50-km model resolution had more metrics that were closer to the observed values (temperature: bias,

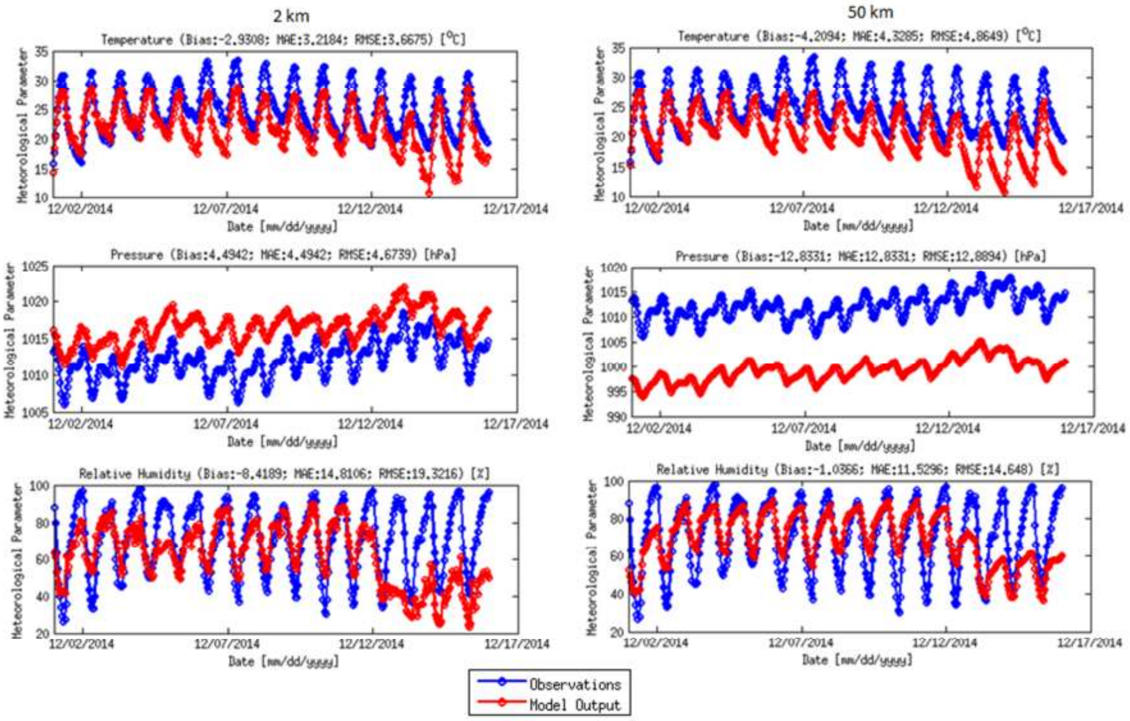

Figure 7. Time-series of temperature, pressure and relative humidity observations and model output during the cool-dry season for the Chiang Mai airport TMD station. The plots on the left are for the 2-km model resolution while the plots on the right are for the 50-km model resolution.

