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Forecasting severe rainfall in the equatorial Southeast Asia

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Accurate prediction of monsoon heavy rainfall events in the equatorial region has always been a challenge to weather forecasters. In this paper, forecast of a severe precipitation event that occurred over the eastern central coast of Peninsular Malaysia was attempted using the state-of-the-art Florida State University (FSU) Global and Regional Spectral Models. The sensitivity of parameterized convection in these models on precipitation forecast skill is studied using two different parameterization schemes for cumulus convection (the Relaxed Arakawa-Schubert scheme and the modified Kuo scheme). Low precipitation threshold of rainfall less than 2 mm day^{-1} was successfully predicted by both versions of the FSU model. However, the convection schemes lacked skill in predicting the correct placement of the area and amount for the high precipitation threshold greater than 40 mm day^{-1}. Further evaluation of the predictive skills showed that the Relaxed Arakawa-Schubert scheme was a consistently better predictor of rainfall due to its low bias and lower root mean square errors (RMSEs) compared to the modified Kuo parameterization scheme.

Keywords: monsoon rainfall, equatorial Southeast Asia, global and regional spectral models, rainfall prediction

1. Introduction

The Asian monsoon generally comprises of several different regional components such as the Indian, Southeast Asian, the East Asian and the Australian monsoon systems (Qian and Yang, 2000) that exhibit different circulation components, which are interactive in a complex manner and still independent from each other (Wang et al., 2003a). This is complicated further by the

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air-sea coupling near the South China Sea (SCS) and the maritime continent. The interconnectivity of these monsoon systems is still not well understood and many theories have been offered by different researchers to explain the regional variability of different features of the Asian monsoon (Lau et al., 2000; Ding et al., 1999; Luo, 1999).

Observational and numerical studies have by far focused on the Indian and East China monsoons, whilst research on the southern SCS monsoon has been relatively scarce (Qian and Yang, 2000). Observational studies by Jin (1999), Luo (1999) and Ding et al. (1999) have presented various explanations for the onset of the SCS monsoon displayed by enhanced precipitation, deep convection and low level wind convergence. The SCS monsoon is also affected by several factors including northward expansion of equatorial convection; migration of cloud clusters from western Pacific; influence of development and transport of moisture from the tropics and mid-latitudes, and early onset of monsoon over the SCS as a precursor to the Asian summer monsoon.

The maritime continent, of which Malaysia is part of, is recognized as the main heating source of the Asian winter monsoon. The heat source from convective precipitation drives the planetary scale meridional circulation (Chang et al, 2005). However, the temporal and spatial scales of the atmospheric phenomena of the winter monsoon and their interactions with the tropical oceans are not well understood (Zhang et al., 1997).

One of the main features of the winter monsoon of the northern hemisphere is the cold surge related to synoptic and planetary-scale disturbances from the tropical and mid-latitude regions. It was suggested that deep convective heat source near the maritime continent may interact with the cold surges to modify the intraseasonal oscillations of the planetary-scale motions such as the Madden Julian Oscillations (MJO) and synoptic-scale motions in the tropics and mid-latitudes (Lau, 1981; 1982). The MJO is an equatorial eastward propagating pattern of enhanced and suppressed convection, mainly observed in the Pacific Ocean and the Indian Ocean. The Asian/Australian monsoon has also been linked to the Southern Oscillation in the formation of the El Niño (ENSO) cycle (Lau and Nath, 2000). The interannual variation of the monsoon winds near the South China Sea and the maritime continent is highly related to the Southern Oscillation Index (Zhang et al., 1997). The Australian winter monsoon and likewise, the East Asian winter monsoon, play an important role in the development of the eastward propagation of the low level westerly wind anomaly and the anomalous convection of the MJO over the maritime continent and western Pacific (Wang et al., 2003b).

Numerical prediction of the monsoon rainfall has produced limited success so far due to complexities in the evolution of state of the atmosphere from problems such as development of regional hydrodynamical instability from non-linear error growth and the modeling of the monsoon itself. In a pioneering study, Dixit et al. (1999) found that the chaotic transitions of the intraseasonal oscillations are difficult to forecast and the predictability of mean precipitation of the

Indian monsoon even by simple coupled atmosphere-ocean models have been elusive. Another study using an ensemble of four general circulation models (Sperber et al., 1999) concluded that these models were incapable of simulating correctly some features of the seasonal and interannual variabilities of the monsoon such as precipitation, the cross-equatorial flow, and the cyclonic vortices in the Bay of Bengal. Tropical systems are controlled more by organized convection unlike the systems in the mid-latitudes which are governed largely by the upper-tropospheric Rossby waves interacting with the surface weather through baroclinic instability mechanism. On the other hand, tropical convection is controlled mostly by combined barotropic/baroclinic instability and heat contrast between the land mass and warm tropical oceans. The location and strength of organized convection in the tropics is determined by several factors including pre-existing sources of moisture, active phase of Inter-Tropical Convergence Zone (ITCZ) and up-scale transfer of energy from cloud-scales to synoptic scales (Krishnamurti et al., 1998). Moist atmospheric convection in the tropics is also controlled by mid-tropospheric humidity (Derbyshire et al., 2004); availability of moist static energy and saturation of tropospheric humidity (Raymond et al., 2007) and distribution of water vapor and its path (Bretherton et al., 2004). Several of these studies laid foundation to improve the existing parameterization schemes for cumulus convection.

Organization of convection in the tropics is mostly governed by the meso-convective precipitating elements on cloud resolving scales, making it further difficult to simulate and predict tropical rainfall using coarse resolution global models (Krishnamurti et al., 1998). These convective systems exhibit faster growth of errors due to the data sparse tropical oceans (Young and Lazzara, 2004). Most of the tropical convection occurs on horizontal scales of individual cumulus clouds of the order of hundreds of meters to about 10 km. The present generation operational numerical weather prediction models have a resolution of about 100 km for the global models and about 50 km for the regional mesoscale models. Thus, grid spacing in these models will not allow them to explicitly resolve the convection, leading to the need of representing sub-grid scale convective processes in the form of parameterized convection. Several such schemes have been designed for this purpose, the most popular among them for tropical precipitation are the moist convective adjustment schemes like Kuo-type schemes (Kuo, 1965, 1974) and a more complex mass flux type Arakawa-Schubert (1974) schemes. The basic difference between these two types of schemes is the closure assumption upon which these schemes were designed. While mass flux type approach is used to parameterize the effects of cumulus convection by using an ensemble of clouds with varying cloud tops and heights in the Arakawa-Schubert type schemes, a more simple convective instability and large-scale moisture convergence forms basis for Kuo type cumulus parameterization schemes.

