Exploratory Case Studies Evaluating Convective Parameterization Schemes for Model Predictions of Heavy Rainfall in Thailand

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Abstract: Numerical weather predictions have been made to evaluate selected convective parameterization schemes in forecasts of typical heavy rainfall events in Thailand. The Betts-Miller (BM), Grell (GR), Kain-Fritsch (KF), and new Kain-Fritsch (KF2) schemes were used in the Penn State/NCAR non-hydrostatic mesoscale model (MM5) with grid resolutions of 45 km and 15 km. The examples studied were in four important convective conditions, namely days with heavy rain in the hot season (NE region), the cold season (S region), the rainy season (E region), and a tropical depression (NE region).
Total rain patterns from the models were compared qualitatively with rain patterns derived from records at rain gauge stations, and with cloud patterns derived from geostationary meteorological satellite infrared images. Quantitative evaluation was obtained by calculating the bias and the Peirce skill score in small study areas with heavy rain as a function of accumulated rainfall over thresholds in the range zero to 80 mm every 12 h up to 48 h.
The four convective parameterization schemes gave widely different results. In the hot season case, none of the schemes predicted the rainfall well. In the other cases, the GR scheme was usually the best. The new KF2 scheme usually gave better results than the original KF scheme, indicating a potential for improvement in this scheme. The BM scheme was less successful than the other schemes.

Keywords: Numerical weather prediction; tropical precipitation; MM5; Betts-Miller; Grell; Kain-Fritsch; forecast verification.

1. Introduction

Most of the heavy rain in Thailand is produced by convective clouds. This rain can cause flooding or landslides in vulnerable locations, so the prediction of heavy rain in Thailand is an important goal of the Thai Meteorological Department, which is responsible for official weather forecasts and warnings in the country. Numerical weather prediction models are used to assist the forecasters. In these models, convection is parameterized because the grid sizes are greater than the cloud sizes. Comparisons between predictions of rainfall using different convective parameterization schemes have been made in various parts of the world, but few comparisons have been made in the tropics and none have been made in Thailand. The research reported in this paper is a preliminary exploration of the performance of four convective parameterization schemes for the numerical prediction of heavy rain in Thailand with a grid resolution of 15 km.

There are two main types of convective parameterization (CP) for predicting precipitation: those, such as the Kuo and Betts-Miller schemes, that remove convective instability by adjusting the vertical temperature and moisture profiles towards predetermined reference profiles, and those, such as the Grell and Kain-Fritsch schemes, that use cloud models to calculate the vertical redistribution of energy and moisture. In both types of schemes, excess moisture is precipitated as rain. Convective parameterizations are theoretically valid only for model horizontal grid sizes greater than 10 km [1], but sometimes the CP schemes have been found useful in triggering convection with fine grid sizes of 5-10 km. It is expected that when the grid resolution is 1-2 km, the model will predict convection directly without convective parameterization.

A 2007 technical progress report by the World Meteorological Organization (WMO) [2] gives information about the convective parameterization schemes currently being used in Asia and the tropics. The Japan Meteorological Agency (JMA) uses the Arakawa-Schubert scheme in a global model with a 60-km horizontal resolution. The Hong Kong Observatory (HKO) also uses this scheme in a regional model with a 20-km horizontal resolution. In a high resolution models (5 km), JMA and HKO use the Kain-Fritsch scheme. The Korea Meteorological Administration uses the new Kain-Fritsch scheme in regional models with grid resolutions of 30 km and 10 km. China uses the Betts-Miller-Janjic and Kain-Fritsch schemes in a Meso-scale Ensemble Prediction System. India uses the Kuo scheme in a regional model with 75 km in horizontal resolution. South Africa uses the Betts-Miller scheme in a regional model with 48 km horizontal resolution.

Four CP schemes: Betts-Miller-Janjic (BM), Grell, Kain-Fritsch (KF), and new Kain-Fritsch (KF2) schemes were used in this study based on the results of previous research done for middle latitudes and on the availability of CP schemes in the MM5 model [3- 8]. These results were variable and show that one cannot say in advance which convective parameterization scheme is expected to be best in mesoscale models for predicting heavy rain in Thailand. An experimental investigation of this question is therefore needed.

For the present study, four heavy rain events in Thailand in 1993 were chosen to represent a variety of convective conditions in the summer season (Case 1) , the rainy season (Case 2), the cold season (Case 3), and a tropical cyclone (Case 4).

2. Experimental

2.1 The Numerical Model

The Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model MM5, version 3.5, used in this study is a limited-area non-hydrostatic numerical model with vertical terrain-following sigma-coordinate [9]. Two nested domains were used. The outer domain had 135×110 grid points (E-W and N-S, respectively) with resolution 45 km covering the area 75.58°E to 129.42°E and 9.22°S to 32.55°N; the inner sub-domain had 142×151 grid points (E-W and N-S, respectively) with resolution 15 km covering the area 93.26°E to 112.14°E and 3.55°N to 23.01°N. In both domains, there were 31 sigma levels in the vertical between the top at 10 hPa and the Earth's surface.

