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Quantitative Precipitation Forecast using MM5 and WRF models for Kelantan River Basin

Wardah, T., Kamil, A.A., Sahol Hamid,A.B., and Maisarah,W.W.I

***Abstract*—**Quantitative precipitation forecast (QPF) from atmospheric model as input to hydrological model in an integrated hydro-meteorological flood forecasting system has been operational in many countries worldwide. High-resolution numerical weather prediction (NWP) models with grid cell sizes between 2 and 14 km have great potential in contributing towards reasonably accurate QPF. In this study the potential of two NWP models to forecast precipitation for a flood-prone area in a tropical region is examined. The precipitation forecasts produced from the Fifth Generation Penn State/NCAR Mesoscale (MM5) and Weather Research and Forecasting (WRF) models are statistically verified with the observed rain in Kelantan River Basin, Malaysia. The statistical verification indicates that the models have performed quite satisfactorily for low and moderate rainfall but not very satisfactory for heavy rainfall.

***Keywords*—**MM5, Numerical weather prediction (NWP), quantitative precipitation forecast (QPF), WRF

I. INTRODUCTION

FLOOD forecasting systems that integrate the hydrological with the atmospheric model are now operational in many areas. The lead time between occurrence of a flood event and warning can be extended by coupling atmospheric and the hydrological models as indicated among others by Jasper *et al.* [5] and Wardah *et al*. [12]. Jasper *et al.* [5] have coupled the grid-based hydrological catchments model with forecast data from five high-resolution numerical weather prediction (NWP) models with grid cell sizes between 2 and 14 km while Wardah *et al*. [12] have developed a QPF using the infrared satellite images combined with NWP model products using a neural network model. Habets *et al.* [4] have used QPF for daily stream flow prediction over the Rhone basin, France. The precipitation forecast is fed to a one-way atmosphere–hydrology coupled model to predict the river flow. A QPF model to forecast flood up to 24 hour in advance, which use both NWP output, rainfall and radiosonde data has been detailed by Kim and Barros [6]. The integrated model appears to be very comprehensive and potentially able to function as a reliable flood forecasting system. Meneguzzo *et al.* [8] experienced that the complexity of handling the high thresholds and rare events is a strong limitation for operational activities using NWP, particularly for flood forecasting. In addition, the rainfall location, magnitude and time depend on how the used numerical model is able to determine the size, scale and the evolution of atmospheric systems involved. Though many studies have been done on the effectiveness of NWP models in producing QPF, several researchers comment that the use of numerical weather prediction models alone do not seem to be able to provide accurate rainfall forecasts at the temporal and spatial resolution required by many hydrologic applications as discussed in Toth *et al.*[11]. Habets *et al.* [4], comment that the potential of NWP rainfall forecast to be used by hydrological models to predict river flow is constraint by the three following types of error: (i) localization of the events, since an error of a few kilometers can lead the precipitation in the wrong watershed; (ii) timing of the events, since the response of the basin depends on previous events and on the timing of the present event; and (iii) precipitation intensity.

Wardah, T., Kamil, A.A., and Sahol Hamid,A.B., are with the Faculty of Civil Engineering, Universiti Teknologi MARA,Shah Alam Malaysia (email: warda053@ salam.edu.my).
Maisarah,W.W.I is with Numerical Weather Prediction Development Section, Malaysian Meteorological Department, Malaysia.

II. MM5 AND WRF MODELS

The theoretical basis for numerical weather prediction is dynamical meteorology, which provides the equations that describe the development processes of the atmosphere and uses numerical approximations to predict the future state of the atmospheric circulation from the knowledge of its present state .The initial variables describe the current state of the atmosphere which represents many different characteristics such as: humidity, temperature, wind velocity, pressure, and other aspects of the region for forecast. Several modelling systems were implemented, global, hemispheric or as limited area models (LAMs). LAMs ran with a higher resolution over a smaller area and took boundary conditions from a larger hemispheric or global model. During the last decades, several regional LAMs have been developed such as the MM4 and later the MM5 [3] and the new WRF model [9], Today, numerical weather prediction is the most widely used prediction system, and can predict future states for up to 10 days.