Various cumulus convection schemes have been utilized by different general circulation models and regional mesoscale models to study different characteristic features of the monsoon. The use of the different schemes produced different results of precipitation features such as the intensification of monsoon depressions (Vaidya et al., 2004; Trivedi et al., 2002), tropical cyclones (Tibbetts and Krishnamurti, 2000; Prater and Evans, 2002; Rao and Ashok, 1999; 2001) or improved precipitation forecasts over the tropical belt (Shin and Krishnamurti, 1999). Rajendran et al. (2002) established that the moist convective adjustment scheme of Manabe et al. (1965) produced realistic seasonal and intraseasonal precipitation of the monsoon in contrast to the mass flux scheme of Hack (1994). However, cumulus parameterization schemes have not always been successful in simulating precipitation in some regions, such as in the East Asian monsoon region (Leung et al., 1999; Lee and Suh, 2000; Wang et al., 2003a). While most of the convective schemes have been designed based on processes in the mid-latitudes, and tuned for tropics based on data from a limited field experiments like GATE (Global Atmospheric Programme Atlantic Tropical Experiment, 1974) and MONEX (International Monsoon Experiments, 1979), these schemes fail to perform well in the tropics due to the inherent complexity of processes that govern tropical convection in the equatorial latitudes.

In this study, an attempt is made to simulate a case of a severe rainfall period that caused extensive floods to the eastern coast of Peninsular Malaysia during the northeast monsoon in December 2001. The major heavy rainfall event occurred along the eastern coast of the peninsula, mainly in the states of Kelantan, Terengganu, Pahang and Johor from the 21st to 22nd December 2001 (Figure 1). More than 9479 people were evacuated to 35 emergency centers in Pahang (Utusan Malaysia, 2001). Several rivers such as the Sungai Lembing, Kuala Kenau and Sungai Kuantan overflowed and water levels reached as high as seven meters due to more than twenty four hours of continuous rain (Malaysian Meteorological Services, 2007). The Kuantan station, located on the central eastern coast, registered the heaviest rainfall of 355 mm on the 21st December 2001 (Figure 1b). Mersing, located in the southeastern coast of the peninsula also recorded a daily total of 209 mm. This was substantiated by the infrared Geostationary Meteorological Satellite (GMS) images on the 21st December 2001 that illustrated presence of a deep convective cloud system over the southeast of Peninsular Malaysia. Prior to this event, bifurcation of strong westerlies over east Africa due to the presence of a persistent upper level anticyclone contributed to a blocking situation. Easterly waves and trade surges were also noted to influence the development of heavy rainfall.

The Florida State University (FSU) Superensemble wind analysis showed the existence of a deep trough along 60°E from 20°N to 10°S during the period from the 18th to 22nd December 2001 (Krishnamurti et al., 2002). Of interest is the development of an eastward propagating upper level anticyclonic circulation over the South China Sea-Indochina region from 19th December that traversed to the Philippines by 21st December. The presence of a low level surge of northeasterlies over the South China Sea region on 21st and 22nd December contributed to the heavy rainfall in Peninsular Malaysia. A cyclonic circulation near southern Peninsular Malaysia was intensified by this strong surge, particularly on 22nd December 2001.

The present study will focus on the performance of the global and regional FSU numerical weather models in predicting the heavy rainfall event. Precipi-

