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Contributed Paper

Weather Research and Forecasting (WRF) Model Performance for a Simulation of the 5 November 2009 Heavy Rainfall over Southeast of Thailand

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ABSTRACT

In seasonal northeast monsoon, heavy rainfalls caused many natural disasters in the southern east-coast of Thailand. A thorough study of simulations of heavy precipitation phenomena could provide a better understanding of their nature, inducing the better forecasting of similar cases. The cumulus parameterization technique was used to determine the appropriate cumulus physics for a model. Three cumulus parameterization schemes, such as, the Kain-Frisch (KF), the Grill-Devenyi (GD), and the Betts-Miller-Janjic (BMJ) schemes were applied for the Weather Research and Forecasting (WRF–ARW version) modeling system. Their performances were evaluated by validation of the simulated rainfall by mean of calculating the categorical skill scores, such as, frequency bias (BIAS), critical success index (CSI), and equitable threat scores (ETS). The rainfall data observed from the Tropical Rainfall Measuring Mission (TRMM), and the Thai Metrological Department (TMD) were used to verify the rainfall simulation results. During the heavy rainfall events in this study, the maximum rainfalls simulated by KF, GD and BMJ schemes were recorded 146, 120, and 38 mm, respectively, while TRMM showed 187 mm of the maximum rainfall. The specific location of the intense rainfalls and their magnitude were excellently simulated in KF scheme. The positions of the maximum rainfall simulated by KF and GD schemes were also more accurate than the positions simulated by BMJ scheme.. The categorical skill scores evaluation revealed that the KF scheme outperforms the GD and BMJ schemes if heavy precipitation is used as the threshold.

Keywords: WRF model; heavy rainfall simulation; the categorical skill scores

1. INTRODUCTION

Thailand form the past frequently experienced severe weather; especially, natural disasters caused by heavy rainfalls. Normally, they caused natural disasters such as flash floods, landslides, etc., that gave rise to extensive loss of human lives and properties. In the southern east-coast, the heavy rainfalls annually occurred during the seasonal northeast monsoon from mid October to mid February. The active monsoon, affect orographically precipitation higher along the east-coast than over the rest of this region. Large floods occurred over the eastern south. As seen Hatyai city, a major trade center in southern Thailand, suffered the extreme flood disasters in November 2000 [1], November 2009 [2] and November 2010.

Figure 1 showed the 850 and 925 hPa streamlines and isotachs at 00Z on 6 November 2009. The strong northeast wind (stronger than 25 m/s) blew from the anti-cyclonic region in Siberia. A cold surge crossed the South China Sea and flowed to the center of cyclonic circulation in the east of the Malay Peninsula. This surge might be a main factor that caused heavy rainfalls along the eastern coast of southern Thailand. The coast then received a large amount of rain resulting in a wide area of floods. The Department of Disaster Prevention and Mitigation (DDPM) reported that during 3-9 November 2009, flash floods and landslides had occurred along 9 coastal southern provinces, that is, Surat Thani, Nakhon Si Thammarat, Trang, Phatthalung, Songkha, Satun, Narathiwat, Yala, and Pattani. Besides, severe winds and waves induced fishing vessels wrecked at sea. In 3 districts of Chumphon province, roads, shops, and residences along the beach were destroyed [3].

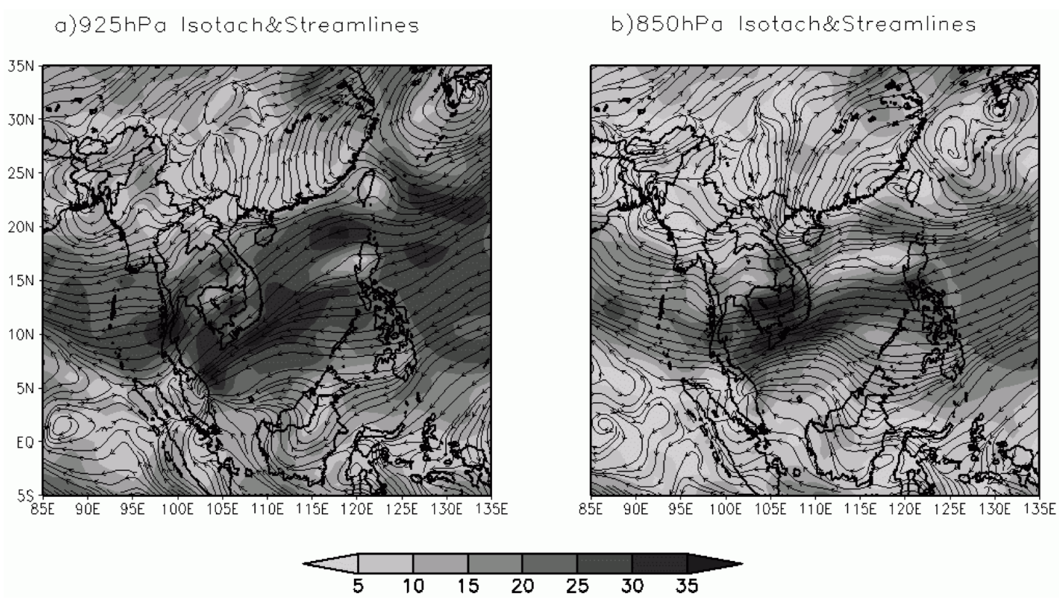

Figure 1. Streamlines and isotachs (m/s) over Southeast Asia, on 6 November 2009.