The experiments for each case study used the same model settings, the same initial conditions and the same model physics options, but different cumulus parameterization schemes, as discussed above. The physical parameterization included the simple ice resolvable-scale microphysics scheme, the Medium-Range Forecast (MRF) planetary boundary layer scheme, and the cloud radiation scheme [9].

The model runs were started 24 h before each heavy rain event (Spin-up was assumed to take about 12 h.). The input data used were 6 h uninitialized analysis data with a resolution of 1.125×1.125 degrees obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). These data provided initial values on the outer domain at the start of each run, and boundary values on the outer domain every 6 h. The two-way interaction option was chosen for the forecasting runs. Here, the outer domain provides boundary values on the inner domain, and the inner domain updates the variables in the outer domain. Each case was run with the four selected convective parameterization schemes (Betts-Miller, Grell, Kain-Fritsch, and New Kain-Fritsch) for 60 h forecasts.

The Betts-Miller (BM) scheme [10] refined by Janjic [11] does not use a cloud model. Convection triggers when there is convective available potential energy (CAPE) and sufficient moisture in the air column. The large-scale temperature and moisture profiles are adjusted towards a post-convective reference profile based on climatology. When the humidity after the occurrence of convection is greater than the humidity before the occurrence of convection, convective precipitation is deduced.

The Grell (GR) scheme is a single-cloud model simplified from the Arakawa-Schubert scheme [9,12]. There are two vertical drafts: an updraft from the cloud base to the cloud top, and a downdraft from an intermediate level in the cloud to the cloud base. Mixing between the cloud and the environment occurs only at the cloud base and the cloud top. Convection is initiated when the net column destabilization rate increases. The precipitation is equal to the condensation in the updraft minus the evaporation in the downdraft.

The Kain-Fritsch (KF) scheme arose from numerous modifications in the Fritsch-Chappell scheme [13]. It employs a one-dimensional cloud model with updrafts and downdrafts and two-way exchanges of air between the cloud and its environment through entrainment and detrainment at all levels [14]. The triggering is accomplished by lifting parcels of air near the surface to the lifting condensation level and determining whether the parcel is then warmer or cooler than its environment. The exchanges of mass between the cloud and the environment are assumed to remove 90% of the CAPE within a time period of 30-60 min. Some water in the cloud model evaporates in the downdraft, and some falls to the surface as rain.

The New Kain-Fritsch (KF2) scheme has more flexible updraft and downdraft formulations for precipitating clouds under different conditions [15]. The updraft formulation includes a minimum entrainment rate diluting the updraft to prevent the prediction of widespread light rain and to increase the maximum rainfall within the precipitation areas. The cloud radius is variable and depends on the vertical velocity at the lifting condensation level, which promotes convection when large-scale forcing is strong, and suppresses convection when the large scale forcing is weak. Shallow non-precipitating clouds are included. The calculation of CAPE in the updraft is also improved.

2.2 Method

2.2.1 Precipitation Events Studied

2.2.1.1 Case 1, Summer Season, 21 April 1993

Convective clouds with thunderstorms and heavy rain in the NE region were caused by the interaction of two different air masses: a cool high-pressure air mass from China (to the north) and a warm moist air mass from the South China Sea (to the east).

2.2.1.2 Case 2, Rainy Season, 8 September 1993

Heavy rain in the E region was caused by a strong SW monsoon drawing warm moist air from the Indian Ocean over the Gulf of Thailand into a low-pressure trough lying across NE Thailand.

2.2.1.3 Case 3, Cold Season, 21 December 1993

Heavy rain and flash floods occurred in southern Thailand because of high pressure and a strong NE monsoon from China that drew warm moist air from the Gulf of Thailand over the area.

2.2.1.4 Case 4, Tropical Storm, 12 July 1993

Tropical storm “Lewis”, which had moved up the coast of Vietnam, weakened to a depression and crossed into northern Thailand causing flooding over NE and northern Thailand.

2.2.2 Verification

2.2.2.1 Rain Patterns

Qualitative verifications were obtained by comparing model-derived rain patterns with rain patterns derived from measurements at the rain gauge stations of the Thai Meteorological Department on the days having the heaviest rain, i.e. during the periods from 24 h to 48 h after the beginning of each model run. Maps of the model-derived rain patterns were obtained by adding the predicted convective and non-convective rainfall with the help of the GrADS program [16]. Since the rain gauge stations are typically 50-100 km apart, cloud patterns from the composite geostationary meteorological satellite GMS-4 infrared images were used to supplement this evaluation. Although infrared images over-emphasize cold high clouds, the most intense patches in an image indicate deep cloud where there is likely to be heavy rain.