Malaysian Meteorological Department (MMD) currently uses the Fifth Generation Penn State/NCAR Mesoscale (MM5) and the Weather Research and Forecasting (WRF) for the weather forecasting purposes. NWP model outputs include forecasts for rainfall, humidity, wind speed and a range of other derived variables which may be useful for flood forecasting. With advances in NWP in the recent years as well as an increase in computing power, it is now possible to generate very high resolution rainfall forecast at the catchment scale. However the accuracy of QRF produced by the MMD are still lacking even though significance progress has been made on the technical aspects as described by Low [7]. This study investigates the performance of MM5 and WRF models in forecasting rainfalls in Kelantan River Basin, Malaysia.

The MM5 model used in this study is a non hydrostatic primitive equation model, with versatility to choose the domain region of interest; horizontal resolution; interacting nested domains and with various options to choose parameterization schemes for convection, planetary boundary layer, explicit moisture, radiation and soil processes. The model was designed to have three interactive nested domains with horizontal resolutions at 36, 12 and 4 km with the inner most domain covering the Peninsular Malaysia, Sabah and Sarawak. The WRF model is a mesoscale NWP model, suitable for research and operational forecasting [9]. The currently installed version in the MMD makes use of the ARW (Advanced Research WRF) solver, which is composed of several initialization programs for idealized and real-data simulations, and a numerical integration program. The model was designed to have three interactive nested domains with horizontal resolutions at 36, 12 and 4 km with the inner most domain covering the Peninsular Malaysia, Sabah and Sarawak. This study used the model outputs from the highest spatial resolution of 4 km with initialization time 00 UTC for both NWP models.

III. Methodology

A. Case study of Kelantan River Basin

Kelantan river basin is located in north eastern part of Peninsular Malaysia. The basin has an annual rainfall of about 2700 mm and most of it occurs during the north east monsoon between mid October and mid January. The mean annual temperature is about 27.5^{o}C with mean relative humidity of 81%. In the year 2009, Kelantan received an annual rainfall of 3688.79 mm which is 36.6% more than average annual rainfall. For that particular year, the north east monsoon was reported to have caused flooding which had resulted in the evacuation of 4856 people from the affected area and total deaths of 3 people. Damages of properties worth approximately RM 39 million had been recorded as the impact of the severe monsoon flood at Kelantan [1].

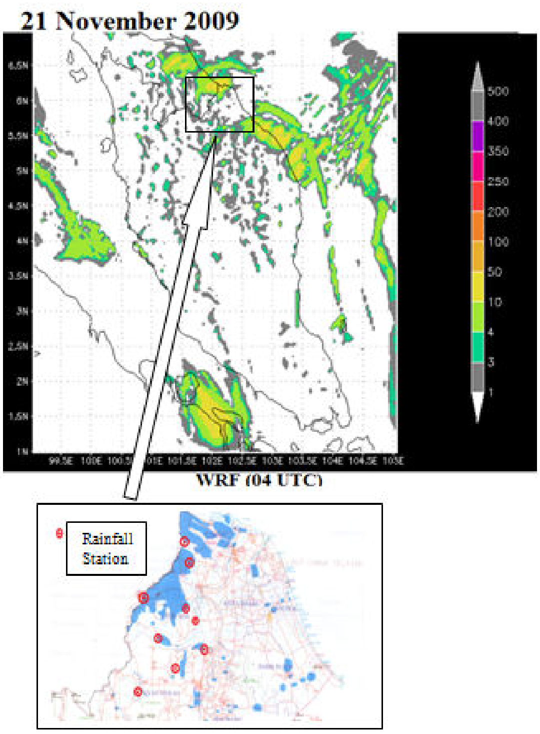


Fig. 1 Kelantan River Basin location and rainfall station

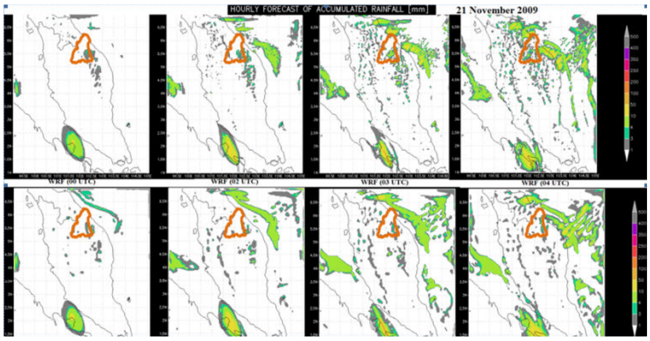


Fig. 2 Displays of hourly forecast of accumulated rainfall over Peninsular Malaysia

B. Datasets Used

The hourly rainfall data, measured in millimeter (mm), was obtained from the Drainage and Irrigation Department. In this study, ground truth data of hourly accumulated precipitation from 9 rain gauges in the flood-prone areas of Kelantan river basin are used for verification of NWP model precipitation forecasts.

