Applicability of RAMS for A Simulation to Provide Inputs to an Air Quality Model: Modeling Evaluation and Sensitivity Test

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Abstract: - In this study, the Regional Atmospheric Modeling System (RAMS) is applied to simulate historical wind and temperature fields in the Bang Pakong area of Thailand in order to support a photochemical air quality modeling system in summer and winter time. We use high-resolution datasets of Digital Elevation Model (DEM), global monthly Sea Surface Temperature (SST), and global reanalysis data as a part of the global analysis information for a preparation of geo-terrestrial processes. The studied domain covers the Central and Eastern regions of Thailand. The based model setup includes one-way with the nesting grid of the Bang Pakong area using typical modeling parameters. The configurations of each domain (i.e., time steps and grid resolution) are formulated by grid specifications. The results indicate that RAMS can be applied to the historical meteorology (i.e., wind and temperature fields) over the complex terrain and the coast area. The statistical evaluation is applied in an average basis of the ground surface and found acceptable agreement between available observed and simulated results. Data assimilation by nudging analysis is applied to Thailand's weather information obtained from the Thai Meteorological Department (TMD) to improve modeling simulations. This technique shows the better improvement of modeling performance. Sensitivity tests on some physical parameters and schemes (i.e., convective cumulus and radiation parameters) are conducted to investigate their influence on modeling responses. The modeling performance of physical parameters to the area of study are discussed

Key-Words: - Meteorological model, Evaluation, Modeling performance, Data assimilation, Sensitivity test

1 Introduction

The Bang Pakong area is located in the Central and Eastern regions of Thailand at the Gulf of Thailand, having a large number of industrial facilities and power plants [1] (Fig.1). It is an area of high pollution resulting from various emission sources and the local wind and heat circulation (i.e., complex terrain and land/sea breeze). The air quality index shows the high level in summer and winter comparing with other seasons [2]. In this research, the Regional Atmospheric Modeling System (RAMS) [3, 4], developed by the Colorado State University and the ASTER division of Mission Research Corporation, is applied to simulate historical meteorology and atmospheric physics. Some key parameters (i.e., wind and temperature fields) are of interest to the investigation of the characteristics of the local wind circulation and temperature fields. Good atmospheric modeling performance is needed in simulating meteorological fields. The results can show acceptable inputs required to support photochemical air quality model [5, 6].

It is significant that the results of the RAMS used in the air quality model are validity. To test the reliability of RAMS, a comparison between meteorological simulation and monitoring observation is conducted. Performance evaluation is deployed by several statistical methods being recommended by the meteorological simulations to air quality studies [7, 8]. In addition, we hypothesize a nudging type of data assimilation and sensitivity studies on some physical schemes with observational information to improve the performance of the RAMS.

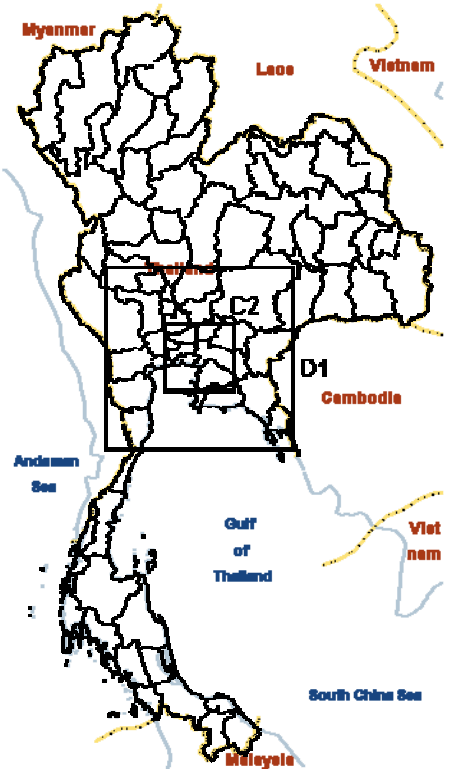

Figure 1. The map illustrates the studied area and domain with political boundaries and sub-regions. Domain 1 (D1) covers the Central and Eastern region of Thailand at the Gulf of Thailand. Domain 2 (D2) covers Bang Pakong and surrounding areas.