2.2.2.2 Statistical Score Indices

Quantitative verifications of model precipitation were obtained by calculating statistical score indices in small study areas selected where very heavy rain occurred. These study areas (approximately 2°×2° in each case) were divided into small squares as shown in Figure 1. The scores were found as functions of accumulated rainfall thresholds in 10 mm steps over the range zero to 80 mm every 12 h up to 48 h.

Since the precipitation values given by the model are area averages, precipitation from the rain gauge stations were converted to area averages by the isohyetal method [17]. In this method contours of precipitation are drawn to fit the rain gauge data, and the average precipitation over each small square is calculated from these contours. The model precipitation amounts were averaged over the same small squares. These averages were compared using the bias (*BIAS*) score and the Peirce skill score (*PSS*, also called the Hanssen-Kuipers discriminant) [18- 22].

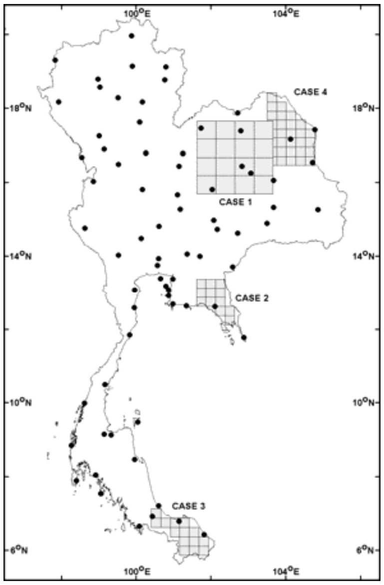

Figure 1. Map of rain gauge stations (dots) and the areas for each quantitative case study.

For each threshold value of accumulated precipitation at every 12 h up to 60 h a contingency table (Table 1) was constructed containing the following frequencies: the number of hits (*A*), the number of false alarms (*B*), the number of missed events (*C*), and the number of correct negative events (*D*).

Table 1. Contingency table for accumulated precipitation greater than a threshold.

	Observed	Not observed
Forecast	A	B
Not forecast	C	D

The bias, $BIAS = (A + B)/(A + C)$, is the ratio of the frequency of the forecast events to the frequency of the observed events. The Peirce skill score, $PSS = (AD - BC)/(A + C)(B + D)$, is the skill score calculated from the relative frequency of hits minus the relative frequency of hits that could have been obtained by random chance.

3. Results and Discussion

3.1 Rain Patterns

The discussions below are focused only on areas within the borders of Thailand because rain gauge data were not available outside Thailand. Figures 2-5 show the patterns of accumulated precipitation in the four case studies. The rain patterns in Thailand from rain gauges and the cloud patterns from satellite images were qualitatively consistent with each other in all four case studies.

In the hot season (Case 1, Figure 2), the model-derived rain patterns using the four convective parameterization schemes were significantly different from the rain pattern derived from the rain gauge stations. These differences were confirmed by the composite satellite image. This may have been due to differences between the predicted wind fields and the wind field found in the analysis of observations at the forecast time.

In the rainy season (Case 2, Figure 3), the heavy rain patterns of all the schemes were roughly similar and consistent with the observed precipitation over Thailand. However, there were discrepancies between the predicted patterns and the patterns indicated by the satellite images outside the Thai borders. The BM and GR schemes matched the observed patterns more closely than the KF and KF2 schemes in E Thailand since there was strong dilution of updraft parcels by entrainment from the moist environment in the KF and KF2 schemes that yielded clouds of depth less than the real depth.

In the cold season (Case 3, Figure 4), the heavy rain was over southern Thailand; the other parts of the kingdom were dry. The rain patterns from the models were generally consistent with the rain patterns from the observed precipitation. However, the BM and KF2 schemes failed to predict heavy rain on the eastern side of southern Thailand between latitudes 8-9°N, and there was a location error in the BM prediction of rain in the extreme south of Thailand. The location and intensity of the heavy rain area was predicted best by the GR scheme. The prediction by the KF scheme was second best.

In the tropical depression case (Case 4, Figure 5), the GR and KF2 schemes were fairly good in their predictions of the rain patterns in northern and NE Thailand. The BM and KF schemes predicted the principal rain pattern some 100-200 km to the northeast of the observed pattern.

3.2 Statistical Score Indices

The bias scores and the Peirce skill scores are shown in Figure 6 as functions of thresholds of rainfall accumulated from the start of each model running up to 48 h. A thin line represents scores for the BM scheme, thin dots and dashes represent scores for the GR scheme, bold dots are used for the KF scheme, and bold dashes are used for the KF2 scheme.

