ANALYSIS OF THE CYCLONIC VORTEX AND EVALUATION OF THE PERFORMANCE OF THE RADAR INTEGRATED NOWCASTING SYSTEM (RAINS) DURING THE HEAVY RAINFALL EPISODE WHICH CAUSED FLOODING IN PENANG, MALAYSIA ON 5 NOVEMBER 2017

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ABSTRACT

Even though Malaysia is relatively safe from the direct path of tropical cyclones nevertheless the passage of such systems over the neighbouring seas and their tail effect present a unique challenge for forecasters. In rare situations, tropical cyclones had made landfall on Malaysian shores such as Typhoon Vamei in 2001 and Tropical Storm Greg in 1996. Hence it is vital to forecast the severity of the heavy rainfall events associated with low pressure systems to assist the disaster management agencies in decision making. Towards this endeavour, the Malaysian Meteorological Department (MMD) utilises a nowcasting system called Radar Integrated Nowcasting System (RaINS) which uses a combination of radar data and Numerical Weather Prediction (NWP) data. RaINS was adapted from SWIRLS (Short-range Warning of Intense Rainstorms in Localised Systems) developed by the Hong Kong Observatory (HKO) and operationalised in MMD in August 2017. This paper studies the cyclonic vortex and synoptic features during the heavy rainfall event that caused major flooding in Penang, Malaysia on 5 November 2017. This paper also investigates the performance of RaINS in predicting the rain cloud distribution and intensity during that event. It is found that RaINS is capable of forecasting the rain cloud distribution and intensity reasonably well in the very short-term period of 1-3 hours. The forecasts are verified by comparing the RaINS forecast data with observed radar echo.

Keywords: cyclonic vortex, RaINS, NWP, SWIRLS, Penang

1. Introduction

Although it is rare to find tropical cyclones in the Malaysian regions due to its proximity to the equator, it is common to find cyclonic vortices especially during the transition or early phase of the winter monsoon season. This is due to the fact that these cyclonic vortices, either quasi-stationary or migratory , are often found embedded in the monsoon trough (Cheang, 1977) that fluctuates around 2°-7°N during this time of the year. The size of these vortices or the monsoon disturbances are similar to that of meso-scale systems. Lim et al. (1982) showed that the stationary monsoon disturbances are more effective in producing heavy rains than the migratory vortices.

On 4th and 5th of the November 2017, continuous rainfall and strong winds were reported in the state of Penang and parts of Kedah (both states are located over the northwest of Peninsular Malaysia) due to the existence of a quasi-stationary cyclonic vortex in the vicinity. Almost all rain gauge stations located in Penang and parts of the Kedah state showed high amount of rainfall which peaked on the night of 4th November. By the wee hours of 5th November, most parts of Penang Island were inundated by flood water, crippling the land transport communications. As the flood subsided in the subsequent days, seven people were killed, about 3,400 people were evacuated from their homes and economic loss of up to RM300 million (about USD 77 million) were recorded.

The case above shows accurate forecast of these events are crucial for early warning in order to minimise the loss of life and economic losses. The Malaysian Meteorological Department (MMD), the agency responsible for issuing weather forecast and severe weather warning, employs the technique of nowcasting to explicitly predict the evolution of short term precipitation (0-3 hours). The nowcasting tools used by MMD, known as Radar Integrated Nowcasting System (RaINS), was developed based on the modifi-

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cation of the Hong Kong Observatory (HKO) latest nowcasting system known as SWIRLS-2. Similar techniques of blending the radar-based nowcast and high-resolution NWP data as described by Wong *et al.* (2009) were also employed in the RaINS.

In this study, the capabilities and performances of RaINS during the heavy rainfall episode in Penang on the 4th and 5th November is discussed. The brief overview of RaINS is described in Section 2 while Section 3 describes the data used in the study. A brief discussion of the synoptic conditions leading to the heavy rainfall episode is provided in Section 4. In Section 5, the performance of RaINS and the heavy rainfall episode is discussed and finally the summary are conclusions are provided in Section 6.