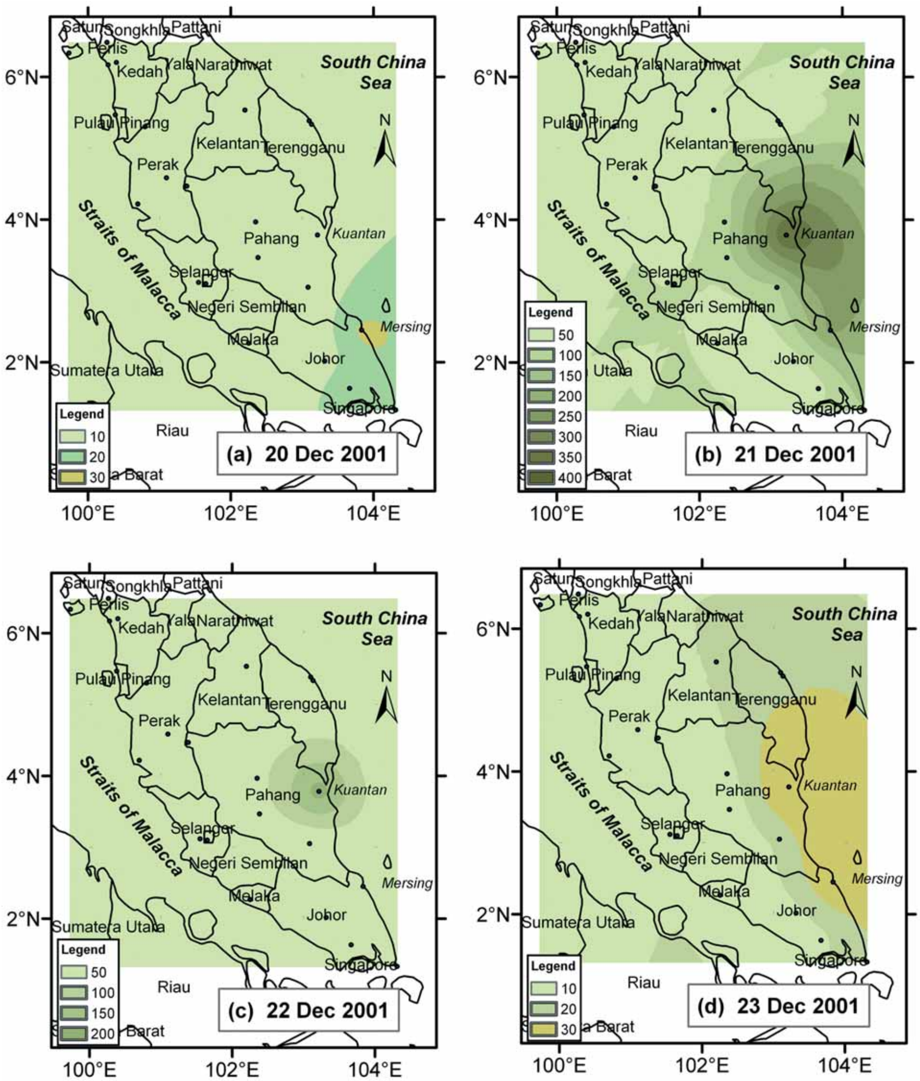

Figure 1. The daily rainfall distributions obtained from rain gauge data for Peninsular Malaysia from (a) 20 to (d) 23 December 2001 showed the spatial extent of heavy rainfall total of more than 80 mm affecting the central east coast on 21 and 22 December.

tation forecasts for the heavy rainfall event by two different cumulus parameterization schemes: the Arakawa-Schubert (Arakawa and Schubert, 1974) and the modified Kuo (Krishnamurti et al., 1983; 1988) are evaluated. Statistical measures such as the threat scores, bias and root mean square errors (RMSE) are analyzed to evaluate performance of the models compared to the observed (TRMM derived) rainfall data.

2. Methods and materials: The FSU models

For the purpose of simulating the heavy rainfall event occurred in the equatorial Southeast Asian region, we have chosen two different versions of the state-of-the-art FSU global and regional spectral models. The FSU Global Spectral Model (FSUGSM) is based on primitive meteorological equations and utilizes the spectral method for its dynamical calculations. Triangular truncation is applied at wave 126 (T126), where the horizontal resolution is equivalent of about 100 km grid spacing near the equator. The FSU nested regional spectral model (FSUNRSM) is a one-way nested perturbation model where the initial and boundary conditions are provided by the output from the FSUGSM (Cocke, 1998). FSUNRSM is designed such that it shares the same dynamics, physics and vertical structure of the global model. The regional fields are composed of a base field (through the FSUGSM) plus a high-resolution perturbation field. Perturbations are relaxed to zero at the lateral boundaries and orography is derived from the perturbation geopotential height at the surface. The horizontal resolution of FSUNRSM is 50 km. Detailed description of FSUGSM and FSUNRSM are well documented by Krishnamurti et al., (1991, 1998) and Kumar (2000).

Initial conditions for FSUGSM are obtained from the high resolution European Center for Medium Range Weather Forecasts (ECMWF) analysis fields. Observed rain rates from the TRMM satellite are incorporated in the model initial state following the physical initialization procedure described in Krishnamurti et al., (1991, 2002) and Kumar (2000). Physical initialization consists of various components such as reverse cumulus parameterization scheme, reverse similarity algorithm, outward longwave radiation matching, Newtonian relaxation of the model variables and a bisection method, and generates variables such as winds, mass fields, rainfall patterns and surface moisture fluxes that closely match the observed fields.

Parameterized convection in FSU spectral model is represented either through the modified Kuo scheme (Kuo, 1965; Krishnamurti et al., 1983) or the Relaxed Arakawa-Schubert Scheme (Arakawa and Schubert, 1974; Moorthi and Suarez, 1992). These two schemes differ in the treatment of heating and moistening profiles. The apparent heat source (Q_1) and moisture sink (Q_2) are slightly different for both schemes, and are represented below.

Arakawa Schubert scheme:

$$Q_1 = \rho\left(\frac{\partial \overline{s}}{\partial t} + \overline{\mathbf{V}}\cdot\nabla\overline{s} + \varpi\frac{\partial \overline{s}}{\partial z}\right) = -DL\widehat{l} + Q_R$$

$$Q_2 = -DL\left(\overline{q}^* - q + \widehat{l}\,\right) - LM_c\frac{\partial \overline{s}}{\partial z}$$

Modified Kuo scheme:

$$Q_1 = a_\theta\left(C_p\frac{T}{\theta}\frac{\theta_s-\theta}{\Delta\tau} + \omega c_p\frac{T}{\theta}\frac{\partial\theta}{\partial p}\right) + c_p\frac{T}{\theta}\left(H_R + H_s\right)$$

$$Q_2 = -La_q\left(\frac{q_s-q}{\Delta\tau} + \omega\frac{\partial q}{\partial p}\right)$$

where ρ is density, θ is potential temperature, s is the dry static stability, $\boldsymbol{V}$ is the horizontal wind vector, ω is the vertical velocity, q is specific humidity, q^* is the saturation specific humidity, p is pressure, R is the dry gas constant, and C_p is the specific heat of air at constant pressure. Q_R is the radiative heating/cooling rate per unit mass of air. H_R is the total radiative potential temperature rate of change and H_S is the vertical sensible heat flux by subgrid-scale motions. The overbars represent horizontal averages. $\widehat{l}$ denotes the liquid-water mixing ratio and D is the entrainment/detrainment parameter. During assimilation mode, values of Q_1, Q_2 and Q_R evolved around the insertion of the observed rain rates (Krishnamurti et al., 1988). Treatment of tropical convection and reasonably good prediction of rain rates in the equatorial latitudes by these two schemes in various operational numerical models provided motivation to choose these two schemes in the FSUGSM and FSUNRSM (Krishnamurti et al., 1998). The aim of this study is to evaluate the performance of these two schemes in conjunction with sensitivity to model resolution in predicting the precipitation over the equatorial latitudes.

3. Results and discussion

Numerical simulations of a heavy rainfall event (described in Section 1) were performed using the physically initialized FSUGSM and FSUNRSM with varying convective parameterization schemes for the period from 20th to 23rd December 2001. A detailed evaluation of skills scores for precipitation forecasts over the region of interest (Peninsular Malaysia) is presented in this section. Four ranges of precipitation thresholds, 2 mm day^{-1} (light precipitation), 10 and 20 mm day^{-1} (moderate rainfall) and 40 mm day^{-1} (heavy rainfall) were chosen in computing the skill scores. These thresholds are chosen based on our previous work in the Southeast Asian region on a tropical cyclone event (Mahmud and Vijaya Kumar, 2009), which found that light and moderate precipitation (2 mm/day and 20 mm/day, respectively) were abundantly simulated by the FSUGSM and FSURNSM. However, higher precipitation thresholds of more than 40 mm/day were not well simulated by either of these schemes. For brevity, we are not showing results from the control experiments (without physical initialization) as they have a definite lack of skill in providing meaningful rain fall forecasts in the tropics (Krishnamurti et al., 1991, Kumar and Krishnamurti, 2006).