In the hot season (Case 1), the bias scores show that the models tended to underestimate the rainfall. The GR scheme was as good as the KF scheme, but the negative Peirce skill scores showed that all the models had completely failed to predict heavy rainfall. The reason for this was discussed in the previous section.

In the rainy season (Case 2), the bias scores and the Peirce skill scores indicate that all schemes were similar in precipitation prediction at rain thresholds less than 10 mm. The bias scores show that the BM scheme greatly overestimated the rainfall at rain threshold values greater than 20mm, while the KF and KF2 schemes underestimated the rainfall. The forecasting skill, as indicated by the Peirce skill scores, was the best with the GR scheme.

In the cold season (Case 3), the bias scores show that the BM and KF2 schemes gave good predictions of precipitation over the study areas at most thresholds, except for overestimations by the BM scheme above 50 mm. The predictions using the GR and KF schemes were less than the observed precipitation during the whole of the forecast period. The four schemes had positive Peirce skill scores at the intermediate to high rain thresholds with the BM scheme being the best at about 0.8 from 20 mm to 50 mm.

In the tropical depression case (Case 4), the bias scores show that the GR scheme was best at predicting the precipitation amounts. The other schemes underestimated the precipitation, with the KF2 and KF schemes being next best, and the BM scheme being the worst. The GR scheme gave the best Peirce skill scores. The KF2, KF and BM schemes gave lower Peirce skill scores in descending order, respectively.

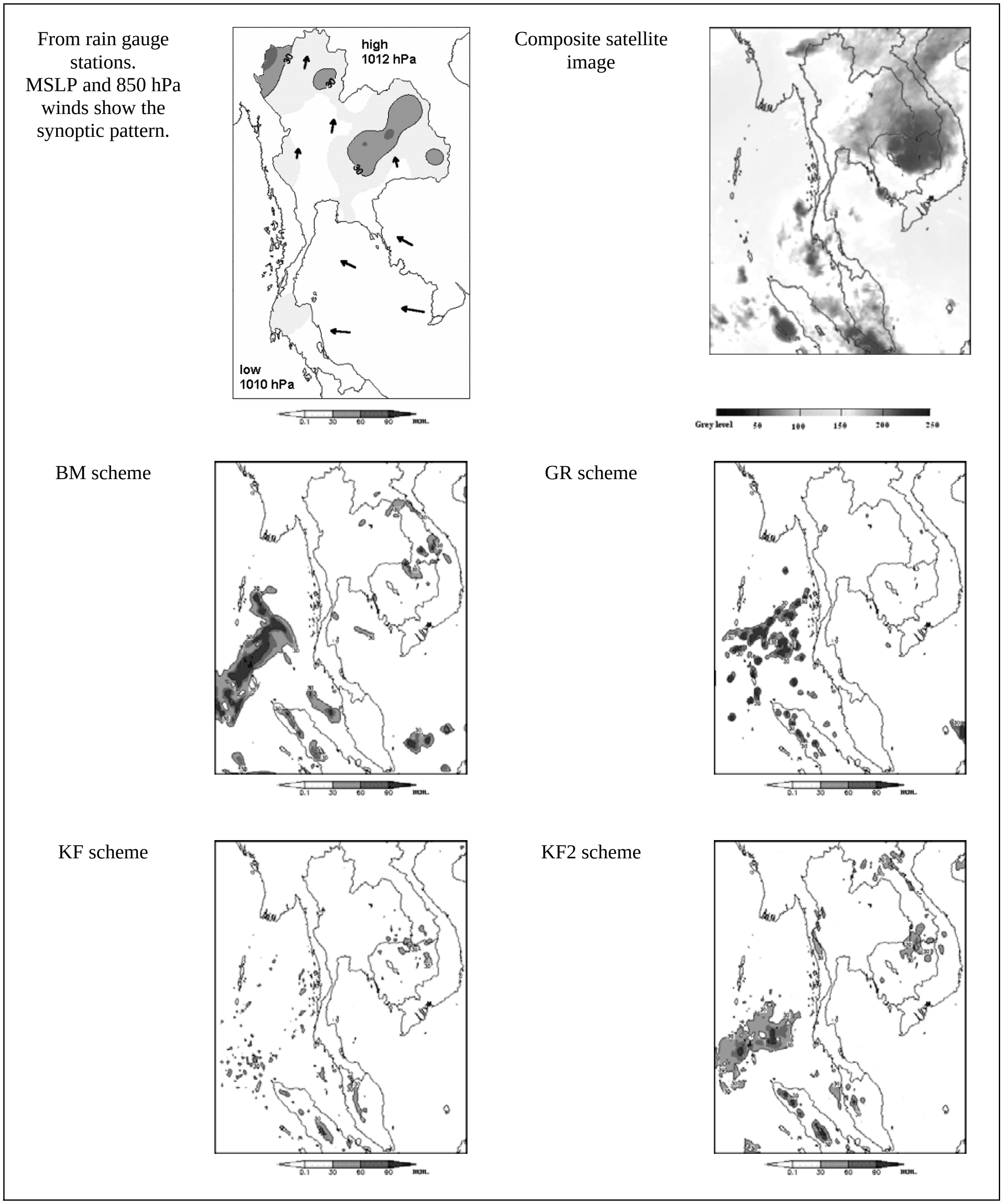

Figure 2. Patterns of accumulated precipitation in Case 1 (hot season) from 00 UTC 21 April 1993 to 00 UTC 22 April 1993.