2. RaINS

The RaINS consists of 2 components namely SWIRLS and NWP blending.

a. SWIRLS

SWIRLS uses the concept of pure advection of radar echoes for short range precipitation forecast. It employs backward semi-Lagrangian scheme to project radar echoes using optical flow velocity. Inverse distance weighted (IDW) interpolation at power 1 and search neigbourhood to the nearest grid is used to interpolate 12 individual stations radar data grid (IDW & How IDW works 2017). Subsequently only the maximum grid value is chosen from the interpolated individual radar data to generate a Malaysian integrated radar grid. An arc-tangent function is employed to map radar data to grayscale image. This step resolves intense individual echoes and eliminates noise (P.Cheung & H.Y. Yeung 2012). Subsequently, radar data undergo further pre-processing prior to optical flow generation which involves Gaussian smoothing. This is to ensure the velocity is smooth. After that the optical flow scheme is used to generate the velocity flow field between the radar input data at -10 minutes and 0 minutes (Andrés Bruhn *et al.,* 2002; Andrés Bruhn *et al.*, 2003; P.Cheung & H.Y. Yeung 2012). Then, a backward semi-Lagrangian advection scheme with a 16-coefficient bi-cubic interpolation which allows rotational motion is used to extrapolate the latest radar reflectivity field up to 3 hours ahead using the velocity flow field (Germann & Zawadzki, 2002).

b. NWP blending

In general, the NWP outputs do not always capture the initial distribution of precipitation well. Therefore the concept of nowcast, employing radar echoes advection to predict the rainfall, is found to have more skill over time scales of several hours compared to NWP. However, over a longer time scales where the larger dynamical flows are better resolved by the NWP, it overtakes the skill of nowcast. In order to have the best of both the NWP and the SWIRLS skills, the SWIRLS is blended with the NWP and the new system is known as RaINS.

First, the bilinear interpolation (Bilinear Interpolation 2017) is used to interpolate WRF reflectivity forecast to the SWIRLS grid. This is followed by linear interpolation in time to convert WRF hourly reflectivity forecasts to 10 minutes intervals. Then a bias correction of intensity is performed on WRF reflectivity forecasts. This is done by assuming the NWP data has the same Weibull Cumulative Probability Distribution (CPDF) function with the radar observation (Wong *et al.,* 2009; Yang *et al.*, 2010; Wang *et al.*, 2015). Subsequently, the WRF and SWIRLS nowcast are blended using a hyperbolic tangent curve weightage given by:

$$w(t) = g \times \alpha \times \frac{(\beta-\alpha)}{2}\left[1 + tanh\left(\gamma(t-9)\right)\right] \tag{1}$$

A 9-member ensemble blended-nowcast is now produced using different weights of SWIRLS and WRF. The optimal weight for the nowcast is chosen using least squares error method from the hindcast of 3 hours ago. Areas without radar coverage or missing radar values will use 100% NWP as their weight. The final Quantitative Precipitation Forecast (QPF) for RaINS is given as:

$$QPF_{RaINS} = \left(1 - w(t)\right) \times QPF_{SWIRLS} + w(t) \times QPF_{WRF} \tag{2}$$

The Marshall-Palmer relationship is then used to convert the final QPF from dBZ to mm/hr for final display.

3. Data

The RaINS nowcast system input consists of NWP maximum vertical dBZ and observed radar data from 12 weather radar stations belonging to MMD. In this case study, only radar data from the Butterworth and Alor Setar stations are used. The radar data is in the form of Constant Plan Position Indicator (CAPPI) at 2-km in dBZ. Each CAPPI grid is interpolated at a constant height of 2 km from 15 sweeps between 0.7° to 32° elevation angle. The observed CAPPI data in each station has a horizontal resolution of 833 m at the range of 300 km which contains 720 x 720 grid points. The CAPPI data is updated in real time every 10 minutes. An integrated radar grid for Alor Setar and Butterworth is produced by combining each of the 2 individual radar station using inverse distance weighting (IDW) as described in Section 2.

The maximum vertical reflectivity data used in this study are produced by the MMD-WRF-ARW version 3.9.1.1 (Skamarock *et al.,* 2008). The forecasts are produced every hour up to 7 days or 137 hours ahead to provide forecast guidance using GFS 0.25° data as boundary condition with 3-way nesting (9 km, 3 km and 1 km). It uses the terrain following hydrostatic pressure ŋ coordinates. The MMD-WRF is configured without any convective parameterisation scheme. The MMD-WRF uses Thompson Scheme

Microphysics, Dudhia Shortwave Scheme and RRTM Longwave Scheme. As for the planetary boundary, the Yonsei University Scheme (YSU) is used.