2 Methodology

2.1 Base case simulation

The simulation of RAMS was conducted a using one-way nesting grid with a nesting ratio of 4:1 and 26 vertical layers with a vertical grid stretch ratio of 1.20. Domain 1, the coarse (mother) domain, has a dimension 392 × 392 km^2 and consists of 98 × 98 grid cells with a grid size 4 × 4 km^2. Domain 2, the finer (child) domain, consists of 150 × 150 grid cells with a grid size 1 × 1 km^2, respectively. It should be noted that domain 1 covers the Central and Eastern regions of Thailand including the Gulf of Thailand while domain 2 covers the Bang Pakong area and the adjacent provincial landmasses.

The 30-second elevation datasets of topography from the global survey and vegetation data from United State Geological Survey / Global Land Cover Characterization (USGS/GLCC) were associated with a geo-processing step of RAMS. Initial and lateral boundary conditions were provided by the National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) with a global resolution of 2.5 × 2.5 degree (this data is available online: http://www.cdc.noaa.gov). Sea Surface Temperature (SST) from NCEP has a 2.5-degree resolution. NCEP reanalysis and SST data were analyzed and then interpolated into the model grid by RAMS/ISAN (ISentropic ANalysis package) [9] for the preparation of initial and lateral boundary conditions.

For the base case, the RAMS was configured using typical schemes: Kuo scheme for convective cumulus parameterization [10], Mahrer/Piekle scheme for short and long wave radiation with cloud effects [11], planetary boundary layer of turbulent mixing scheme [12], and Land Ecosystem Atmospheric Feedback version 2 (LEAF2) model [13]. For adaptive performance, a nudging-type scheme of Four Dimensional Data Assimilation (FDDA) [14] was integrated into the available observed data from the Thai Meteorology Department (TMD). Along with additional variables, these were included into RAMS. The model equation can be referred as follows (Eq. 1):

$$\frac{\partial \phi}{\partial t} = \varepsilon \frac{\left(\phi_{obs} - \phi_{model}\right)}{\tau} \qquad (1)$$

where,

ϕ : prognostic variables for horizontal direction (i.e., wind and temperature).

τ : timescale controlling the strengths of nudging term and varies in three dimensions.

ε: weighting factor of a time scale in (*x*, *y*, *z*) direction

It is important that the vertical direction is the gap due to the possibility of divergence. Therefore, the relationship of timescale with a coordinate system can be demonstrated as follows (Eq. 2):

$$\tau_{lat} = \tau_B \left[\frac{(x - x_I)^2}{(x_I - x_B)^2} \right] \tag{2}$$

where,

τ_{lat}: nudging timescale of the lateral boundary region,

τ_B: timescale specified for the actual boundary point,

x_B : *x* coordinate of the boundary point, and

x_I : *x* coordinate of the interior point where the lateral boundary timescale goes to infinity

It is noted that this equation is valid between x_B and x_I only.

Performance evaluation was initially hypothesized by RAMS Evaluation and Visualization Utilities (REVU) [9] in order to interpolate and reformat RAMS user-specified outputs into graphical and plotting analysis files. Statistical tests were applied in three measurable ways for the comparison of the simulated results with the observed data. They are: (1) measurements of bias: Mean Bias (*MB*), Gross Bias (*GB*), and Normalized Mean Bias (*NMB*) (2) measurements of error: Root Mean Square Error (*RMSE*), Normalized Mean Error (*NME*), and Index of Agreement (*IOA*) (3) measurements of points which model results are over a factor of 1.5, *F*(1.5), and factor of 2, *F*(2.0) of the observations. Mathematical formulation of *MB*, *GB*, *NMB*, *RMSE*, *NME*, *IOA*, *F*(1.5), and *F*(2.0) are expressed as follows (Eqs. 3-9) [15, 16],