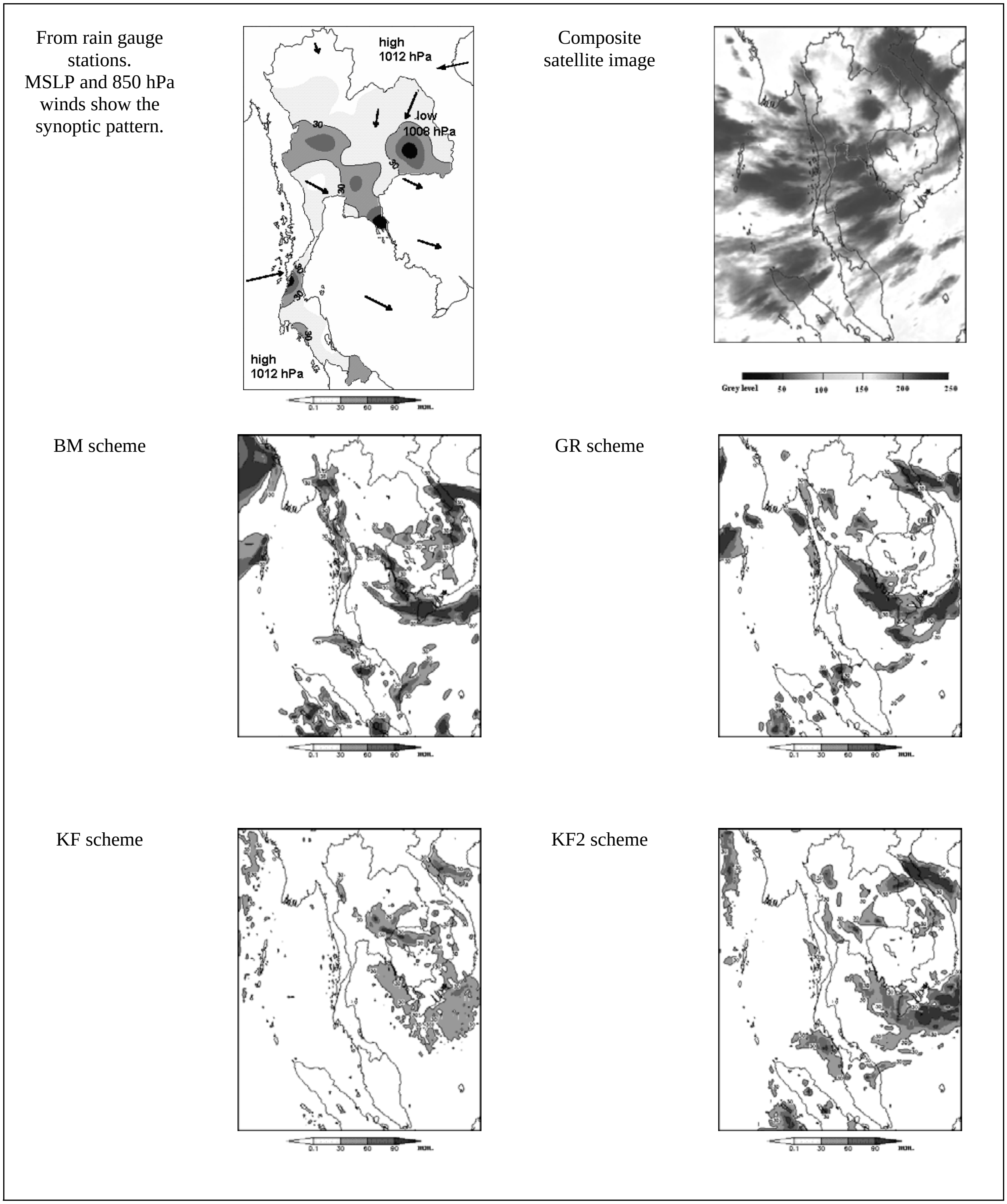

Figure 3. Patterns of accumulated precipitation in Case 2 (rainy season) from 00 UTC 08 September 1993 to 00 UTC 09 September 1993.