In addition to radar and NWP data, the hourly observational rainfall data obtained from selected principal meteorological stations operated by MMD are also used (Figure 3) to describe the heavy rainfall event. Six hourly synoptic charts are plotted using reanalysis data from JRA at 850, 500 and 200 hPa levels.

4. Observational analysis

a. Wind analysis

Prior to the flood in Penang, the cyclonic vortex at 850hPa level was first detected in the southern South China Sea at the last week of October 2017 (figure not shown). This vortex was found embedded in the monsoon trough which is in a northeast-southwest (NE-SW) orientation. It remained in a quasi-stationary state until it was perturbed by the presence of Typhoon Damrey as it entered the western coast of the Philippines and the vicinity of South China Sea on 1st November 2017 (figure not shown). The vortex continued to track westwards on 2nd November (Figure 1a) and is located in the northeastern states of Peninsular Malaysia. This vortex became stronger and more organised. A glimpse at the 500-hPa wind flow showed the vortex extending up to this level (figure not shown) as a result of strong downstream divergence above the vortex (Figure 1b). On the 3rd of November, the vortex remained in the northeastern part of Peninsular Malaysia until it started to move to the northwestern coast of Peninsular Malaysia and remained anchored over the Penang Island for almost 30 hours starting from 18Z 03 November 2017 until 06Z 05 November 2017 (Figure 2a). The upper level divergence persisted from 3rd of November until 5 November (Figure 1b & 2b).

b. Rainfall variations

Associated with movement of the vortex to the northeast coast of Peninsular Malaysia, heavy rainfall was recorded first in Kuantan at around 11Z 02 November 2017 (1900 LST) (Figure 4a). The heavy rainfall seemed to move progressively to the north in tandem with the movement of the vortex. As the vortex deepened and moved to the northwestern coast of Peninsular Malaysia, widespread continuous rains were found at the edge of the vortex as shown in the rainfall recorded in the west coast stations (Figure 4c). Closer to the vortex core, heavier rainfall was recorded. All the three principal stations in Penang recorded maximum rainfall which exceeded 30mm/hour. It is interesting to note that two stations located in the mainland Penang state showed two maxima as opposed to only one maximum observed in the island station. The two maxima exhibited strong diurnal characteristic and influence of the land-sea breeze even in the presence of the cyclonic vortex. By 5 November, the vortex moved slightly southeastward. Rainfall maxima were observed in Lubok Merbau station (Figure 4d) while no rainfall was recorded in Penang. The cyclonic vortex stayed over Penang for almost 30 hours and the total amount of rainfall for 48 hours in Butterworth and Prai station exceeded their monthly means, while in Bayan Lepas, it almost reached its monthly mean.

5. Performance of RaINS

The RaINS's performance is verified objectively using two skill scores, that is, the Probability of Detection (POD) and False Alarm Rate (FAR). The POD measures the fraction of nowcast grid greater than 10 dBZ in agreement with the observed radar grid taken as ground truth. Meanwhile, the FAR gives the fraction of nowcast grid forecast to be more than 10 dBZ but not consistent with the observed radar grid. The contingency table (Table 1) and equations (3) explain these indices in a concise manner. Details of the method can be obtained from http://www.cawcr.gov.au/projects/verification/ .

$$\left.\begin{aligned} \mathrm{POD} &= \frac{\mathrm{HITS}}{\mathrm{HITS+MISS}} \\ \mathrm{FAR} &= \frac{\mathrm{FALSE_{ALARMS}}}{\mathrm{FALSE_{ALARMS}} + \mathrm{HITS}} \end{aligned}\right\} \tag{3}$$

Figure 5 summarizes the POD and FAR of SWIRLS and RaINS nowcast from 18 LST 3 November to 16 LST 5 November 2017. The verification domain is a square region from 99.5-106°E and 0.5-7.25°N (Peninsular Malaysia domain) which uses data from 8 radar stations. It shows that SWIRLS have a useful period of 140 minutes beyond which it gives more false alarms than correct forecasts while RaINS is observed to have a slightly longer useful period of 160 minutes. This implies that the blending of NWP forecast into SWIRLS has extended the useful nowcast range in this case. Figure 6 qualitatively compares the average radar observation with the average nowcast of up to 3 hours from SWIRLS and RaINS. In general, the observation and nowcast agree with the exception of the false alarm region (overestimate) in the northern part of the interior of Peninsular Malaysia.