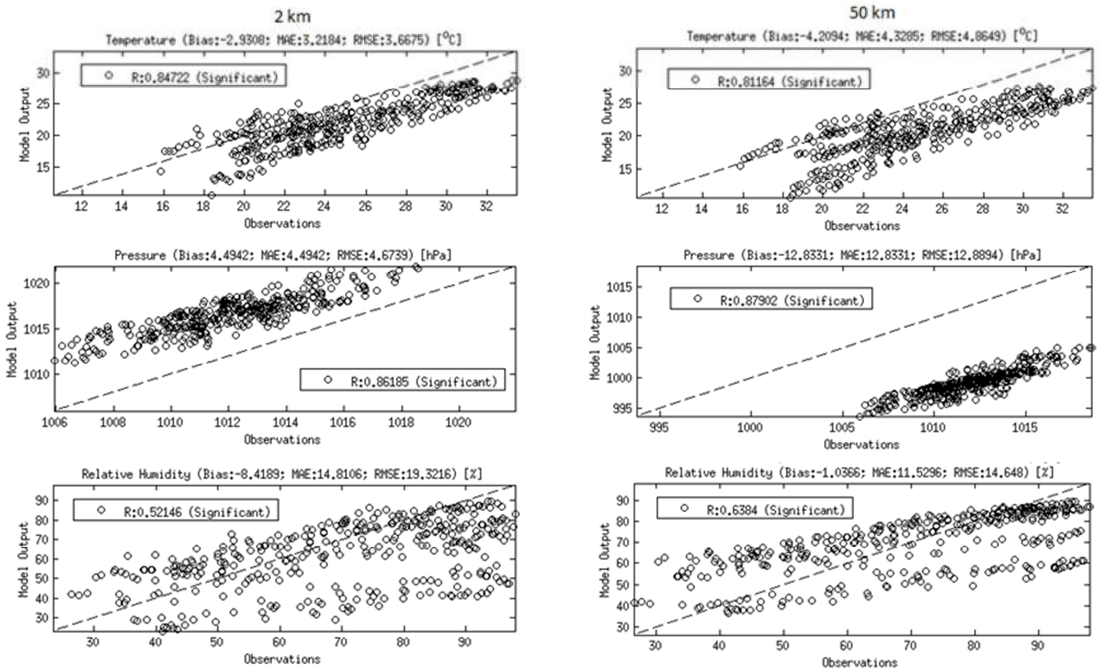

Figure 8. Correlation of temperature, pressure and relative humidity observations and model output during the cool-dry season for the Chiang Mai airport TMD station. The plots on the left are for the 2-km model resolution while the plots on the right are for the 50-km model resolution.

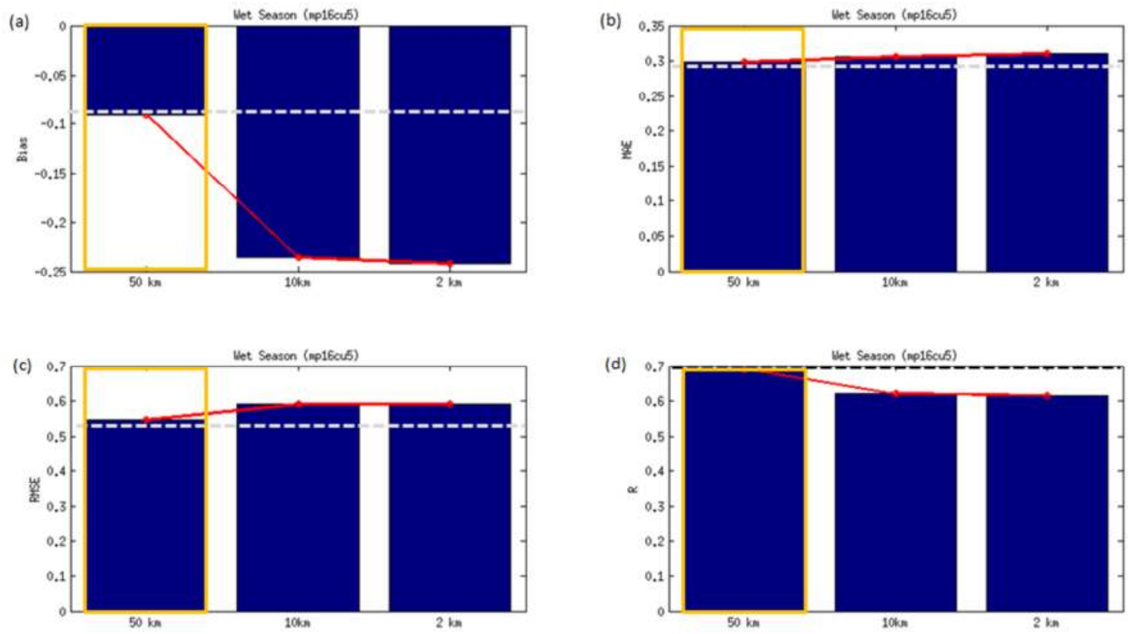

Figure 9. Performance metrics for the wet season for different model grid resolutions (50 km, 10 km and 2 km) using the mp16cu5 scheme: (a) % Bias; (b) % Mean Absolute Error, %MAE; (c) % Root-Mean-Square Error, %RMS; and (d) Correlation Coefficient, R.

MAE, RMSE, R; pressure: R; relative humidity: bias, MAE, RMSE, R; rain: bias, MAE, RMSE, R; 13 metrics) as compared to the 2-km grid resolution (pressure: bias, MAE, RMSE; 3 metrics).

Also, for the **hot-dry season**, the **50-km** model grid resolution was optimum. This indicates that the cumulus parameterization (present for the 10-km and 50-km resolution and absent for the 2-km grid size) is essential for the hot-dry and wet seasons since more convective processes occur that convection resolving model grid sizes still fail to capture.