Figure 1 shows the extent and amount of heavy rainfall received in Peninsular Malaysia from the 20th to 23rd December 2001, as observed through the rain gauge network. Values more than 300 mm day^{-1} can be seen affecting the

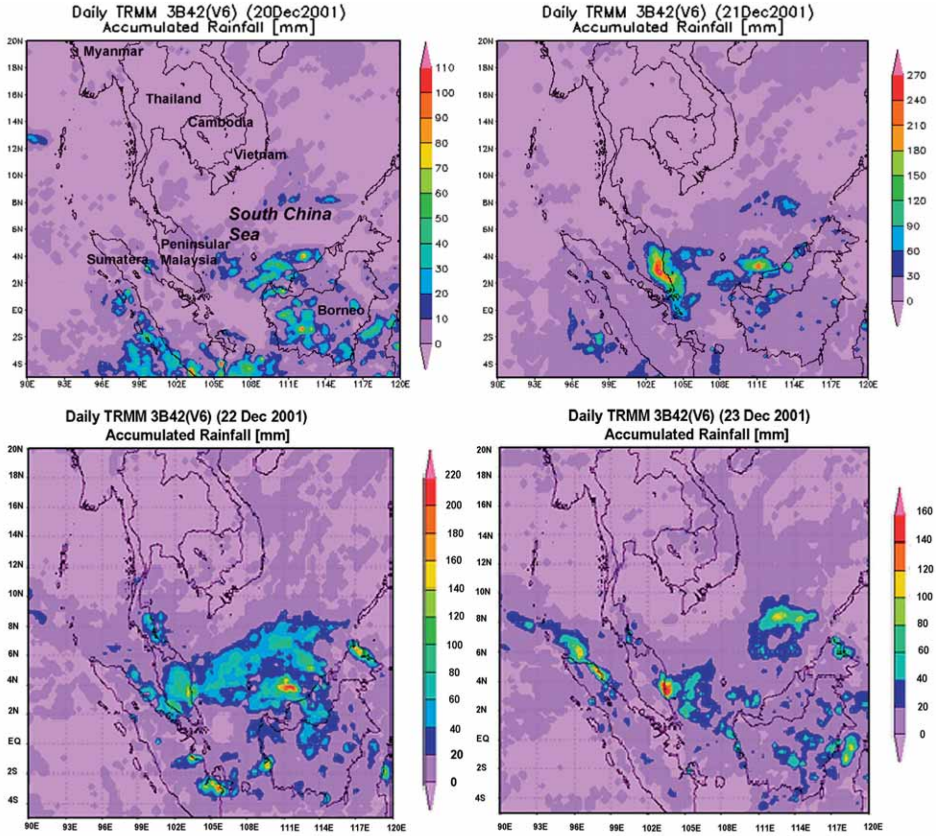

Figure 2. The daily TRIMM rainfall for Peninsular Malaysia from 20 December to 23 December 2001.

central east coast of the peninsula on 21st December 2001. A similar distribution of rainfall was observed on the following day (22nd December), but with reduced maximum of 160 mm over the central east coast. The rainfall system was weakened by 23rd December 2001. The corresponding observed accumulated rainfall from TRMM 3B42 data is shown in Figure 2. Rain rates in excess of 270 mm day^{-1} over the Peninsular Malaysia are well resolved by the TRMM satellite observations (Figure 2b, 21st December 2001), and the rainfall patterns are somewhat in close agreement with the ground truth shown in Figure 1.

The precipitation forecast results obtained from FSUGSM and FSUNRSM with Arakawa-Schubert parameterization scheme (denoted by (A)) are shown in Figure 3. Day-0 forecasts (Figs. 3a and 3b) represent the physically initialized rain rates during the pre-integration period (from Day -1 to Day 0) which have a close match to the TRMM derived rain rates, particularly the low rainfall intensities of less than 20 mm/day (with correlation coefficients of 0.91 and 0.94 respectively for FSUGSM and FSUNRSM). Generally, the Day-1 forecasts from FSU models show underestimation of heavier rainfall compared to the observed rain gauge data of more than 300 mm day^{-1} (Figure 1b) and TRMM (Figure 2b). The Day-0 forecast FSUGSM produced a simulation maximum rainfall of 10 mm over the South China Sea-Peninsular Malaysia region, in contrast to the maximum of 30 mm predicted by the FSUNRSM. The forecasted rainfall patterns and locations of maximum precipitation for Days 1, 2 and 3 have close resemblance to the TRMM rainfall distribution patterns, though not always in rainfall intensities. The higher intensity of precipitation from the regional model which was approximately double the amount predicted by the global model indicates the impact of resolution on rainfall forecasts for the Malaysian region. For example, on the 22nd December (Figure 3c), maximum rainfall forecasted by the FSUGSM was 40 mm compared to more than 80 mm predicted by the FSUNRSM (Figure 3d).