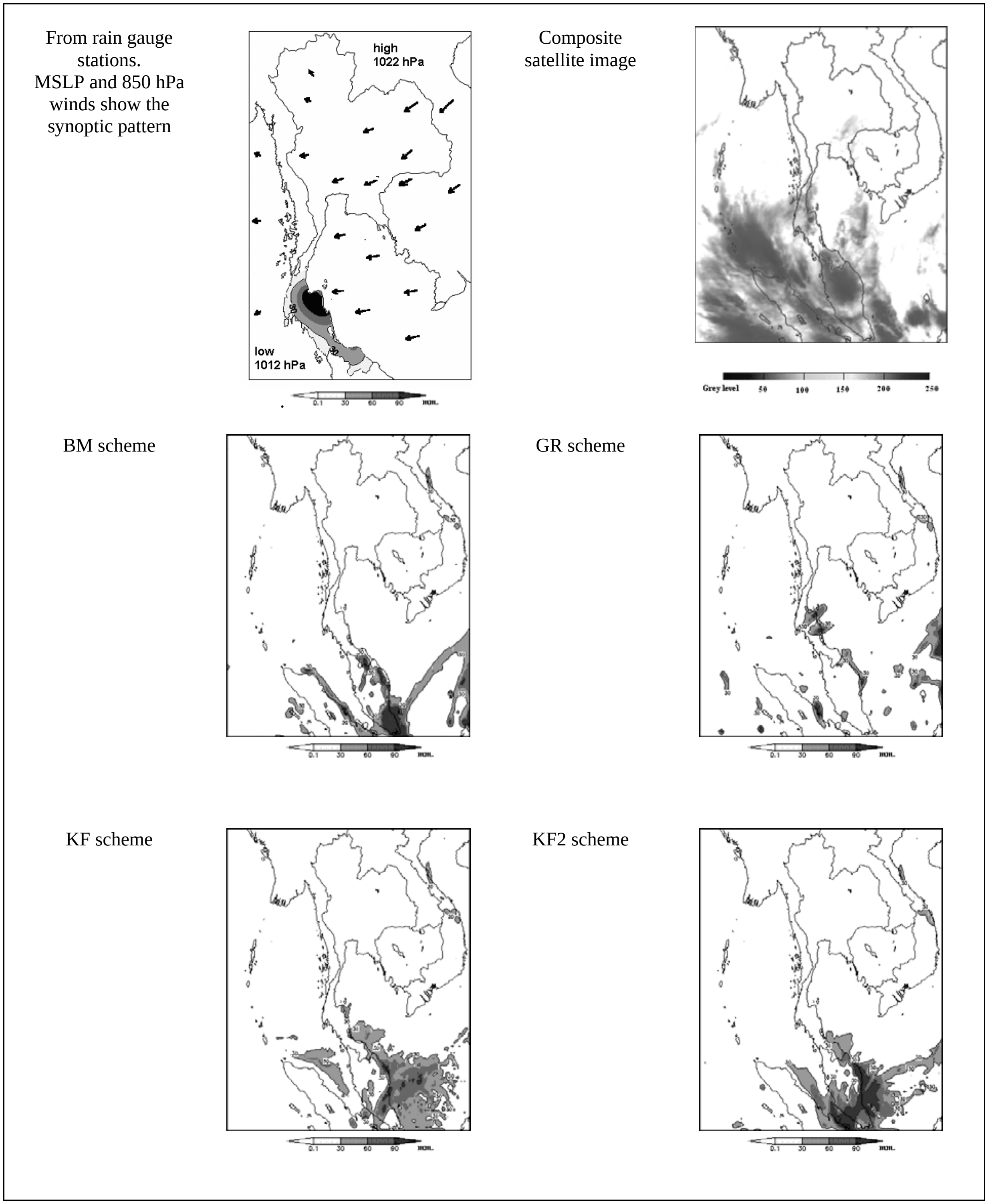

Figure 4. Patterns of accumulated precipitation in Case 3 (cold season) from 00 UTC 21 December 1993 to 00 UTC 22 December 1993.