$$MB = \frac{1}{N}\sum_{1}^{N}(model - obs) \tag{3}$$

$$GB = \frac{1}{N}\sum_{1}^{N}\left|model - obs\right| \tag{4}$$

$$NMB = \left[\frac{\sum_{1}^{N}(model - obs)}{\sum_{1}^{N}(obs)} \right] \tag{5}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{1}^{N}(model - obs)^2} \tag{6}$$

$$NME = \left[\frac{\sum_{1}^{N}\left|model - obs\right|}{\sum_{1}^{N}(obs)} \right] \tag{7}$$

$$IOA = 1 - \left[\frac{\sum_{1}^{N}(model - obs)^2}{\sum_{1}^{N}\left(\left|model - \overline{obs}\right| + \left|obs - \overline{obs}\right|\right)^2} \right]$$

$$0 < IOA < 1 \tag{8}$$

$$F(1.5) \le \frac{obs}{model} \le F(2.0) \tag{9}$$

Referring to the previous researches, statistical tests were conducted as a standard baseline [7, 17]. These values were based upon the evaluation of variety sets of RAMS simulation for air quality applications. The result of this study is contributed in order to compare with existing prior researches. Comparative with these results, the use of these values was not for an evaluation of a pass or failure of meteorological modeling performances. It only offers suggestions of acceptable and reliable results in the proper way. Another important consideration of statistics testing for an adequate meteorological performance to photochemical models depends on how one develops and represents a meteorological model of a given domain and on selected episodes of the study. Unsatisfied statistical evaluation shows that the model requires critically considering all related parameters and aspects of modeling parameters, inputs diagnostic, and process approaches [7, 17].

2.2 Sensitivity test

Different locations have their unique meteorological characteristics and physical properties influenced by local effects. It is thus inadequate to use only typical schemes for a meteorological simulation. For clarification, sensitivity studies on some parameters of RAMS were conducted to investigate the suitability of meteorological parameters for the studied domain. The use of updated datasets of the surface and the upper air levels for improving the initial and boundary conditions was exploited. Sensitivity runs were performed to investigate various meteorological parameters and physical schemes resulting in wind and temperature fields.

The summary of sensitivity runs can be seen on Table 2. For consistency, the technique of modeling evaluation for sensitivity test used the same method of the base case simulation described in section 2.1.

In comparing with the previous datasets, the NCEP Global Final Analysis (FNL) dataset covering a 1 × 1 degree grid updated every six hour was prepared for geo-processing step of the RAMS. The datasets are composed of 26 parameters of the surface and upper air level ranging from 1,000 mb to 10 mb (these datasets are available online: http://dss.ucar.edu/datasets/ds083.2).

There are three available alternatives in RAMS, for a simulation of convective parameters of the grid: (1) No convective simulation, (2) Modified Kuo scheme [10], and (3) Kain-Fritsch scheme [18, 19]. No convective simulation ignores the importance of convective parameter. The Kuo scheme is the typical convective parameter scheme to simulate updraft and downdraft formulation of clouds. The Kain-Fritsch scheme is a mass flux parameter scheme using the Lagrangian parcel method and vertical momentum dynamics to estimate the properties of convective clouds.

The available specified options for evaluating solar radiation transferring in RAMS are: (1) No solar radiation, (2) Chen-Cotton scheme [20], (3) Mahrer-Pielke scheme [11], and 4) Harrington [21]. No solar radiation ignores the importance of solar radiation during the simulation. Mahrer-Pielke scheme is the simplest method that consumes less computational time. This is due to ignoring liquid, ice, and cloud formation in the atmosphere, although water vapor is taken into account. The Chen-Cotton scheme includes the effects of cloud processes considering all condensate as liquid. Harrington scheme includes each particular form of condensate (i.e., cloud water, rain, pristine ice, snow, aggregates, graupel, hail, and water vapor) based on the integration of two-stream interaction between liquid and ice. This also considers the characteristics of ice crystals. This scheme also estimates upper air levels for radiation, thus becoming the most sophisticated parameterization.