Figure 2 showed the 24 hour accumulated rainfall over the south on 6 November 2009. The heaviest rainfall was recorded at 301.8 mm in Yaha District, Yala by the Thai Meteorological Department (TMD). This event made large floods, especially in Hatyai, the commercial and financial center in Southern Thailand. This was also the most severe

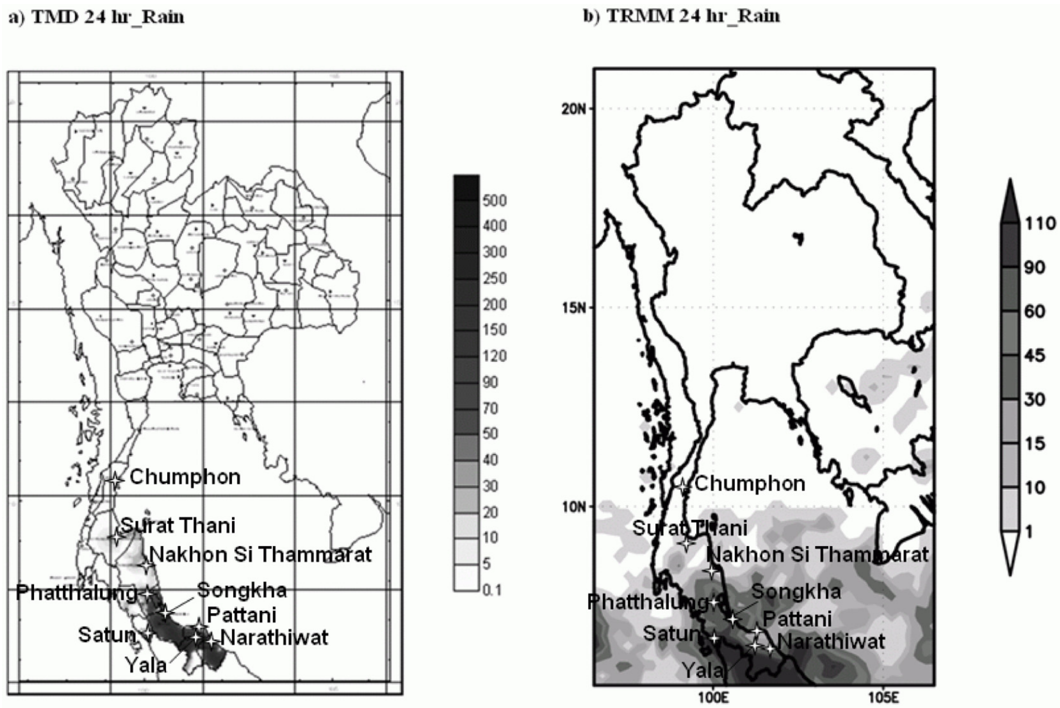

Figure 2. Daily rainfalls (mm) observed over southern Thailand from a) TMD, and b) Tropical Rainfall Measuring Mission (TRMM), on 6 November 2009.

flooding caused by cold surge since the heavy flooding in November 2000.

Numerical Weather Prediction (NWP) system is widely used in the current weather forecast. Actual weather conditions will be input into mathematical models of the atmosphere for predicting weather. Atmospheric models incorporate meteorological data into mathematical equations based on the fundamental law of dynamic. The principal equations related to the motion in the atmosphere are as followings: a) Newton's second law of motion, b) the first law of thermodynamics, c) the law of conservation of mass or continuity equation, d) the equation of state, and e) the conservation equation for the water substance. WRF model, one of NWP, is a computer program with a dual use for forecasting and simulation. It was developed by several organizations, such as, the National Center for Atmospheric Research (NCAR), the National Center for Environmental Prediction (NCEP) and the National Oceanic and Atmospheric Administration (NOAA), etc. WRF is selected to simulate the phenomenon of heavy rainfall. This model is of fully compressible non-hydrostatic, and its governing equations are written in flux form for the purpose for conservation of mass, dry entropy, and scalars. In addition, to provide higher resolution simulation, Arakawa C grid is chosen in WRF to gain better accuracy than B grid in the Penn State/NCAP non-hydrostatic mesoscale model (MM5) [4]. Some recent studies of heavy rainfall simulations are as follows:

Kirtsaeng et al., had carried out the study of the simulation of heavy rain events over Mumbai, using WRF modeling system. Simulation using bivariate initial conditions and cumulus parameterization schemes helped examine the model performance. The WRF performance of the model was evaluated by examining various predicted parameters, such as, upper level circulations, temperature, moisture content and rainfall. The study found that the Betts-Miller-Janjic (BMJ) cumulus parameterization had the highest predicting capability compared to Kian-Fritsch (KF) and Grell-Devenyi (GD) schemes for this event [5]. Deb et al., had examined WRF performance for simulating heavy rainfalls over Ahmedabad. The quantitative validation of the simulated events was performed by calculating the categorical skill scores. As a result, KF has outperformed GD [6].

For simulation of heavy rainfalls during the active northeast monsoon across south-eastern Thailand, Wangwongchai et al. [1] and Yavinchan et al. [7] had simulated rainfalls by MM5, and Kirtsaeng S. and Kreasuwun J. [2] had applied WRF. All papers revealed the KF outperformed BMJ and GD.

The objectives of this study were to simulate the heavy rainfalls over southern Thailand on 5 November 2009 and also to verify the best performance of each scheme. WRF model, as well as KF, GD, and BMJ schemes, was applied. To make a decision on an appropriate scheme from observed data, all of the categorical skill scores, namely, frequency bias (BIAS), critical success index (CSI) and equitable threat scores (ETS), were made calculation.

2. MATERIALS AND METHODS

WRF mesoscale model has been chosen in this study for simulating the severe weather on 5 November 2009. Three cumulus parameterization schemes: KF, GD and BMJ, available in WRF, were used widely in atmospheric models [8]. WRF outputs were then verified by the categorical skill score method.

2.1 Cumulus Parameterization Schemes

2.1.1 Kain-Fritsch

The modified version of the KF-Eta is based on Kain and Fritsch, but its modification is based on testing within the Eta model. KF scheme is reformulated into an entraining-detraining model, with parcel buoyancy calculated as a function of parcels mixed laterally between the environment and the updrafts. The differencing is reformulated to conserve mass, thermal energy, mass, and momentum.

The convective precipitation (*PR*) is computed as

$$PR = ES,$$

where E is the precipitation efficiency, and S represents the sum of the vertical fluxes of vapor and liquid at about 150 mb above the lifting condensation level [8-12].

2.1.2 Grell-Devenyi Ensemble

GD scheme is a one-cloud version of Arakawa-Schubert scheme. This scheme assumes that deep convective clouds are all of one size. The original GD scheme used the Arakawa-Schubert cloud-work function for its closure, but this was later changed to use a convective available potential energy (CAPE) closure, as in KF. It does not have direct mixing laterally with the environment, except at the levels of origin or termination of updrafts and downdrafts. Thus mass flux is constant with height. Since there is no lateral mixing, it is unimportant to assume that the fractional area coverage of updrafts and downdrafts in the grid column is small. This allows the scheme to operate easily at finer scales, although some degree of scale separation remains important. The subgrid precipitation (*P*) is calculated as equation below;

$$P = I_1 m_b (1-\beta)$$

where I_1 means the integrated condensate in the updraft, m_b is the cloud-base mass flux of the updraft, and $(1-\beta)$ is the precipitation efficiency, which is assumed to be a function of the mean wind shear in the lower troposphere. The effects of the convective-scale downdrafts are parameterized in this scheme [8, 11-13].

2.1.3 Betts-Miller-Janjic

In this scheme, the deep convection profiles and the relaxation time are variable and depend on the cloud efficiency, a non-dimensional parameter having the convective regime. The cloud efficiency depends on the entropy change, precipitation, and mean temperature of the cloud. The shallow convection moisture profile is derived from the requirement that the entropy becomes small and non-negative. BMJ scheme has been optimized over years of operational application at NCEP, so that, in addition to the described conceptual differences, many details and parameter values differ from those recommended in Betts and Miller. The parametric precipitation resulting from this adjustment is defined as

$$PR = \int_{P_B}^{P_T} \frac{q_R - q}{\tau} \frac{dp}{g},$$

where q is the model's specific humidity, q_R is the reference profile specific humidity (a function of height), τ stands for the timescale over which the adjustment occurs, and p_T and p_B are pressures at cloud top and bottom, respectively [8, 14-16].

2.2 Evaluation Methods

The observed rainfall is used to verify the simulated rainfall. The precipitation is verified by the categorical skill score method, where forecasts are varied against the occurrence or non-occurrence of specific categories of predicted rainfall [17]. The common methods of categorical verification of the precipitation fields are based on the calculation of BIAS, CSI and ETS. These indexes explain how well the model can predict rain.