4. Conclusion and Recommendations

A sensitivity analysis was performed on the microphysics and the cumulus/convective parameterization schemes, as well as on the model grid resolution size of the Weather Research and Forecasting model for Northern Thailand. After comparison of the model output with observations, it was found out that the optimum resolution and parameterization schemes depend on the season:

(1) the **WRF Single-Moment 3-class** microphysics scheme and the **Kain-Fritsch** convective parameterization on a **2-km** model grid resolution was optimum during the **cool-dry** season;

(2) the **Lin et. al (Purdue)** microphysics parameterization and the **Betts-Miller-Janjic** cumulus scheme on a **50-km** grid was optimum for the **hot-dry** season;

(3) and the **WRF Double-Moment 6-class** microphysics parameterization scheme and the **Grell-3D** on a **50-km** resolution was optimum for the **wet** season.

The seasonality on the two parameterizations that were examined can be inferred to be due to

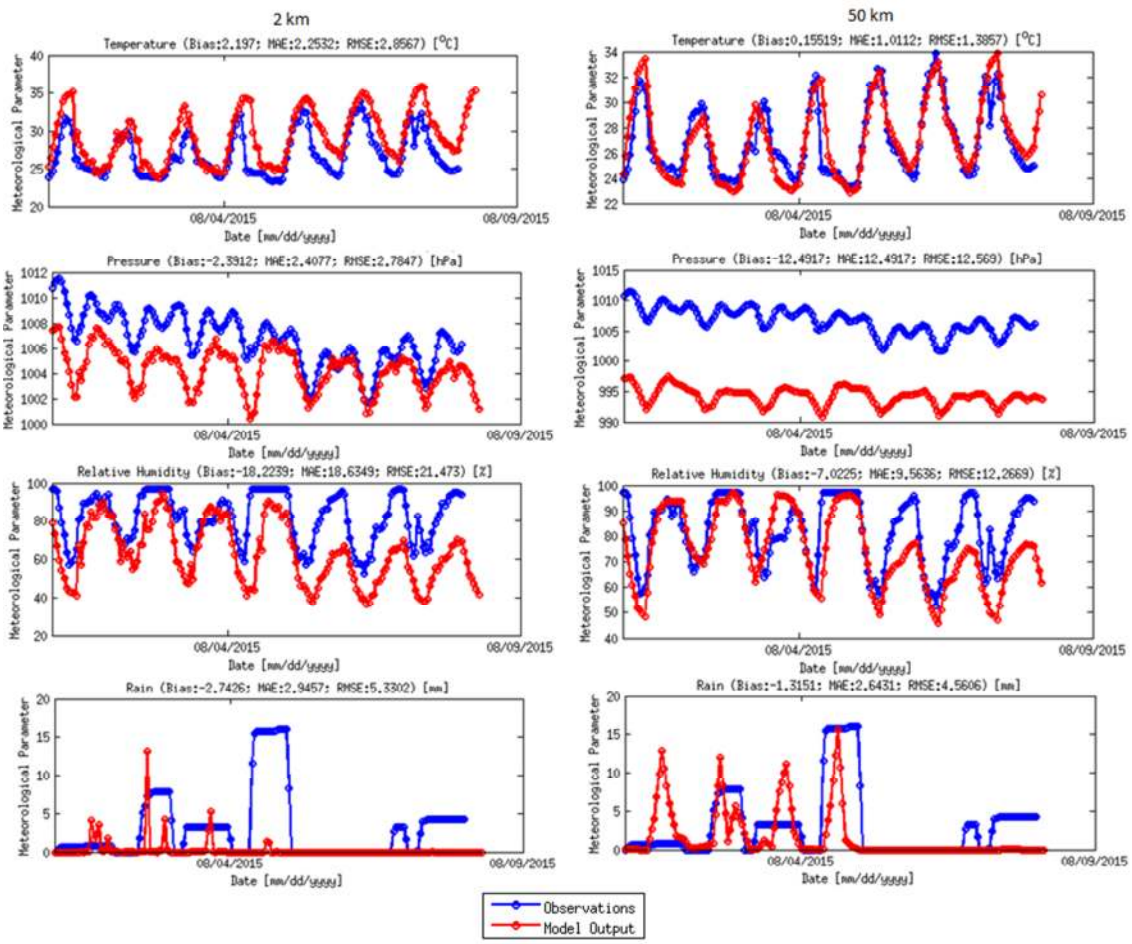

Figure 10. Time-series of temperature, pressure, relative humidity and rain observations and model output during the wet season for the Lampang airport TMD station. The plots on the left are for the 2-km model resolution while the plots on the right are for the 50-km model resolution.

the seasonal presence and abundance of the hydrometeor classes, as well as to the type of convective processes that occur at different seasons. This will be investigated further by looking at the hydrometeor vertical profiles from the model output and with available observations, and by comparisons of instability parameters from the simulations with radiosonde data.