3 Results and discussion

3.1 Base case simulation with FDDA

Fig.2 illustrates the wind fields over the studied domain, considered as the coastline areas at the Gulf of Thailand. It also shows temperature fields in the shaded contour over the high and complex terrain on the Northeastern and Southeastern area. The results are acceptable and satisfactory in term of magnitude and trends for a simulation of land/sea breezes on the entire coastline. In addition, it indicates the synoptic conditions by land/sea breezes with a strong pressure gradient resulting in light south-west wind flowing over the land. Temperature fields show a well-defined convergence area from the sea (south and west) to the land opposing the onshore area.

Table 1. Sensitivity studies on some physical parameterization and scheme

SENSITIVITY RUN	ANAL. / OBS. DATA	CUMULUS	RADIATION
S0: Normal run	NCEP	Kuo	Mahrer/Pielke
S1: Base case	NCEP / TMD	Kuo	Mahrer/Pielke
S2: FNL	FNL / TMD	Kuo	Mahrer/Pielke
S3: No cumulus	NCEP / TMD	None	Mahrer/Pielke
S4: Kain-Frish	NCEP / TMD	Kain-Frish	Mahrer/Pielke
S5: No radiation	NCEP / TMD	Kuo	None
S6: Chen-Cotton	NCEP / TMD	Kuo	Chen
S7: Harrington	NCEP / TMD	Kuo	Harrington

This research applied a forward trajectory technique to track wind parameters *u* and *v* (where, *u* is east-west wind component and *v* is north-south wind component) from the center point. The results clearly demonstrate the effects of land/sea breeze circulation on the wind field. The wind from the Gulf of Thailand developed over the land near coastlines within ~4 km. This circulation is a daily phenomenon causing an increasing in temperature difference between the land and the sea surface. It is the fact that temperature difference creates pressure over the land to drive wind fields. Due to its relative warmness and higher pressure, this wind forces cooler air from the sea to move into the land. Another direction of wind trajectory is the movement from coasts to the mid-land because of the urban area effect, which generates the wind circulation back to the onshore areas.

In some parts of the inland areas of Thailand, which are of highly complex topography (i.e., Northeastern area of the studied domain), it is noticed that RAMS performs a good simulation of the pattern of wind and temperature fields at the boundary regions of Thailand. A variation in wind fields around these areas can be distinguished from other urbanized or flatted areas, indicating the effects of topography on the patterns of wind circulation. In addition, temperature fields change considerably depending upon the altitude.

For comparison, two simulations of RAMS (with and without data assimilation techniques) and observed data are illustrated. Fig.3 shows the results of a time-series plot of the wind speed in summer and winter at a point of monitoring observation located in the middle of the domain during the events on 21st-23rd Apr. and 14th-16th Dec. 2005. Fig.4 shows the comparison between the predicted results of temperature fields plotting against the time-series and observed data. Figs.5-6 show the hourly wind vectors indicating both wind speed and direction. It clearly indicates that RAMS could be used to reproduce the movement and magnitude of wind and temperature fields for historical episodes at ground level. The difference of a base case simulation and observation can result in 1) 0.54 *MB*, 0.70 *GB*, and 0.82 *RSME* of temperature 2) -0.30 *MB*, 0.65 *GB*, and 0.81 *RSME* of wind speed, and 3) -25.53 *MB*, 115.15 *GB*, and 139.45 *RSME* of wind direction. With data assimilation, the modeling performance showed an increasing level of improvement by 44.97 % of temperature, 52.71% of wind speed, and 50.55% of wind direction.

Table 2 shows the statistical summary of RAMS base case simulation together with observed data. Modeling evaluation is applied by various statistical test approaches (i.e., bias, error, and factor test). Most of the testing results show a satisfactory level, particularly on temperature and wind speed. It should be noted that wind direction shows slightly more differences compared to observed data. Without data assimilation, we aimed to investigate if the simulation could produce an accurate wind and temperature field. With the data assimilation technique, it was found that RAMS increased reliability and is more suitable for use in photochemical air quality models. This study provides relevant results compared to the prior studies of RAMS (see Table 3). It is important that the prior studies are arranged in different spatial domains, episodes, and runs focusing on the objective to evaluate the results of wind and temperature fields.