The FSUGSM with modified Kuo cumulus parameterization scheme (denoted by (K), Figure 4) produced a large area of heavy rainfall of greater than 30 mm day^{-1} over equatorial southern South China Sea, particularly on Day 1, corresponding to 21 December. The intense rainfall of more than 240 mm displayed by the TRMM or rain gauge data was not well predicted by the Kuo scheme in the global and regional models. Moderate rainfall of more than 20 mm day^{-1} extended to central east coast of Peninsular Malaysia, in contrast to lighter rainfall of 15 mm day^{-1} predicted over Peninsular Malaysia by the FSUNRSM (right panels of Figure 4). Excessive rainfall of more than 80 mm was found over southern South China Sea region on Day 2 (22nd December 2001), with only moderate rainfall of over 20 mm day^{-1} forecasted over central east coast of the peninsula. This is in contrast to either the TRMM or rain gauge observed rainfall of more than 120 mm. Instead, the areal extent of precipitation was reduced in the regional output with the total 24-hour rainfall amounting to only 8 mm. The locations of the simulated maximum rainfall by both the global and regional models were slightly displaced than the locations

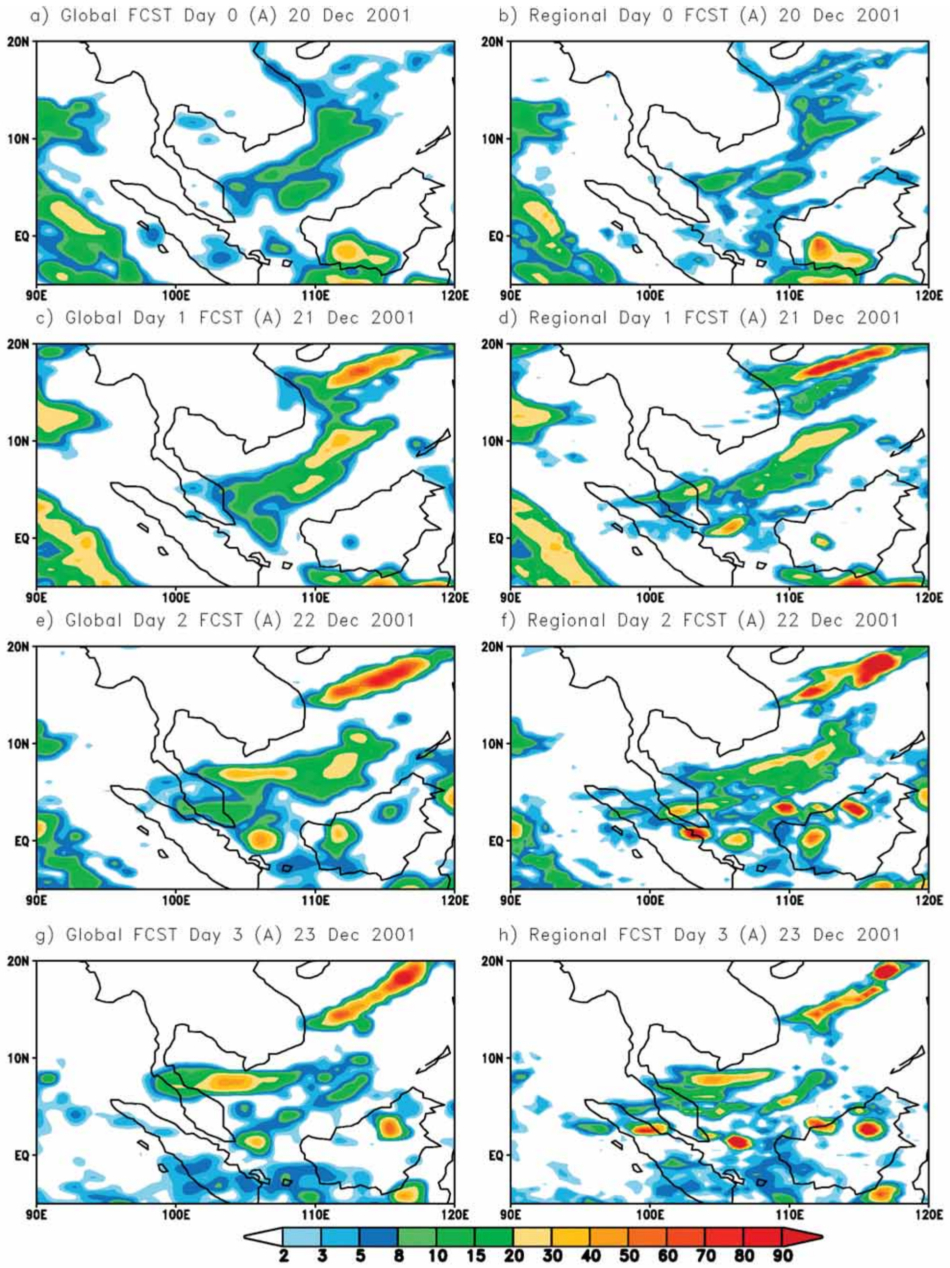

Figure 3. The FSUGSM and FSURSM physical initialized rainfall forecast for four days beginning from 20 December 2001 utilizing the Arakawa Schubert cumulus parameterization scheme.