Cloud resolving model grid sizes (e.g. below 10 km) still fail to capture convective process as indicated by the derived optimum resolution for the hot-dry and wet seasons. This needs to be investigated further.

Improvements to the model configuration, such as using an updated and higher resolution land use data and investigating the effects nudging will be applied for the forecasting mode of the model runs.

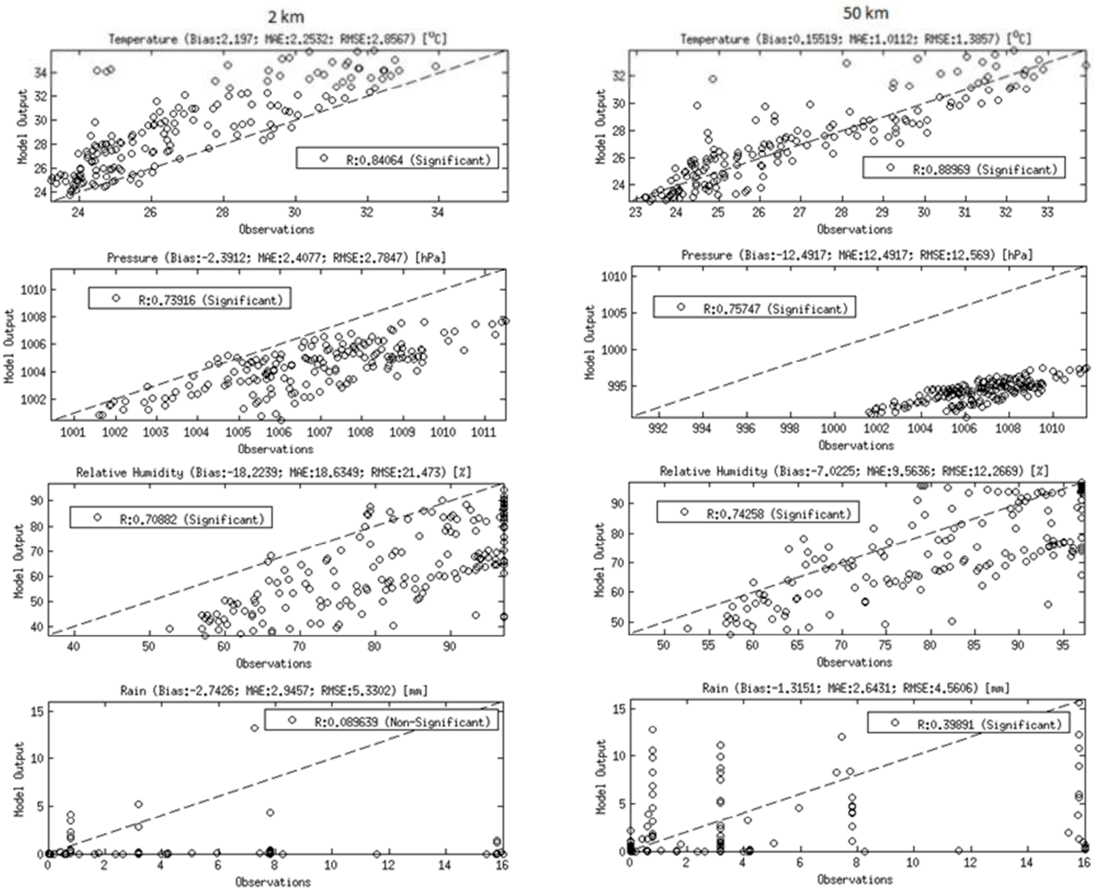

Figure 11. Correlation of temperature, pressure, relative humidity and rain observations and model output during the wet season for the Lampang airport TMD station. The plots on the left are for the 2-km model resolution while the plots on the right are for the 50-km model resolution.

Acknowledgments

The authors would like to thank **Utane Sawangwit**, **Saijai Cumwan**, **Wannisa Kanta**, **Suparerk Aukkaravittayapun**, **Saran Poshyachinda**, **Boonrucksar Soonthornthum**, **Nirun Hirunsook** and **Kanlaya Thapiang** for their assistance and support of this study. We would also like to thank the **Ministry of Science and Technology of Thailand** for funding this work.

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