3.2 Sensitivity studies

Table 3 shows the sensitivity tests on perturbing reanalysis datasets, convective cumulus parameterization, and radiation scheme. This is also compared to the prior studies [8, 16, 22, 23] on RAMS. In this study, the sensitivity results clearly indicate that the use of finer reanalysis data contributes to a more realistic simulation. This is because the high resolution of datasets can draw detailed information of isentropic analysis to initial and boundary conditions, especially for the local- and regional- scale. However, for global- and continental-scales, this approach is not robust enough for a highly significant improvement.

For convective parameterization, the simulation by ignoring vertical convective motion can derive miscalculations in both wind and temperature fields. Therefore, the meteorological simulation should include cumulus parameters. For other cases, we do not recognize a significant difference of wind and temperature fields when using two schemes (Kuo and Kain-Frish). These two schemes implement the vertical circulation in different ways; however, the results show similar patterns. We suspect that our selected episode is not in the rainy season (high rainfall) which is rarely influenced by cloud effects. Another reason can be from the grid resolution. Convective circulation requires a few grid cells to span horizontally, which a deep convection would require the horizontal cell size to be less than 1 or 2 km. Coarser resolution of the studied domain (~32 x 32 km^2) can result in a strong vertical motion that is difficult or impossible to simulate the required vertical exchange of heat and moisture. Thus, it is on coarser grids where an adjustment of convective parameterization becomes more necessary. Nevertheless, convective schemes currently assume the grid size in the horizontal direction to be around 20 km. Convective parameterization can be formed at any grid of this resolution between 2 and 20 km. As the result, there is no need of a convective adjustment scheme.

For the radiation scheme, the simulation that ignores solar radiation effects can generate poor temperature results and can perhaps affect other meteorological parameters. In this study, the Mahrer-Pielke scheme can be used to simulate temperature fields in the acceptable level; however, this scheme should not be applied for the case study of solar radiation by clouds. Chen-Cotton scheme is found to improve the RAMS simulation since the implementation of this scheme includes condensates (i.e., cloud water, rain, or ice). On the other hand, the Harrington scheme is found to return failure after 3 hours of running although the scheme is formulated to improve the modeling performance using the concept of two-stream. This failure can be due to the most computationally expensive scheme that leads to an undesirable simulation when applying to the tropical area (i.e., Thailand) that has neither snow nor hail.

4 Conclusions and recommendations

In general, RAMS can be well simulated to predict meteorological fields for historical and seasonal episodes. The complexity of elevated terrain (i.e., mountainous areas) plays a significant role on the mesoscale wind and temperature fields. In addition, an area along the coastline can affect the local wind circulation (i.e., land/sea breeze). In line with other studies [8, 16, 22, 23], modeling performance of RAMS is found to have a good agreement based on statistical tests on wind and temperature fields.

Data assimilation techniques, using local monitoring information, can be used to support the improvement of modeling performance to assure reliability. Additional ground and upper observational data is needed for the prognostic model to improve a nudging type of data assimilation.

Sensitivity studies indicate the impact of perturbation datasets, physical schemes, and parameterizations to RAMS simulating response. For local or regional scale, low resolution of datasets is acceptable. However, the high-resolution datasets can be drawn for better information on boundary and initial conditions. We recommend that the future study on meteorological simulation should include cumulus and radiation scheme. For a typical simulation, any scheme is well-defined considering under the typical conditions. However, the Kain-Frish convective parameterization and the Chen-Cotton radiation scheme are preferable for the purpose of meteorological simulations to provide meteorological inputs to photochemical grid models.

For future research, updating the inputs by the integration of local information into the model (i.e., soil texture or land use) is expected to have a better representation of geo-terrestrial data, thus enhancing the modeling the performance. For an in-depth analysis, sensitivity tests of RAMS incorporated with microphysics, physical schemes, and more parameterizations should be further investigated.