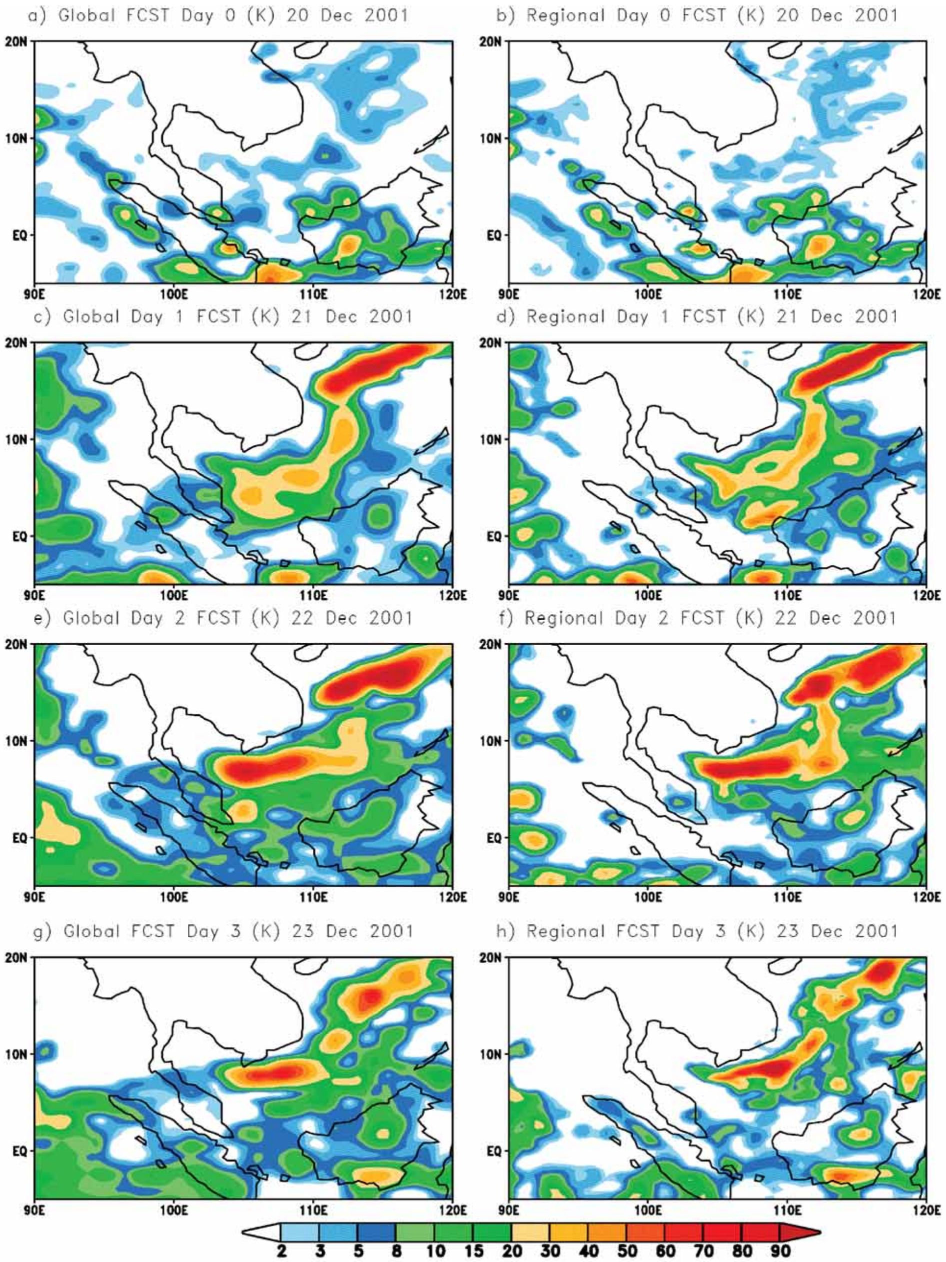

Figure 4. The FSUGSM and FSURSM physical initialized rainfall forecast for four days beginning from 20th December 2001 for the modified Kuo cumulus parameterization scheme.

of the observed maximum rainfall. The Kuo parameterization scheme produced excessive rainfall over the southern South China Sea region, but the heavy rainfall intensity was underestimated over the location of maximum rainfall over the central eastern coast of Peninsular Malaysia. Both the global and regional runs predicted no precipitation over Peninsular Malaysia on 23rd December, the Day 3 in contrast to the observed rain gauge precipitation of 40 mm and an excessive of 140 mm estimated by the TRMM derived rain rates. It can be inferred from Figures 3 and 4 that the FSUNRSM with Arakawa-Schubert convective parameterization scheme has produced a slightly more realistic amount of heavy precipitation both in terms of spatial extent as well as the timing compared to the experiments with Kuo scheme or with FSUGSM. This result is not surprising, given that the FSUNRSM has high resolution and the Arakawa-Schubert scheme has certain merits over the Kuo scheme in representing the convective type of precipitation in the Malaysian region. While the overall predictive performance of FSUNRM with Arakawa-Schubert scheme is impressive, it is important to evaluate these model results for a wide range of rainfall thresholds.

To evaluate performance of the model forecasts from these experiments, we have measured the threat and bias scores for all the three days of forecast and presented the results in Figure 5 (a and b). The threat score, which is a measure of the correct placement of the precipitation for a given threshold, was found to be low, with values of less than 0.3 for the first two forecast days on 20th and 21st December 2001 for the Arakawa-Schubert parameterization scheme (Figure 5a). The score for the heavier rainfall threshold of 40 mm day^{-1} was even lower at less than 0.1. This implied that the low intensity rainfall of 2 mm day^{-1} or the heavy precipitation of more than 40 mm day^{-1} was not well predicted by the Arakawa-Schubert scheme. This is in contrast to the results of the Kuo scheme, which was able to predict the placements of the lower threshold of precipitation with moderate success, better than the Arakawa-Schubert scheme. The threat score for the low rainfall intensity of more than 2 mm day^{-1} predicted by the Kuo scheme was comparatively higher than the Arakawa-Schubert scheme. Higher threat score values greater than 0.4 was persistent for the entire forecast period, implying a moderate skill of forecast in terms of the placement of the precipitation. The higher rainfall threshold of more than 40 mm day^{-1} produced high value on Day 0 but deteriorated to less than 0.1 on the subsequent three days, indicating the poor prediction, with increase in time.

Bias is a measure that indicates the accuracy of predicting the precipitation threshold. The Arakawa-Schubert parameterization scheme for both the global and regional models with physical initialization presented a slight under prediction for lighter precipitation (Figure 5b). However, the heavier rainfall of more than 40 mm day^{-1} was poorly predicted by the Arakawa-Schubert scheme from Day 1 to Day 3. The modified Kuo scheme predicted a near perfect forecast for the low intensity precipitation of more than 2 mm day^{-1} on