Data processing and analysis of the QRF from the NWP models have been carried out using Grid Analysis and Display System (GrADS). Figure 1 shows the location of Kelantan River Basin and rainfall stations involved and Figure 2 shows the display of hourly forecast of accumulated rainfall over Peninsular Malaysia on 21st November, 2009 from the MM5 and WRF models.

IV. Results and Analysis

A. Rainfall Analysis

Rainfall over Kelantan river basin is analysed with three ranges of rainfall thresholds which are 0.1-10 mm h^{-1}(light precipitation),10.1-30 mm h^{-1}(moderate rainfall) and more than 30 mm h^{-1}(heavy rainfall). Figure 3 shows the frequency of rainfall events for threshold value greater than 30 mm h^{-}. An analysis of heavy rainfall events (intensity > 30 mm/hr) recorded at 9 raingauge stations in the Kelantan river basin for year 2009 shows that most of the events occur early morning and early evening as illustrated in Figure 4. The analysis indicate that 78% of the 150 heavy rainfall events that have been recorded are occur between 01:00 and 08:00 LT (local time) and 16:00 and 24:00 LT.

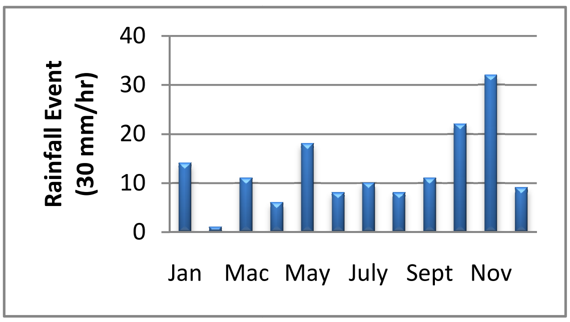


Fig. 3 Frequency distribution of rainfall events for (>30 mm/hr)

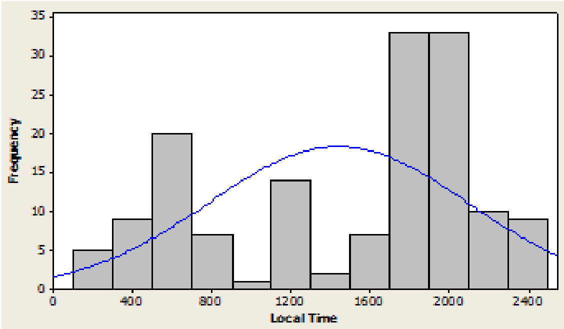


Fig. 4 Timing of intense rain (>30mm/hr)

B. *Statistical verification of MM5 and WRF*

A general observation on the performance of MM5 and WRF can be examined from Figure 5 which illustrates the mean 24-hr rainfall forecasts derived from the models as compared to the accumulated 24-hour rainfall recorded in the river basin. Though the model overestimates the 24-hr rainfall quite notably during Mac, April, May, August and September, they follow almost similar pattern of the mean daily rainfall amount

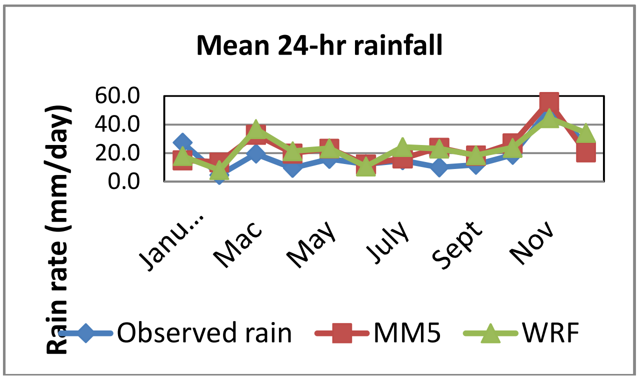
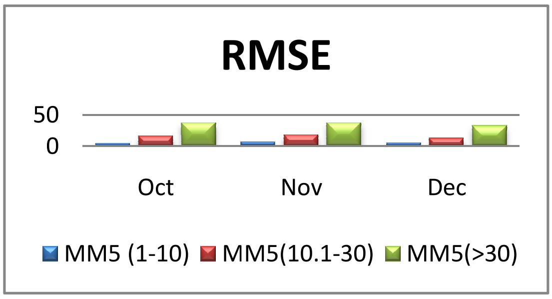