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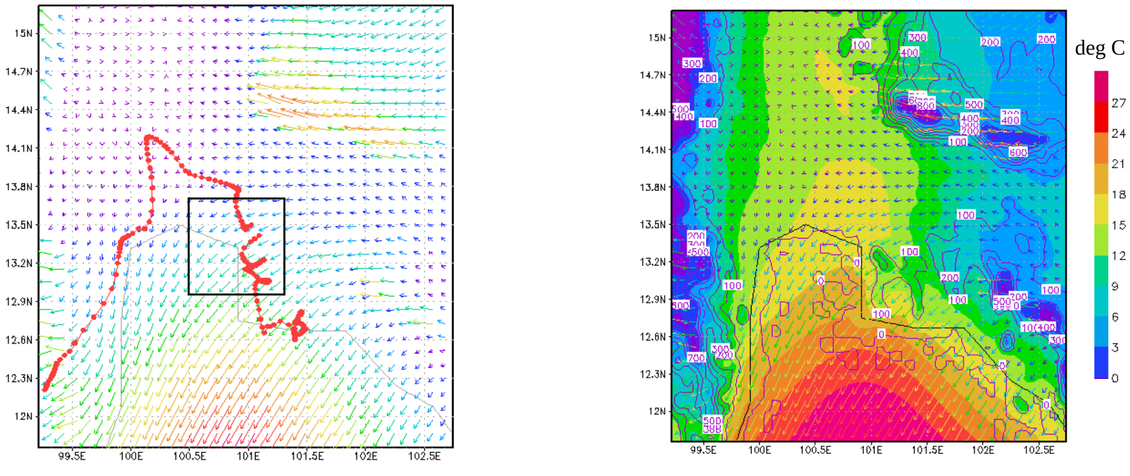

Figure 2. An hourly average simulation of wind fields with forward trajectory (left) and temperature fields (right) over the studied domain influenced by land/sea breeze near coasts during 22-23, Apr 2005

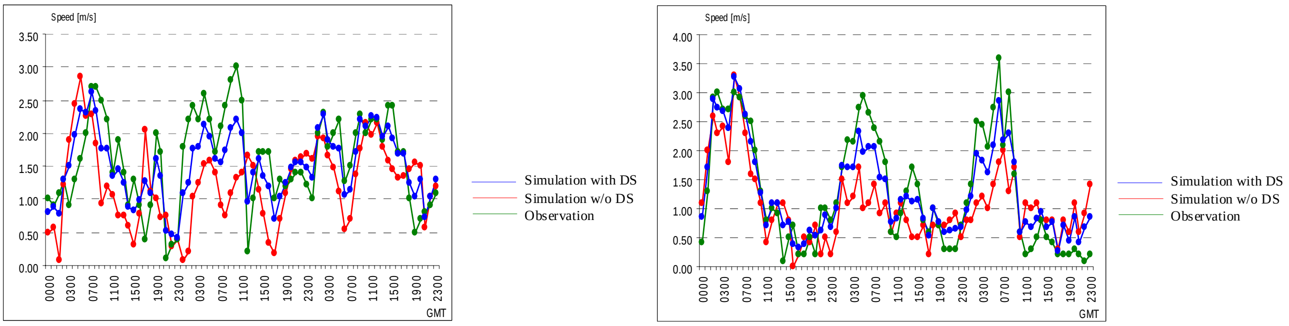

Figure 3. Comparison of hourly average of wind speed between two simulations and observation during the summer and winter time (21-23 Apr. and 14-16 Dec., respectively)