On verifying the RaINS over regional scale, a smaller domain bounded by 99.5-102.5°E and 3.5-7.25°N under the coverage of 2 radar stations were created. A better skill

TABLE 1 Contingency table

		OBSERVED RADAR GRID	
		YES	NO
RaINS Grid	YES	HITS	FALSE ALARM
	NO	MISS	CORRECT NEGATIVES

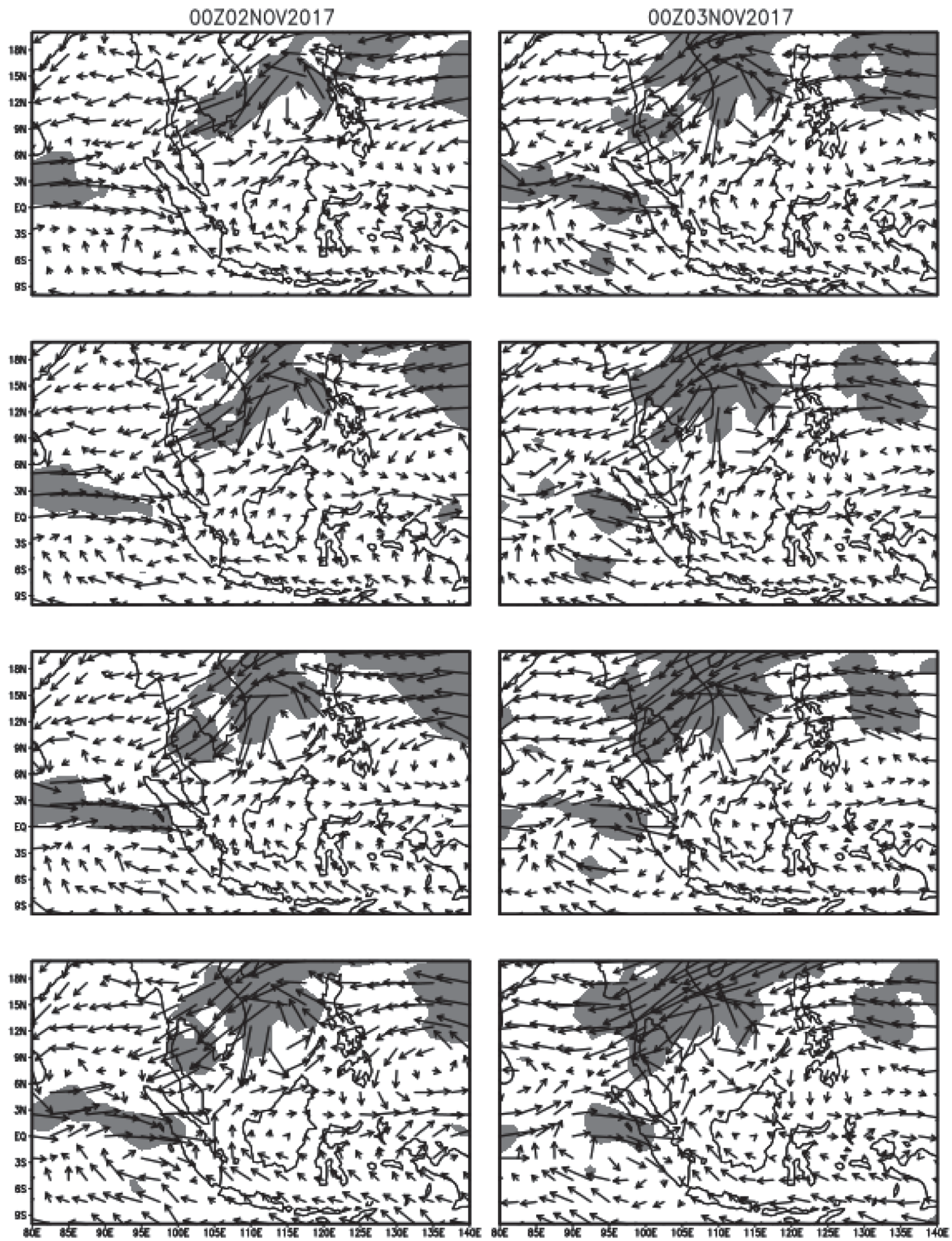

FIG. 1a. Wind analysis at 850hPa. Left panel, top to bottom, 00Z-18Z 02 Nov 2017. Right panel, top to bottom, 00Z-18Z 03 Nov 2017. Shaded area indicates wind exceeds 10 m/s.