The bias score measures the ratio of the frequency of forecast events to the frequency of observed events. The area frequency bias is defined as;

$$BIAS = \frac{h+m}{h+f},$$

where h is an event forecast to occur, and did occur. While, f and m account for an event forecast to occur, but did not occur and an event forecast not to occur, but did occur, respectively. It can have any value from zero upwards. When BIAS < 1 the model underforecasts the rainfall, and when BIAS > 1 the model overforecasts the rainfall.

CSI is frequently used, with good reason. It considers both false alarms and missed events, and is therefore a more balanced score. CSI is somewhat sensitive to the climatology of the event, tending to give poorer scores for rare events. It has a range of 0 to 1. A value of 0 occurs when the model fails completely to predict the actual occurrence of rain, and a value of unity occurs when rain is forecasted if and only if rain actually occurs. The critical success index is defined as:

$$CSI = \frac{h}{h+f+m},$$

A related score, the Equitable Threat Score is designed to help offset this tendency. It must be in the interval -1/3 ≤ ETS ≤ 1, but the minimum value depends on the verification sample of climatology. The equitable threat score is defined as:

$$ETS = \frac{h-r}{h+f+m-r},$$

where

$$r = \frac{(h+f)(h+m)}{n}$$

The r is a random forecast, it determined by assuming that the forecasts are totally independent of the observations, and the forecast will match the observation only by chance, and n is the sample size. For rare events, the minimum ETS value is near 0, while the absolute minimum is obtained if the event has a climatological frequency of 0.5, and there are no hits. If the score goes below 0 then the chance forecast is preferred to the actual forecast, and the forecast is said to be unskilled.

2.3 Utilized Data

The Global Data Assimilation System (GDAS) was used for initial and boundary condition data. It is a one degree resolution, taken at six hour intervals. This analysis was then interpolated to the model grid to provide an initial condition taken at 00Z on 4 November 2009. Run for 60 hours (up to 12Z on 6 November 2009), the model used various terrestrial datasets for terrain, land-use, soil type, soil temperature, vegetation fractions and monthly albedo etc., taken from the WRF user website.

The NCEP analyses with one degree resolution were used to compare the non-precipitation produced from the model. The rainfall products were compared with the TRMM observation. Its data included micro-wave precipitation, microwave-calibrated IR precipitation, microwave overpass time and gauge station [18]. Furthermore, the outputs were also compared to the data from TMD rain gauge station.

2.4 Experimental Design

The heavy rain on 5 November 2009 was selected as the subject of the study. Two nested domains were configured as shown in Figure 3. The domain center was 6.42°N 101.82°E and contained 27 vertical levels. Domain 1, the outer domain, had 100 × 75 grid points in the horizontal plane with west-east and south-north directions, respectively, covering 93.85°E to 109.78°E, and 0.50°S to 12.27°N, with a grid space of 18 km. Second, the inner domain was set in a ratio 1:3. It had 178 × 133 grid points, covering 97.05°E to 106.58°E and 2.88°N to 9.93°N, with a 6 km resolution.

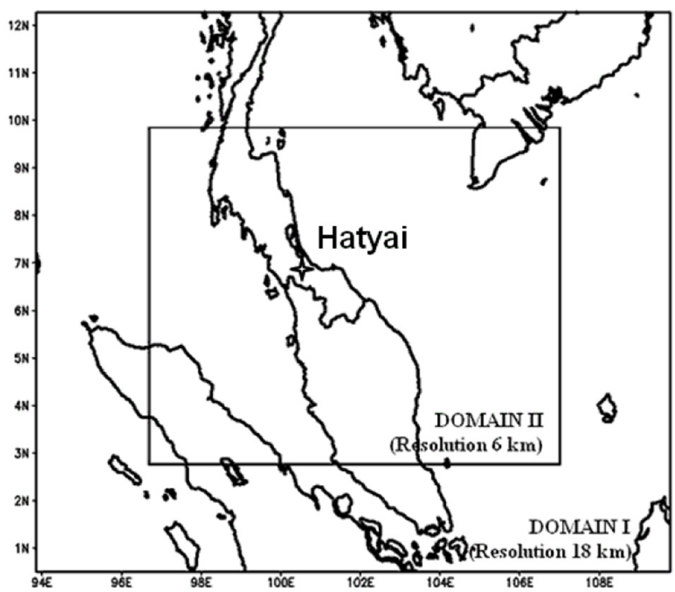

Figure 3. Computational domains used in this study.

This study used WRF single-moment 6-class Graupel (WSM-6) microphysics scheme, along with the Rapid Radiative Transfer Model (RRTM) scheme for long waves. The Duhia scheme was also used for short-wave physics, the Monin-Obukhov scheme for the surface layer, the Noah Land-Surface Model for surface physics, and the YSU scheme for PBL treatment. Three different cumulus parameterization schemes were, further, used as follows: KF, GD, and BMJ.