Fig. 5 Mean daily rainfall comparison

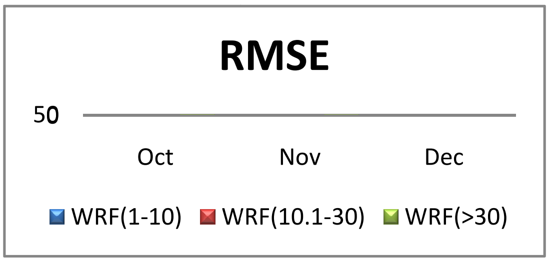
There are various methods available to measure the performance and accuracy of the NWP model products. Among the most common measures for model verification are the Root Mean Square Error (RMSE) Probability of Detection, POD and False Alarm Ratio (FAR) [2,10,13,14]. POD is also known as the hit rate, measures the fraction of observed events that were correctly forecasted whereas FAR gives the fraction of forecast events that were observed to be nonevents and is also known as the probability of false detection.

a) *RMSE for different rainfall thresholds*

Figure 6 illustrates the summary of mean RMSE for all rainfall thresholds. As shown in the figure, the higher rainfall threshold value, the larger the RMSE value. The results indicate the deterioration of forecast quality for high rainfall threshold value.



(a)

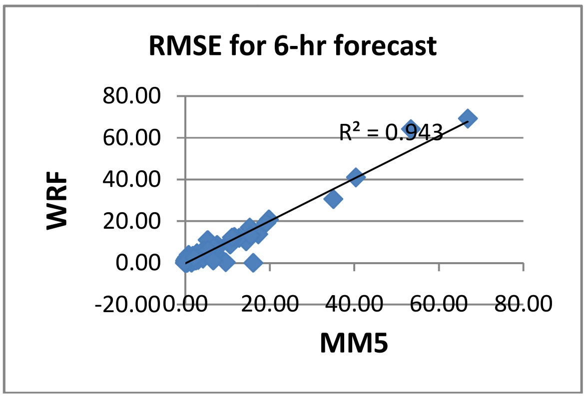


(b)

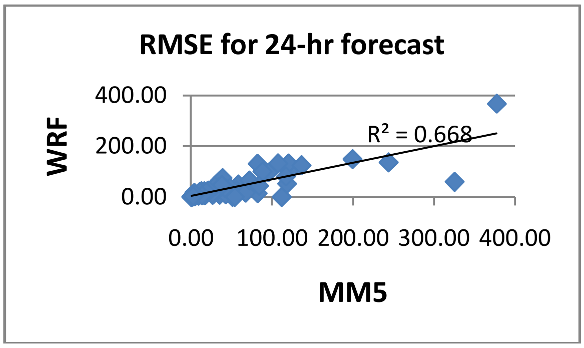
Fig. 6 Comparison of mean RMSE for three rainfall thresholds over Kelantan River Basin for the month of October, November and December 2009 (a) MM5 (b) WRF

b. *Comparison of the two models*

Comparison between the two models, indicate that there is insignificant difference between the two models' performance. Figure 7 (a-d) shows RMSE plotted for 3-hr, 6-hr, 12-hr and 24-hr forecasts for both MM5 and WRF. The graphs show that for longer forecast duration, there will be greater RMSE involved. However it can be seen from the graphs that WRF performed better especially for 12-hr and 24-hr forecast.



(a)



(b)

Fig. 7 RMSE plots for different forecast (a) 6-hr (b) 24-hr

The above results can be further elaborated by the scrutiny of Figure 8 which shows time series RMSE from November to December 2009. Both models show similar pattern of RMSE but the WRF model outperforms the MM5 for several days.