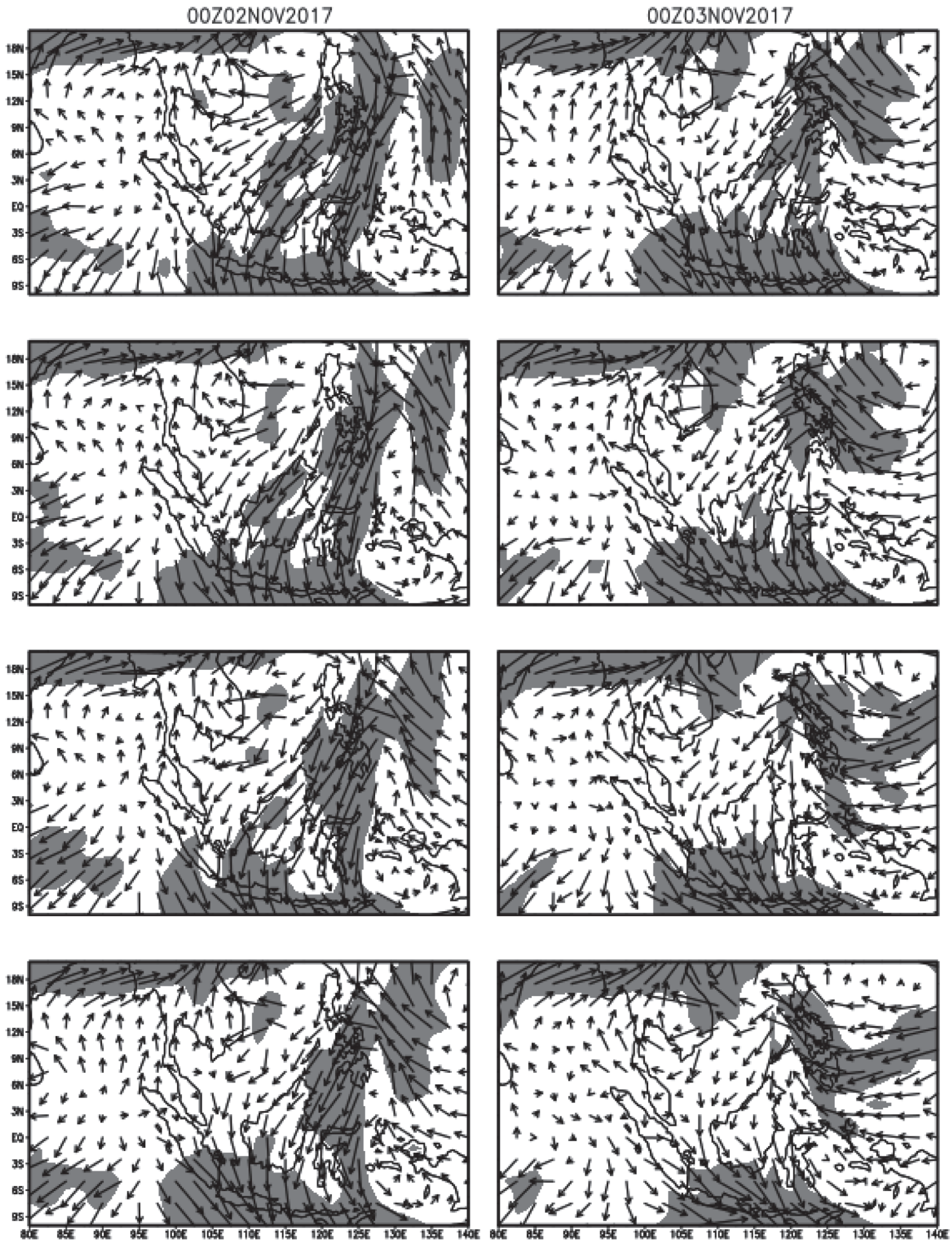

Fig. 1b. Wind analysis at 200hPa. Left panel, top to bottom, 00Z-18Z 02 Nov 2017. Right panel, top to bottom, 00Z-18Z 03 Nov 2017. Shaded area indicates wind exceeds 10 m/s.