The accuracy of maximum rainfall was carried out by validation. The precipitation produced from three experiments, with maximum accumulative rainfalls from TMD rain gauges and TRMM. The forecast skill performance of these three schemes were evaluated by computing the frequency BIAS, CSI and ETS scores. The non-precipitation products were studied by comparing with NCEP reanalysis data.

3. RESULTS AND DISCUSSION

The recent study of the event on 5 November 2009 has explained the cause of heavy rain. This phenomenon was due to the strong northeast wind flowing from an anti-cyclonic circulation in China to the South China Sea. The wind could generate an offshore cyclonic circulation in the Gulf of Thailand. With the cyclonic flow of moist air around a low pressure area, the cloud and rain formations were likely expected [2]. In this study the vorticity, the horizontal divergence, the velocity, and the moisture field were computed as the outputs of the domain 1, then compared with NCEP data for understanding this event. They also compared the simulated heavy rainfall in domain 2 with TMD rain gauge and TRMM.

3.1 Vorticity, Divergence, and Velocity

The vorticity and divergence methods calculated the horizontal vorticity and the divergence of the specified wind field. The wind field must be specified in u (east-west) and v (north-south) components (not magnitude and direction). The vorticity was used to determine the rotation of air-mass (vorticity is a measure of spin around an axis) in the planetary boundary layer. The vorticity at 850 hPa level was computed by changes in wind speed and direction within 850 hPa level. At 12Z on 5 November 2009, the experimental vorticity output had higher value with more specific position. This might result from the different spatial resolution where NCEP analysis resolution was approximately 100 km while the experiments had 18 km resolution. Every scheme yielded the positive vorticity around the southern east-coast at that time. However, KF gave the negative vorticity in the Gulf of Thailand but the positive vortex greater than other schemes around Songkha, as Figure 4 shown.

Convergence was the accumulation of a wind vector in a layer of the atmosphere at a particular point, in term of a signed scalar. The high-speed winds were directly related to the convergence. The horizontal convergence while compensated by the vertical shrinking or convergence, must be accompanied by the vertical stretching or divergence. Any wind components that were increasing downstream were divergent in that component. However, they might be convergent in one or both of the other two components.

Figure 5 showed the horizontal convergence at 850 hPa from NCEP and various experiments. All products detected the horizontal divergence along southeastern Thailand. Due to the lower NCEP resolution, a position of the horizontal divergence was shown in a larger area. The experiments simulated specific position better than NCEP. Around Songkha and neighboring regions, KF showed the horizontal divergence value greater than other schemes. These were

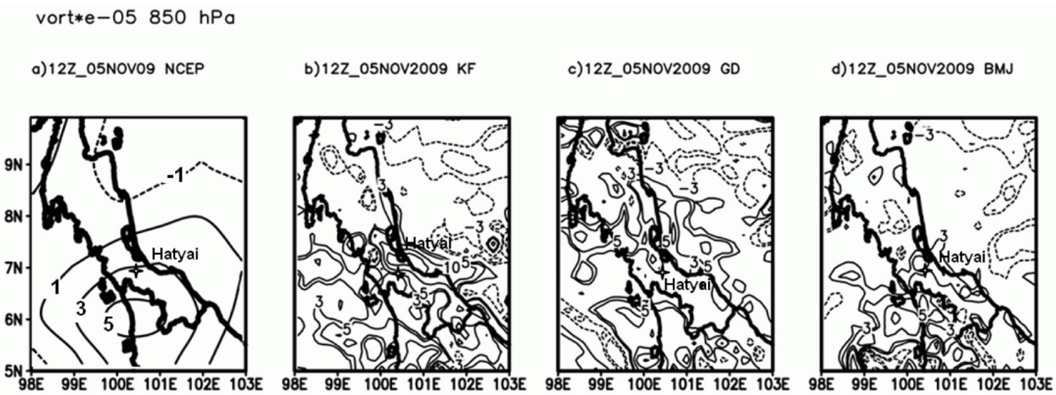

Figure 4. The 850 hPa vorticity (× 10^{-5}) at 12Z on 5 November 2009. Solid lines were the positive value; and dotted lines, the negative value. (Simulations contour levels -15, -10, -5, -3, 3, 5, 10, and 15).