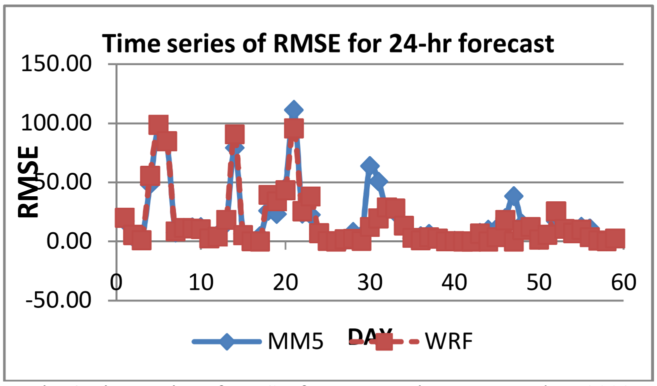
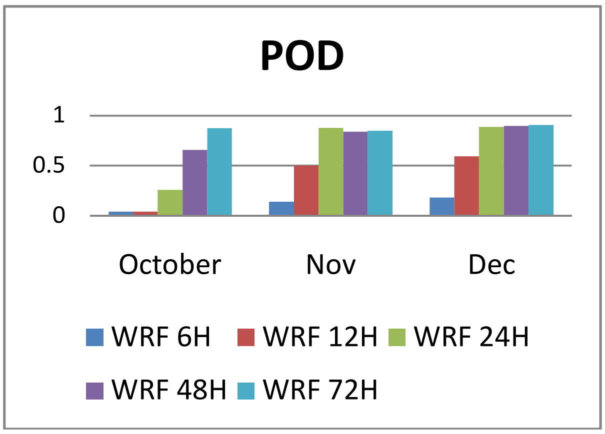
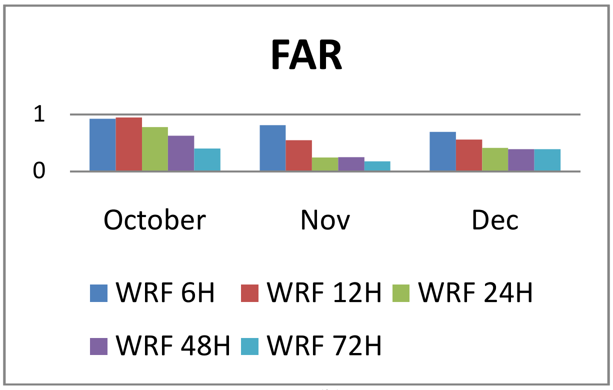


Fig. 8 Time series of RMSE from November to December, 2009

The POD and FAR comparison can be referred from Figure 9 (a) and (b). It can be inferred from the figure that the longer rainfall forecast duration, the higher the probability of detection and the lesser it to be the false alarm ratio. As an example, during 24-hr rainfall forecast there would be higher probability that an event greater or equal to the threshold were correctly forecasted and less probability of being false detection.



(a)



(b)

Fig. 9 (a) Probability of Detection (POD) (b) False Alarm Ratio (FAR)

(b)Rainfall forecast during flood events

The performance of the models is investigated for three major flood events in Kelantan as below:

i) November 5 - 11 (areal average daily rainfall of 234 mm on 5th November)

ii) November 20 – 26 (areal average daily rainfall of 125 mm on 20th November)

iii) December 2 – 6 (areal average daily rainfall of 139 mm on 2nd December)

For the first event, both models forecast well before the flood event, but miss the very heavy rainfall on November 5 as illustrated in Figure 10. During the second flood event, both models produce 24-hr forecast which are closed to the rainfall that had caused the flood with WRF performed slightly better. The third event indicates that the QPF produced by the WRF forecast is much closer than the overestimated value from the MM5

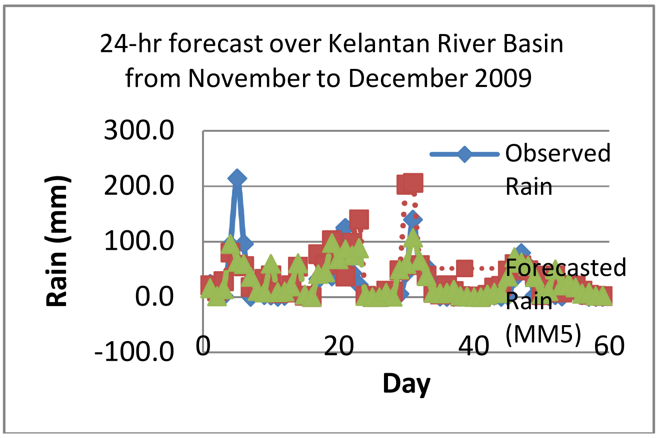


Fig. 10 Time series of 24-hr accumulated rainfall plotted with the forecasts from MM5 and WRF

V. Conclusion And Future Work

In this paper, NWP model precipitation outputs using MM5 and WRF with similar horizontal resolution of 4 km have been validated against gauged rain measurements. The results indicate a very promising potential of the models in producing QPF for flood forecasting purposes. The study will continue by using the NWP model products combined with the infrared and visible geostationary satellite images, in an effort to further improve the developed QPF model by Wardah *et al*. [12] for a more reliable QPF for flood forecasting.

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