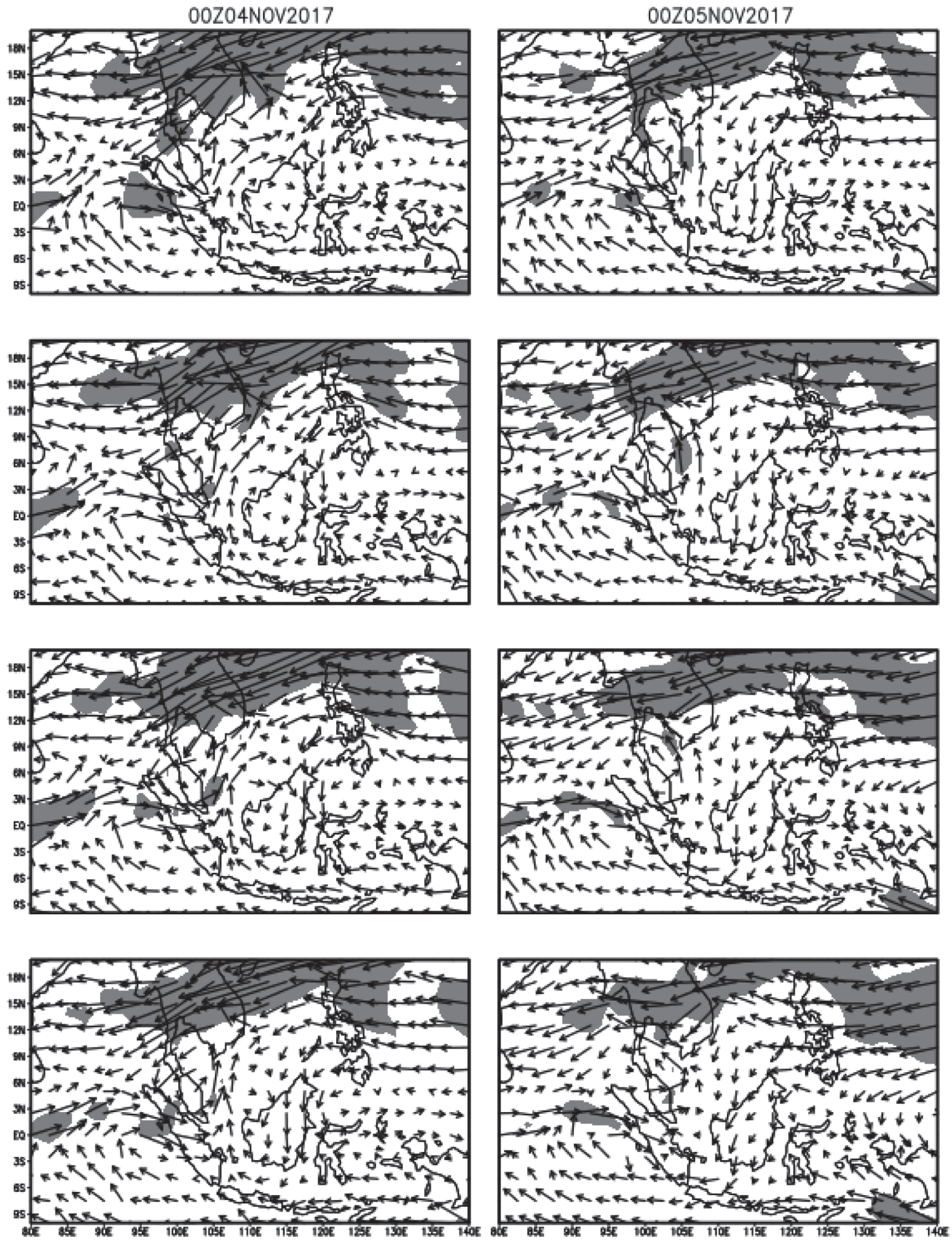

FIG. 2a. Wind analysis at 850hPa. Left panel, top to bottom, 00Z-18Z 04 Nov 2017. Right panel, top to bottom, 00Z-18Z 05 Nov 2017. Shaded area indicates wind exceeds 10 m/s.