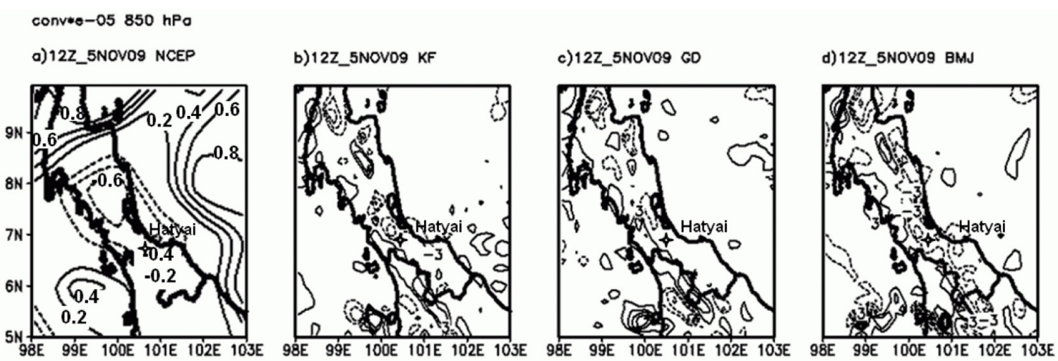

Figure 5. The 850 hPa horizontal convergence (× 10^{-5}) from simulations at 12Z on 5 November 2009. Solid lines indicated horizontal convergence; and dotted line, horizontal divergence. (Simulations contour levels -9, -6, -3, 3, 6, and 9).

consistent with DDPM disaster report [3]. As for both of the vorticity and horizontal divergence, KF scheme provided better result than other schemes.

The heavy rain might be due to the vertical velocity, which transported the moisture to the cloud and then brought the water vapor from the cloud to the earth surface, i.e., in the form of rain. The movement of air in the vertical axis could be interpreted by the vertical velocity. We took as a convention that the positive vertical velocity represented the wind moving upward, like, updraft. On the other hand, the negative vertical velocity appears if the wind blows downward, such as, downdraft. Given the same conditions, more negative vertical velocity brought heavier rainfall. Figure 6 showed the vertical velocity of all experiments. At 12Z on 5 November 2005, all experiments detected updrafts of 0.2-0.4 m/s over the windward side of Surat Thani, Nakhon Si Thammarat, Songkha, Phatthalung, and Narathiwat. At the same time, the downdraft was captured over the mountains.

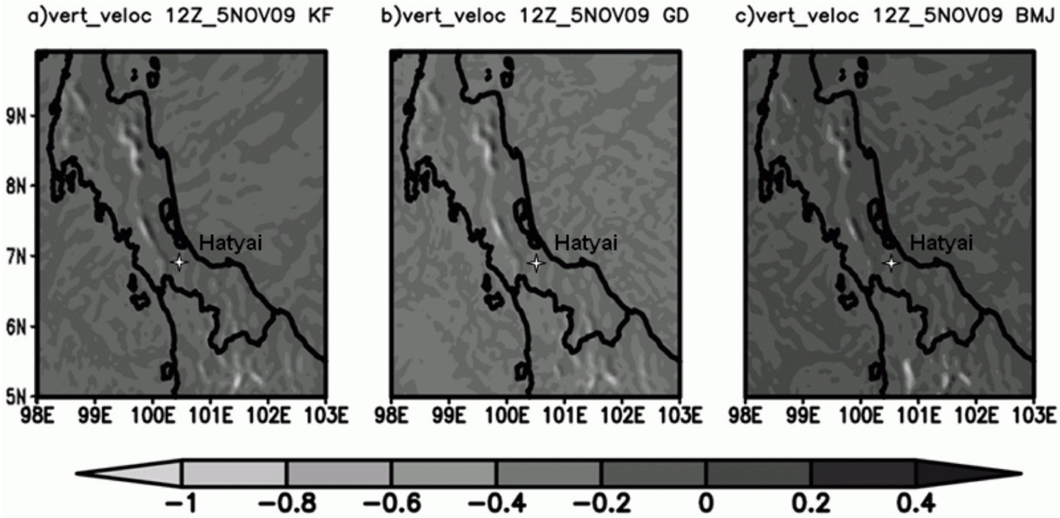

Figure 6. Vertical velocity (m/s) valid at 12Z on 5 November 2005.

3.2 Moisture Field

Figure 7 showed the longitude-height cross-section of the wind vector and the relative humidity around Hatyai, Songkhla Province (average along latitude 6.5°N to 7.5°N) valid at 12Z on 5 November 2005. NCEP and all experiments could detect easterly wind at 400 hPa and slightly turn northeasterly at 925 hPa to the surface. All experiments showed the wind speed about 12-18 m/s at 850 hPa. KF showed the maximum wind speed greater than the other schemes. The source of moisture over the observed area of rainfall was then described. The center of the maximum moisture contour was located around the eastern part of Hatyai, which is near the Gulf of Thailand. High humidity (RH over 80%) was found at height