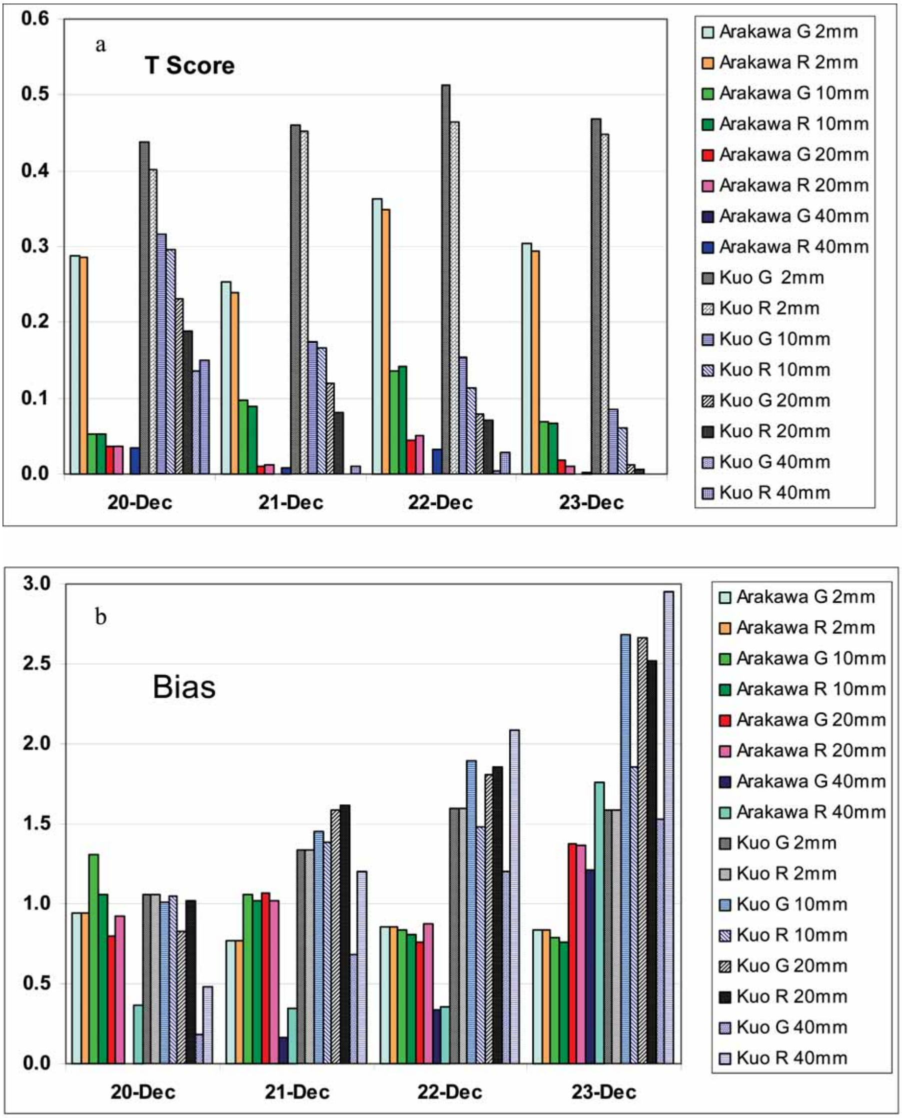

Figure 5. The threat score (a) and bias (b) analyses for the light precipitation threshold (> 2 mm day^{-1}), medium (> 20 mm day^{-1}) and heavier precipitation (> 40 mm day^{-1}). G represents the global and R represents the regional schemes.

Day 0 of forecast, as indicated by the bias analysis. This is a result of the utilization of physical initialization (see Section 2 for details). However, excessively high values of bias on subsequent days imply poor skill of predicting accurate precipitation with increase in forecast times.

Table 1. The RMSE of the selected precipitation thresholds for the forecast simulation.

Cumulus parameterization schemes	Precipitation threshold (mm day^{-1})	Dates			
		20-Dec-01	21-Dec-01	22-Dec-01	23-Dec-01
Arakawa Global	2 mm	0.97	0.88	0.93	0.92
Arakawa Regional	2 mm	0.97	0.88	0.93	0.92
Kuo Global	2 mm	1.03	1.16	1.26	1.26
Kuo Regional	2 mm	1.03	1.16	1.26	1.26
Arakawa Global	10 mm	1.14	1.03	0.92	0.89
Arakawa Regional	10 mm	1.03	1.01	0.90	0.87
Kuo Global	10 mm	1.01	1.20	1.38	1.64
Kuo Regional	10 mm	1.03	1.17	1.22	1.36
Arakawa Global	20 mm	0.89	1.03	0.87	1.17
Arakawa Regional	20 mm	0.96	1.01	0.93	1.17
Kuo Global	20 mm	0.91	1.26	1.35	1.63
Kuo Regional	20 mm	1.01	1.27	1.36	1.59
Arakawa Global	40 mm	0.00	0.41	0.58	1.10
Arakawa Regional	40 mm	0.61	0.59	0.59	1.33
Kuo Global	40 mm	0.43	0.83	1.10	1.24
Kuo Regional	40 mm	0.69	1.10	1.44	1.72

The RMSE of the Kuo parameterization scheme was consistently higher than the Arakawa-Schubert scheme for all of the days predicted, implying errors of prediction being higher than those produced by the Arakawa-Schubert scheme. Ideally an error value of zero indicates perfect positional forecast. The magnitudes of the errors were larger with increase in forecast times (Table 1).

To simplify the assessment, an overall skill that assesses the capability of the models in predicting the precipitation features is calculated as a total skill index. This index is a simple measure that combines the threat score, bias and root mean square error or the standard error of estimate. The total skill index has an optimum value of 2, accumulated from the individual quantity from the bias, threat score and RMSE at 1, 1 and 0, respectively. Table 2 shows the total index for the precipitation thresholds of 2, 10, 20 and 40 mm, respectively. It is evident that the Arakawa-Schubert scheme consistently displayed a higher skill index than the Kuo scheme for the low rainfall thresholds for all the four days. The Kuo scheme excessively overpredicted the high precipitation thresholds. Both the Kuo and Arakawa-Schubert schemes presented poor skills in predicting the high precipitation thresholds. The Arakawa-Schubert scheme tends to underpredict while the Kuo scheme over predicts heavy precipitation. On average, the regional model with Arakawa-Schubert scheme displayed a small deviation of 5 % from a perfect index compared to the high deviations of 40 % and 49 % displayed by the global and regional outputs with Kuo scheme, respectively. The difference between the global forecasts from Arakawa-Schubert and Kuo schemes ranged from 51 % on the Day 1 forecast to 80 % on succeeding days. The difference between the Arakawa-Schubert and Kuo schemes at the regional levels was even more pronounced, with a discrepancy of 56 % on Day 1 to 90 % on Day 2. It can be concluded that the Arakawa-Schubert scheme was approximately 56 % better than the Kuo scheme in predicting all the ranges of precipitation. Improved results of up to 30 % for all the thresholds of precipitation were realized by the regional outputs compared to the global outputs. This is in contrast to the Kuo scheme that presented only a 10 % improvement of the regional forecasts over the global forecasts. The difference ranged from an overprediction of 10 % on Day 1 to an underprediction of 10 % by Day 3. The light rainfall threshold presented the least variation. There was also only a slight improvement of between 2 % to 13 % of the regional over the global forecasts that utilized the Arakawa-Schubert scheme.