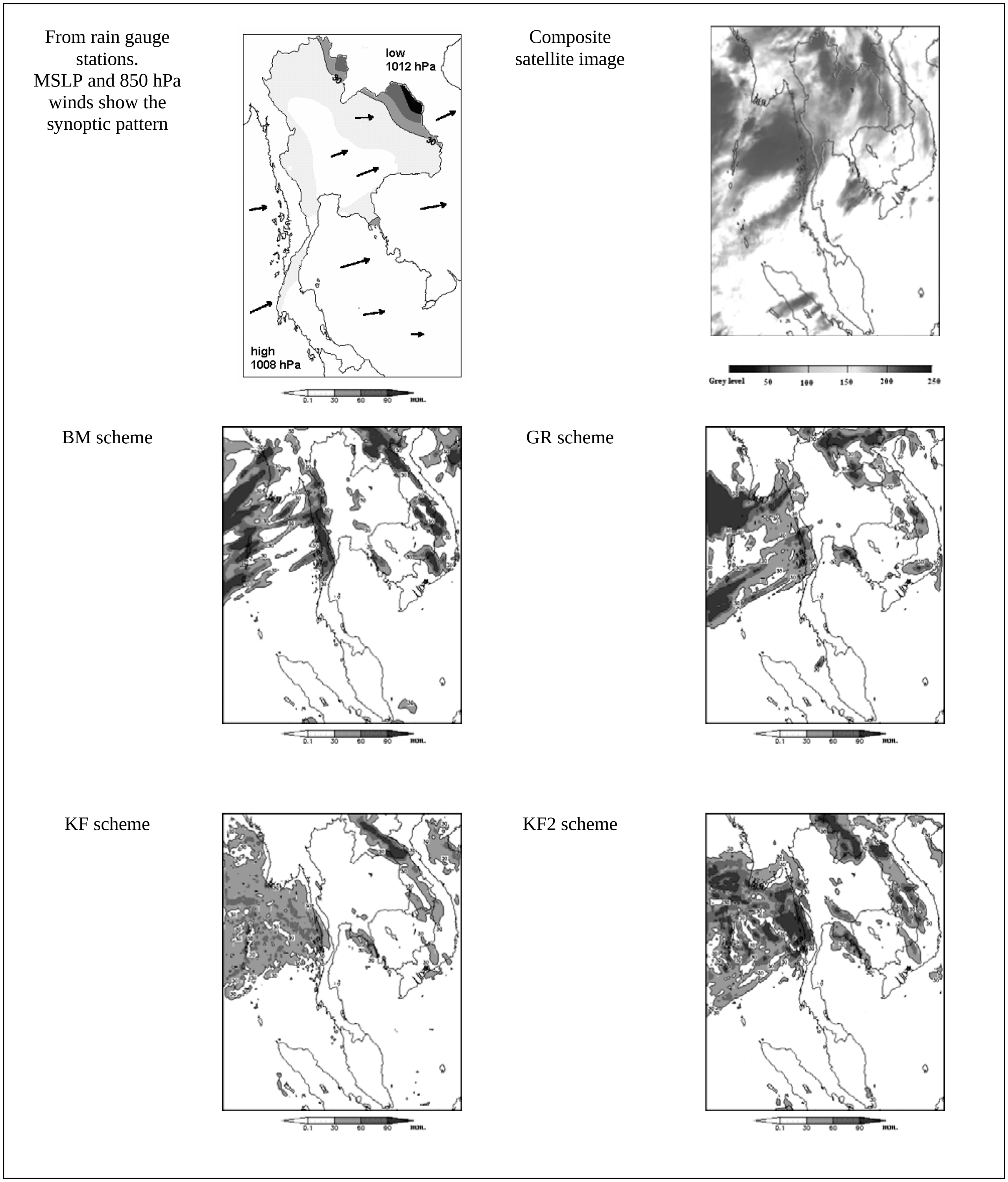

Figure 5. Patterns of accumulated precipitation in Case 4 (tropical depression) from 00 UTC 12 July 1993 to 00 UTC 13 July 1993.