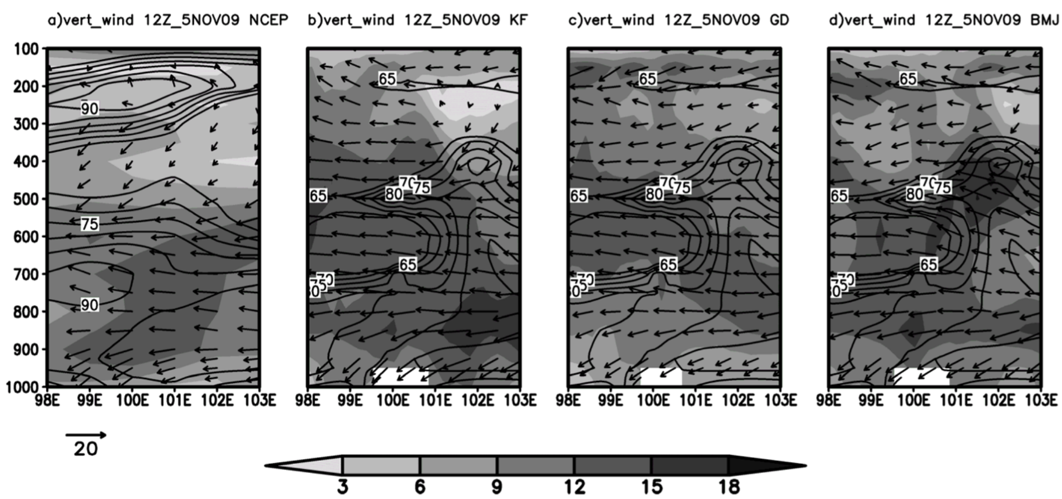

Figure 7. Longitude-height cross-section of wind direction, wind speed (m/s) (shaded) and relative humidity (%) (contour line) valid at 12Z on 5 November 2005. (Contour levels 65, 70, 75, 80, 85, 90, 95, 100).

up to about 500 hPa in all experiments and up to around 600 hPa the NCEP. Advected over the continental area by the strong east to northeast winds, the water vapor, or the moisture over the sea, was the major reason for the cloud formation and pouring rain.

3.3 Rainfall

Figure 8 showed the rainfall simulations of all experiments over southern Thailand. The simulation pattern was similar to TMD and TRMM observations (Figure 1). TRMM detected a band of very heavy rainfall (rain more than 90.0 mm/day) at Satun, Songkhla, Yala and Narathiwat. Meanwhile, KF and GD schemes captured a very heavy rainfall slightly north of above areas, or southern provinces along the east coast especially in Surat Thani, Nakhon Si Thammarat, Songkhla and Narathiwat. BMJ was able to capture heavy rainfall (rain among 35.1 - 90.0 mm/day) in the same region with KF and GD. The shapes of model output look more specific than TRMM. It might be that TRMM resolution was 0.25 degree (25 km resolution) which the actual model was decided to provide the 6 km resolution.

To understand the intensity of this phenomenon, the maximum accumulated rainfalls from simulation were compared with TRMM's and TMD's in-situ data. The center of maximum precipitation simulated by the KF, GD and BMJ schemes were 146, 120, and 38 mm, respectively (Table 2). It could be seen that the intensity, detected in KF scheme simulations, was close to the rainfall observed from TRMM. However, all experiments, together with TRMM,

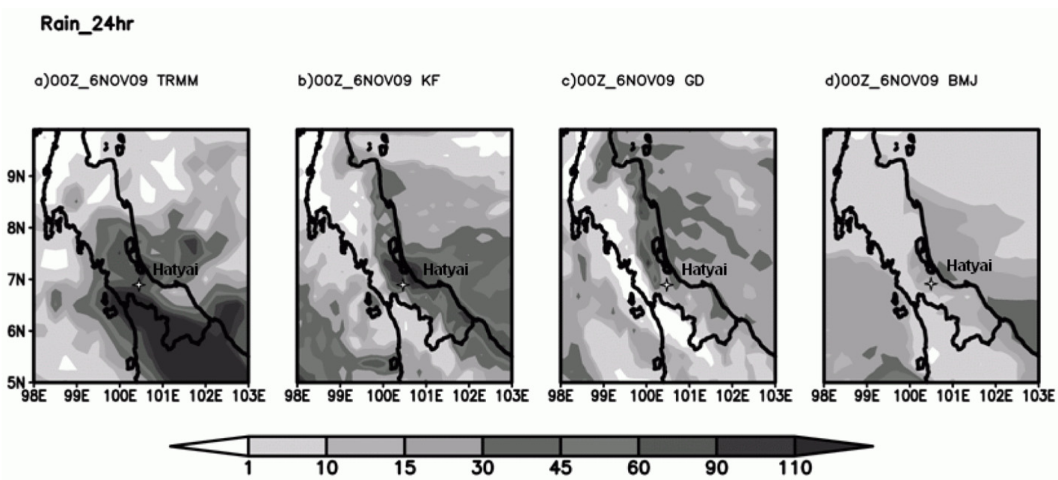

Figure 8. The 24-hour accumulative rainfall (mm) from TRMM and experiments, valid at 00Z on 6 November 2009.