Table 2. The total skill index comparison for the global and regional precipitation redictions.

Cumulus parameterization scheme	Precipitation threshold (mm day^{-1})	Dates			
		20-Dec-01	21-Dec-01	22-Dec-01	23-Dec-01
Arakawa Global	2 mm	2.20	1.90	2.15	2.06
Kuo Global	2 mm	2.52	2.96	3.37	3.31
Arakawa Regional	2 mm	2.20	1.89	2.14	2.05
Kuo Regional	2 mm	2.49	2.95	3.33	3.29
Arakawa Global	10 mm	1.19	1.29	1.39	2.17
Kuo Global	10 mm	1.51	2.06	2.73	3.25
Arakawa Regional	10 mm	1.45	1.45	1.40	2.70
Kuo Regional	10 mm	1.80	2.54	3.42	4.37
Arakawa Global	20 mm	1.72	2.10	1.67	2.57
Kuo Global	20 mm	1.96	2.96	3.24	4.30
Arakawa Regional	20 mm	1.91	2.04	1.86	2.54
Kuo Regional	20 mm	2.22	2.97	3.29	4.12
Arakawa Global	40 mm	1.30	1.46	1.42	1.90
Kuo Global	40 mm	1.58	2.28	2.99	3.92
Arakawa Regional	40 mm	1.70	1.62	1.44	2.09
Kuo Regional	40 mm	1.90	2.49	2.96	3.57

4. Conclusion

The capability of the FSUGSM and FSUNRSM models in producing forecasts of rainfall over Peninsular Malaysia during the northeast monsoon has been demonstrated. The models, in general, were able to realistically reproduce the general pattern of the low level threshold of precipitation, but underestimated the prediction of heavier precipitation. Although the overall performance of the model is encouraging, the bias that gauges the accuracy of the average precipitation showed the Kuo scheme consistently over forecasting both the moderate and high precipitation thresholds compared to the Arakawa-Schubert scheme, which exhibited the tendency of underpredicting rainfall from the Day 1 to Day 3 forecasts. Precipitation still remains one of the difficult features to forecast in the equatorial tropics. Although the inclusion of the TRMM satellite data has improved forecasting, especially in the sparse data over the maritime region, there is room for improvement in obtaining accurate rainfall forecasts. Clearly, a better forecast could be achieved if both the satellite data and the rain gauge data were combined and incorporated into the model. Incorporation of a realistic vertical distribution of heating and moistening through a statistically based empirical cumulus parameterization scheme may offer an improved forecast (Rajendran et al., 2004).

Results from this study illustrate the differences arising from the use of modified Kuo and the Arakawa Schubert cumulus parameterizations, and from varying resolution of the models. In general, versions of high-resolution FSUNRSM have shown relatively higher skill in precipitation forecasts for tropical precipitation compared to the global model. However, the competence of these regional models is still low over the tropics. The complex interaction between the sub-grid and grid-scale moist processes of cloud microphysics is still under-represented, resulting in less accurate precipitation forecasts.

Further work is needed in order to assess the sensitivity of model simulations to representation of cumulus convection and model resolution. Reduction in systematic errors and improvement in model cloud physics could make this model a useful tool for tropical research, particularly for skillful precipitation forecasts, which is the benchmark of forecast quality in the tropics.

The results obtained in this study reflect the differences in highest precipitation rates predicted by global and regional models as well as by the different convection schemes. The inferences drawn in this study are substantiated through a careful comparison of results from different experiments in relation to resolution as well as sensitivity to convection parameterization. Rainfall prediction is a tricky issue – while it is expected that the regional models with high resolution are natural choice for better predictive skills, it is also important to have a better representation of sub-grid scale processes like convection that occurs on cloud-resolving scales. A combination of high resolution with a parameterization scheme that can benefit from the increased resolution in a model is desired to improve the rainfall prediction at different thresholds.

Another technique pioneered at Florida State University is the use of multimodel ensemble/superensemble methodology (Krishnamurti et. al, 1999; 2000; 2003) that increased the forecast skill of precipitation. The superensemble precipitation forecast in the equatorial Southeast Asian region produced better results than any single operational forecast models (Mahmud, 2004; Mahmud and Ross, 2005; 2006). However, prediction of very heavy rainfall threshold is still under-forecasted and would improve if member models of higher resolutions with improved physics could be incorporated.

Major issues associated with the current cumulus parameterization problems were reviewed by Arakawa (2004), who suggested the concept of a 'unified cloud parameterization' rather than the narrow concept of the present cumulus parameterization. The cloud-resolving convective parameterization or 'superparameterization' may have the potential for improving rainfall forecasts, as well as the multiple approaches such as the 3-D multiscale modeling framework that can simulate different scales of the GCM.

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SAŽETAK

Prognoza izrazito obilnih kiša u ekvatorijalnoj jugoistočnoj Aziji

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Točnost prognoza monsunskih obilnih kiša u ekvatorijalnom području predstavlja oduvijek izazov za prognostičare. U ovoj studiji su se pokušale prognozirati izrazito obilne oborine nad istočnom centralnom obalom Malezijskog poluotoka pomoću globalnog i regionalnog spektralnog modela sa Sveučilišta na Floridi (FSU). U ovim modelima se ispitivala osjetljivost parametrizirane konvekcije na uspješnost prognoze oborine pomoću dvije različite parametrizacijske sheme za kumulusnu konvekciju (Relaxed Arakawa-Schubert shema i modificirana Kuo shema). Nizak oborinski prag < 2 mm dan^{-1} je pomoću oba modela uspješno prognoziran. Pa ipak, konvektivne sheme nisu u potpunosti točno predvidjele točnu poziciju i količinu oborina kod oborinskog praga > 40 mm dan^{-1}. Daljnja procjena uspješne prognoze je pokazala da je Relaxed Arakawa-Schubert shema mnogo bolji prediktor kiše zbog svojeg malog odstupanja i nižeg korijena srednje kvadratne pogreške (RMSE) u usporedbi s modificiranom Kuo parametrizacijskom shemom.

Ključne riječi: monsunske kiše, ekvatorijalna jugoistočna Azija, globalni i regionalni spektralni modeli, prognoza oborine

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