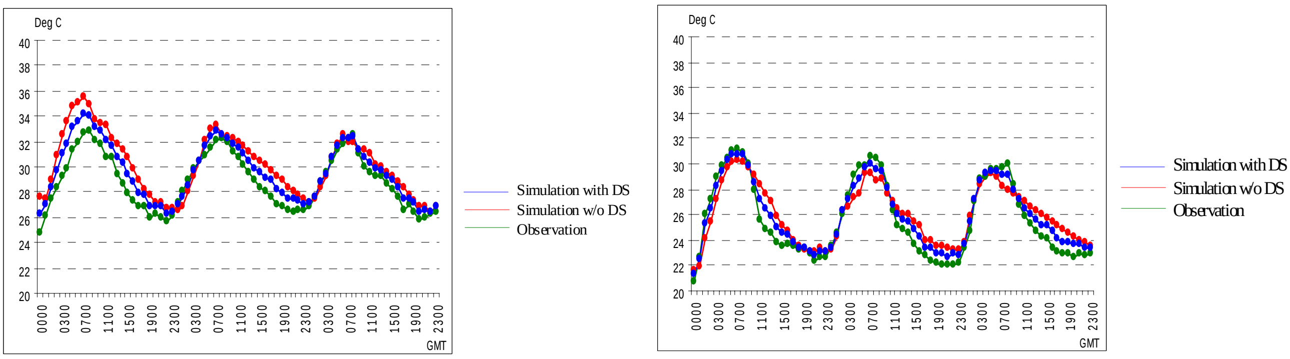

Figure 4. Comparison of hourly average of temperature between two simulations and observatior during the summer and winter time (21-23 Apr. and 14-16 Dec., respectively)

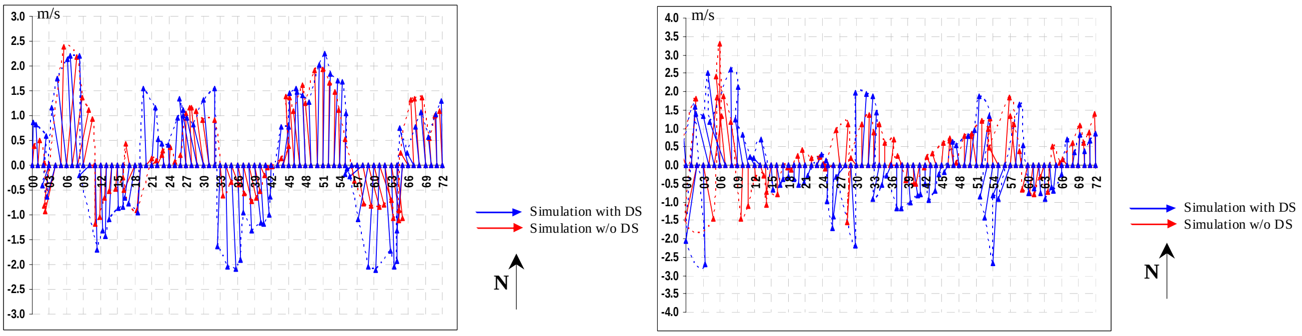

Figure 5. Comparison of hourly average of wind vectors (wind speed and wind direction) between two simulations and an observation during the summer and winter time (21-23 Apr. and 14-16 Dec., respectively)

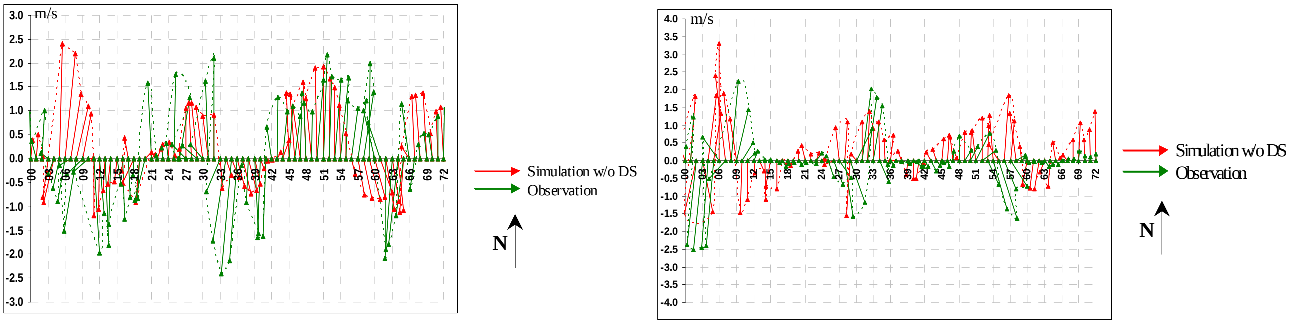

Figure 6. Comparison of hourly average of wind vectors (wind speed and wind direction) between a simulation without data assimilation and an observation during the summer and winter time (21-23 Apr. and 14-16 Dec., respectively)