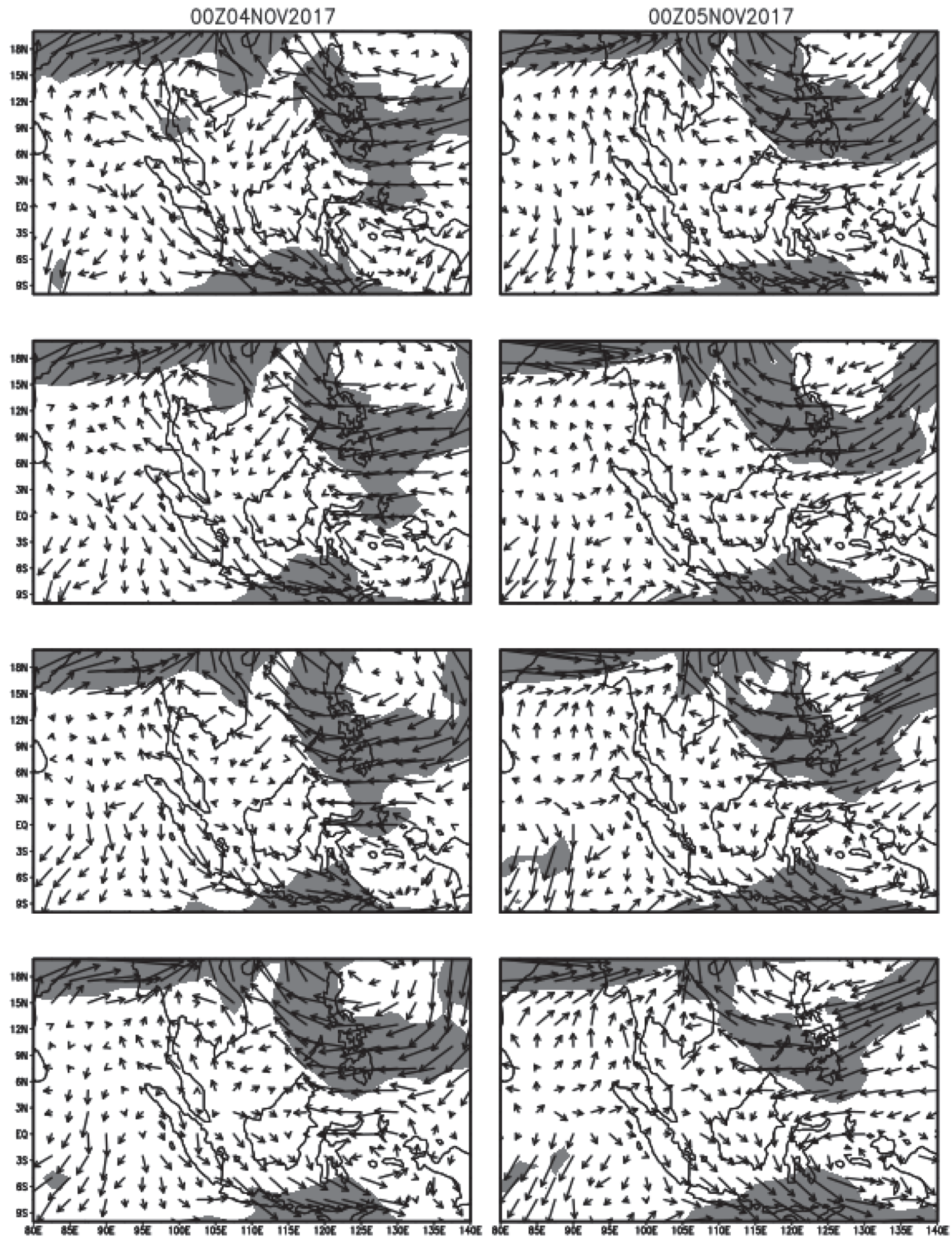

FIG. 2b. Wind analysis at 200hPa. Left panel, top to bottom, 00Z-18Z 01 Nov 2017. Right panel, top to bottom, 00Z-18Z 02 Nov 2017. Shaded area indicates wind exceeds 10 m/s.