Table 2. Maximum accumulative rainfall from actual observation and experiments.

	Synoptic Station	District Rain Gauge	TRMM	Cumulus parameterization schemes		
				KF	GD	BMJ
Total rainfall (mm)	255.3*	301.8**	187	146	120	38

* Yala meteorological station, Yala ** Yaha District, Yala

underestimated the actual rainfall measured from gauge stations. It was because of that the outputs from the models and TRMM observations were also in grid format which yielded lower intensity than in point data format.

3.4 Precipitation Prediction Skills

The evaluation of performance of the various cumulus parameterization schemes in this study compared the precipitation outputs from the models and TMD. These products for testing the forecast skill came from all 148 stations in southern Thailand. In calculation of CSI and ETS, 3 different cut-points (0.1 mm, 10 mm, and 35 mm), were used. Each cut-point yielded CSI and ETS values as shown in Table 3.

The results in Table 3 showed that the skills of model forecasts gave various values according to different thresholds. In case of the precipitation at least light rain ($R \geq 0$), CSI values illustrated that the skill of model forecast in every single scheme was more than 0.7. In addition, all schemes became rainfall overforecast (BIAS > 1). In experiments, KF and BMJ had a good skill of model forecast correlated with ETS display which finds KF and GD with a higher skill of model forecasts, more than BMJ - rainfall forecasting result is similar to rare events.

In terms of the rainfall range of at least moderate rain ($R \geq 10$), CSI and ETS values showed that the forecast skill of KF and GD model was slightly higher than BMJ, but all the schemes were overforecast of rainfall. Regarding the rainfall range of at least heavy rain ($R \geq 35$), CSI and ETS values showed that the forecast skill of KF was more accurate than GD and BMJ. Besides, BIAS indicated that observed rainfall and forecast rainfall in KF had higher ratio than any other schemes.

Table 3. BIAS, CSI, and ETS scores for various precipitation thresholds.

Rain (mm)	Cumulus Schemes	BIAS	CSI	ETS
$R \geq 0.1$	KF	0.99	0.84	0.50
	GD	1.00	0.80	0.41
	BMJ	0.74	0.74	0.00
$R \geq 10$	KF	0.99	0.62	0.27
	GD	0.97	0.65	0.32
	BMJ	0.80	0.49	0.24
$R \geq 35$	KF	0.98	0.49	0.26
	GD	0.74	0.20	-0.02
	BMJ	0.13	0.07	0.04

4. CONCLUSION

The simulation of the heavy precipitation event over the Southeast of Thailand on 5 November 2009 was carried out with WRF model. All of the vorticity, horizontal divergence and velocity, calculated from model output, were good approximation with the calculations from NCEP data. Otherwise, the model outputs in all schemes were more specific in critical areas because of the difference of product resolutions between models (18 km) and NCEP (about 100 km).

These three variables above, including appropriate moisture, could describe the heavy rainfall mechanism. Also, the negative vortex over the South China Sea, Northeasterly winds flowing into southern east-coast of Thailand, and the moisture lifted over the windward side induced heavy rainfall over the area on 5 November 2009.

The above heavy rain was detected by all of the scheme experiments and simulated particularly well with KF and GD. KF scheme experiment simulated high intensity rainfall from Songkhla to Narathiwat. However, the simulated rainfall in GD scheme experiment was reasonably accurate as well, though the maximum intensity rainfall was located around Surat Thani and Nakhon Si Thammarat. The underestimation of BMJ rainfall products might result from the limits of the Cumulus scheme, not including a convective-scale downdraft parameterization and not directly generating mesoscale highs and lows.

In this event, the performance of model tested by BIAS, CSI and ETS scores had shown that KF and GD schemes were good in predicting light and moderate rain. Moreover, KF scheme showed better forecasting skill than GD and BMJ schemes regarding heavy rain. KF scheme based on CAPE, which was reformulated into an entraining-detraining model, with parcel buoyancy, computed as a function of parcels mixed laterally between the environment and the updrafts. The difference was reformulated to conserve as followings: mass, thermal energy, mass, and momentum. It contained the complete treatment of in-cloud physical processes of currently available convective parameterizations. Further, downdraft parameterization allowed better simulation of mesoscale responses than other schemes [12]. This might conclude that factor was one of the main reasons responsible for the high vertical instability in the atmosphere over the southern east-coast of Thailand on this event.

A suggestion for modelers was that KF scheme was appropriate for using in NWP model. Both of KF and GD schemes were, as well, suitable for utilizing to members in ensemble technique. For the long-term flood prevention in important cities, the improvement of irrigation, water management, and urban planning by mean of NWP data was essential.

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