Table 2. Evaluation of RAMS using statistical bias, error, and factor tests between modeling simulation and monitoring observation

SUMMERTIME	**BIAS**			**ERROR**			**FACTOR**	
(21-23 Apr 2005)	**MB**	**GB**	**NMB**	**RMSE**	**NME**	**IOA**	**1.50**	**2.00**
TEMP w/o DS	1.26	1.40	0.04	1.65	0.05	0.88	100.00%	100.00%
TEMP with DS	0.75	0.79	0.03	0.92	0.03	0.96	100.00%	100.00%
WS w/o DS	-0.36	0.70	-0.23	0.87	0.44	0.52	86.30%	91.78%
WS with DS	-0.09	0.32	-0.06	0.40	0.20	0.88	89.04%	94.52%
WD w/o DS	10.20	84.36	0.06	109.89	0.52	0.65	75.34%	87.67%
WD with DS	6.91	40.96	0.04	53.92	0.25	0.88	87.67%	93.15%

WINTERTIME	**BIAS**			**ERROR**			**FACTOR**	
(14-16 Dec 2005)	**MB**	**GB**	**NMB**	**RMSE**	**NME**	**IOA**	**1.50**	**2.00**
TEMP w/o DS	0.41	1.16	0.02	1.33	0.05	0.94	100.00%	100.00%
TEMP with DS	0.33	0.62	0.01	0.72	0.02	0.98	100.00%	100.00%
WS w/o DS	-0.24	0.61	-0.18	0.76	0.46	0.77	69.86%	78.08%
WS with DS	-0.02	0.29	-0.02	0.36	0.23	0.96	72.60%	83.56%
WD w/o DS	-61.26	145.95	-0.29	169.01	0.69	0.49	67.12%	71.23%
WD with DS	-30.10	72.78	-0.14	84.24	0.34	0.87	71.23%	79.45%

Table 3. Comparison of this work with sensitivity studies on some schemes and other RAMS independent researches

RAMS STUDIES	TEMPERATURE			WIND SPEED			WIND DIRECTION		
	MB	GB	RSME	MB	GB	RSME	MB	GB	RSME
Previous studies									
Emery et al. (2001)	±0.50	2.00	-	-	-	2.00	-	-	20.00
Rao et al. (2001)	1.38	2.29	3.03	0.61	1.41	1.80	-	-	-
Zhong and Fast (2003)[a]	-0.74	-	2.50	0.66	-	1.63	-0.43	-	68.37
Zhong and Fast (2003)[b]	-1.78	-	2.62	0.35	-	2.00	-1.11	-	64.58
Castelli et al. (2004)	-	-	3.40	-	-	1.57	-	-	-
Hanna and Yang (2001)	-	-	-	-0.10	-	1.60	-12.00	-	76.00
This study [c]									
S0: Normal run [d]	0.84	1.28	1.49	-0.30	0.65	0.81	-25.53	115.15	139.45
S1: Base case [e]	**0.54**	**0.70**	**0.82**	**-0.06**	**0.31**	**0.38**	**-11.60**	**56.87**	**69.08**
S2: FNL	0.69	1.11	1.67	0.19	0.61	0.92	8.66	25.97	57.91
S3: No cumulus	1.80	2.69	3.46	-0.67	1.25	1.89	-24.74	172.02	231.49
S4: Kain-Frish	0.27	0.79	0.86	-0.11	0.18	0.35	-14.75	66.98	82.12
S5: No radiation	2.07	3.28	4.15	-0.24	0.75	1.04	-11.33	72.83	96.68
S6: Chen-Cotton	0.36	0.59	0.73	-0.13	0.26	0.36	-8.13	44.27	56.63
S7: Harrington [f]	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL

[a] Simulation cases with light wind episode

[b] Simulation cases with strong wind episode

[c] Simulation cases by averaging value between summer and winter time and perform sensitivity run

[d] Simulation using typical datasets and schemes: NCEP global reanalysis, Kuo convective scheme, and Mahrer-Pielkye radiation scheme

[e] Simulation cases with observational data assimilation

[f] Simulation failed after 3 hours run due to the core segmentation faults