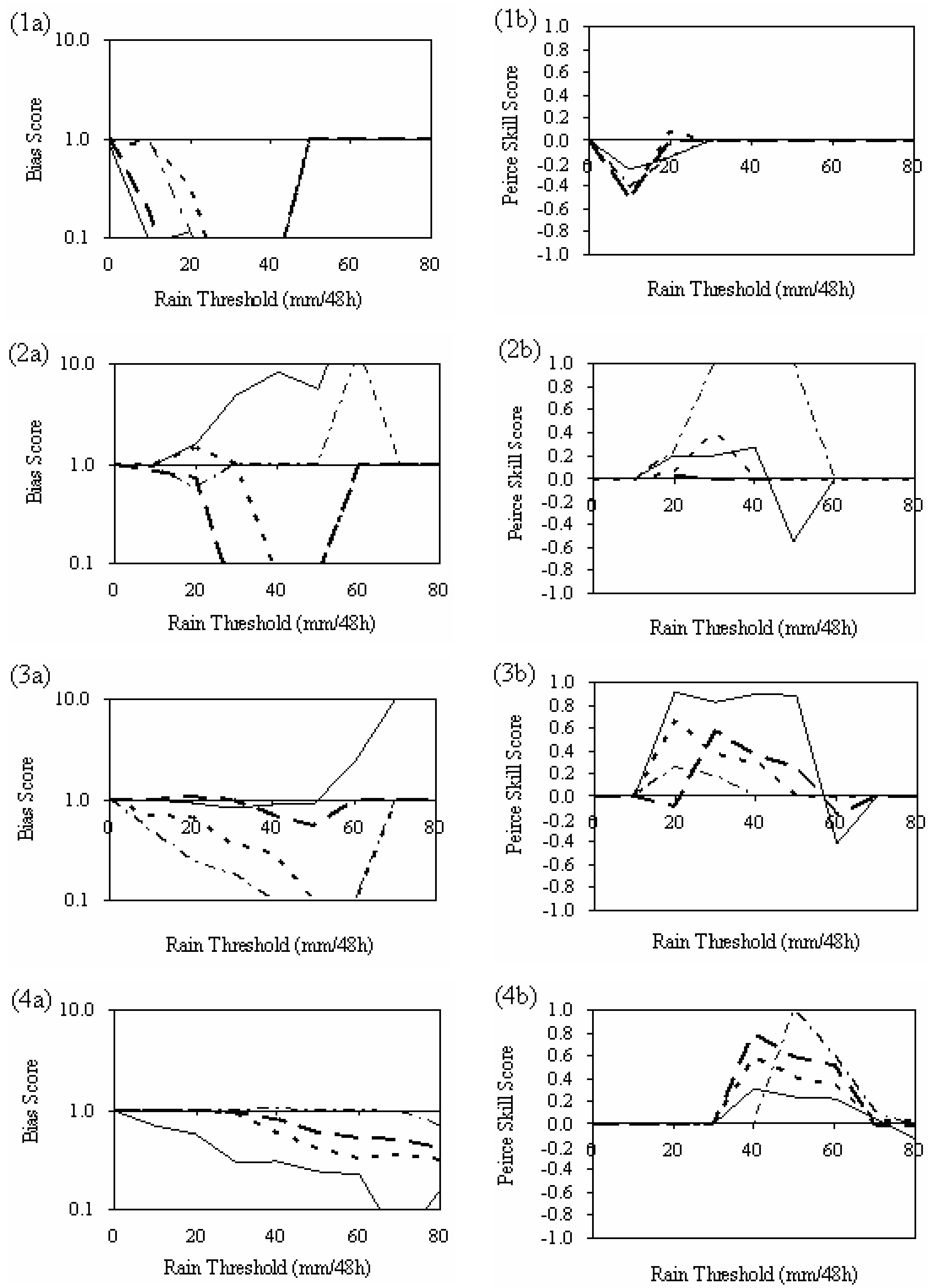

Figure 6. Bias scores (left) and Peirce skill scores (right) for 48 h accumulated precipitation in the study area. (1a-b) Case 1 hot season, (2a-b) Case 2 rainy season, (3a-b) Case 3 cold season, (4a-b) Case 4 tropical depression. — BM, – · – GR, - - - KF, – – – KF2.

4. Conclusions

This exploratory study, undertaken to evaluate selected convective parameterization schemes in predictions of heavy rainfall events in Thailand in an operational MM5 model with a grid resolution of 15 km, found that the Betts-Miller (BM), Grell (GR), Kain-Fritsch (KF), and new Kain-Fritsch (KF2) schemes gave widely different results in the four cases studied—an outcome similar to that found in studies by other researchers. This study particularly resembles the study by Yang and Tung (2003), which found differences between the performances of the BM, GR and KF schemes during different synoptic events that are too varied for meaningful correlation with our results.

In the hot season, all four schemes underestimated the amount of rainfall and failed to predict the heavy rain in NE Thailand. The precipitation patterns from the models were not consistent with the observed patterns.

In the rainy season, the rain patterns predicted by all the schemes in E Thailand were consistent with the observed precipitation patterns. The GR scheme was the best in predicting rain.

In the cold season, the BM and KF2 schemes gave the best predictions of heavy rain in the study area in the extreme south of Thailand; although they had failed to predict the heavy rain around latitude 9°N. The GR and KF schemes underestimated the rainfall over the study area.

In the tropical depression case, the GR scheme was the best followed in order by the KF2, KF, and BM schemes.

Our case studies illustrate the difficulty of predicting localized heavy rainfall in Thailand with the MM5 model using a 15-km grid size and existing convective parameterization schemes. To make a recommendation to forecasters we suggest that the cloud-modelling parameterization schemes (GR, KF, and KF2) will be better than the profile-adjustment (BM) scheme. In particular, the GR scheme may be a provisional choice, while a KF2 scheme, suitably modified for local conditions in Thailand, is expected to give the best results eventually. Accordingly, we are undertaking more studies of the numerical prediction of heavy rain using modified KF2 schemes in the tropical hot season, where convective parameterization is an important challenge. Even though the increasing power of computers is making finer modelling grids possible, together with the possibility of direct simulation of convective processes at the local level, the development of good mesoscale convective parameterization schemes for use in Thailand with a moderate grid size remains a desirable goal.

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