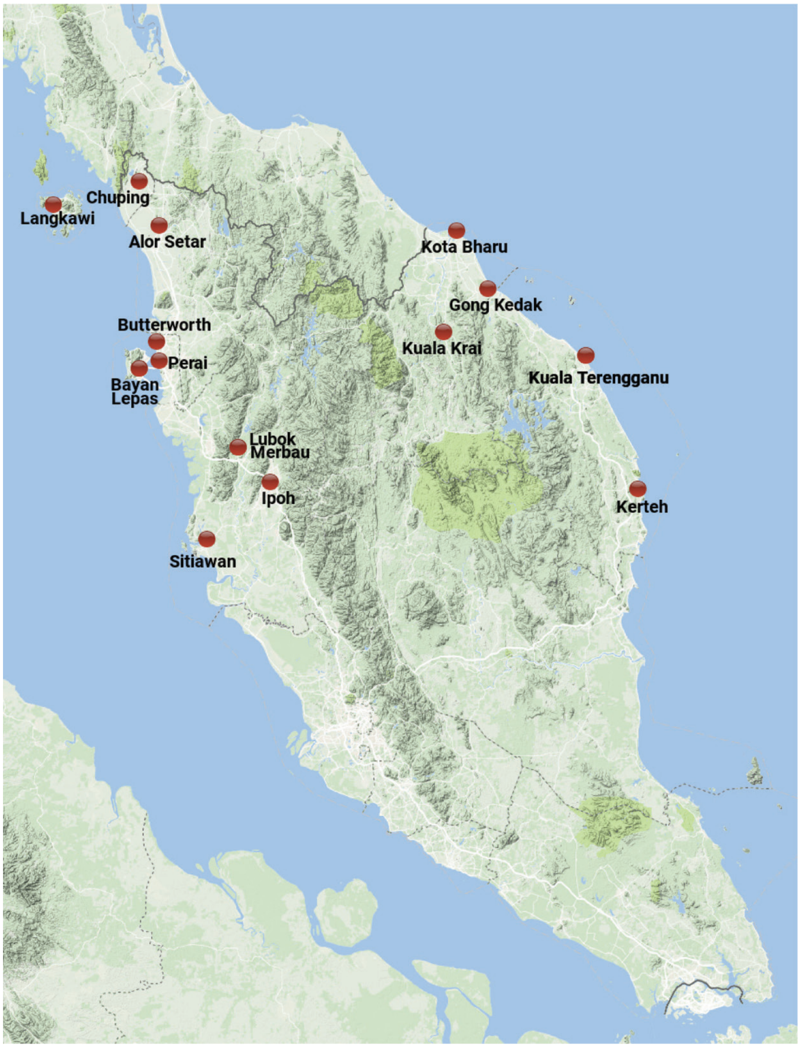

FIG. 3. Location of the Principal Meteorological Stations in Peninsular Malaysia used in this study.

score is achieved closer to the cyclonic vortex (Figure 7). This is because of lesser spatial error in the smaller domain. To investigate the temporal performance of the RaINS, the verification process is divided into three timelines to capture the initial, mature and decaying stages of the storm. The drop in the skill scores in the initial and decaying stages shows RaINS is less skillful during this period while there is almost no drop in the skill scores in the mature stage (Figure 8). This is because of RaINS algorithm assume persistency to determine the weight for the next nowcast. Nonetheless the skill scores in all three timelines are reasonably good for operational purpose (Figure 9).

6. Concluding remarks

The cyclonic vortex that brought heavy rainfall to Penang originated from a stationary vortex embedded in the monsoon trough since late October. It was perturbed by the existence of Typhoon Damrey in the South China Sea-Indochina Peninsula region. As it tracked westwards, it first caused heavy rainfall to the northeast coast of Peninsular Malaysia. As it anchored over Penang for about 30 hours, it brought a long rainy period to the northwestern states of Peninsular Malaysia. Closer to the vortex centre, heavy rainfall were found over the mainland of Penang with two maxima that showed distinct diurnal characteristics.

RaINS performances during this storm was investigated. Overall the RaINS captured the storm very well. However there are several weaknesses in the RaINS that needed to be improved. This is because RaINS tends to have a poorer skill score over a large spatial domain and during the initial and decaying stages of the storm, while it has a very good skill in the smaller domain and when the storm is in the mature stage.

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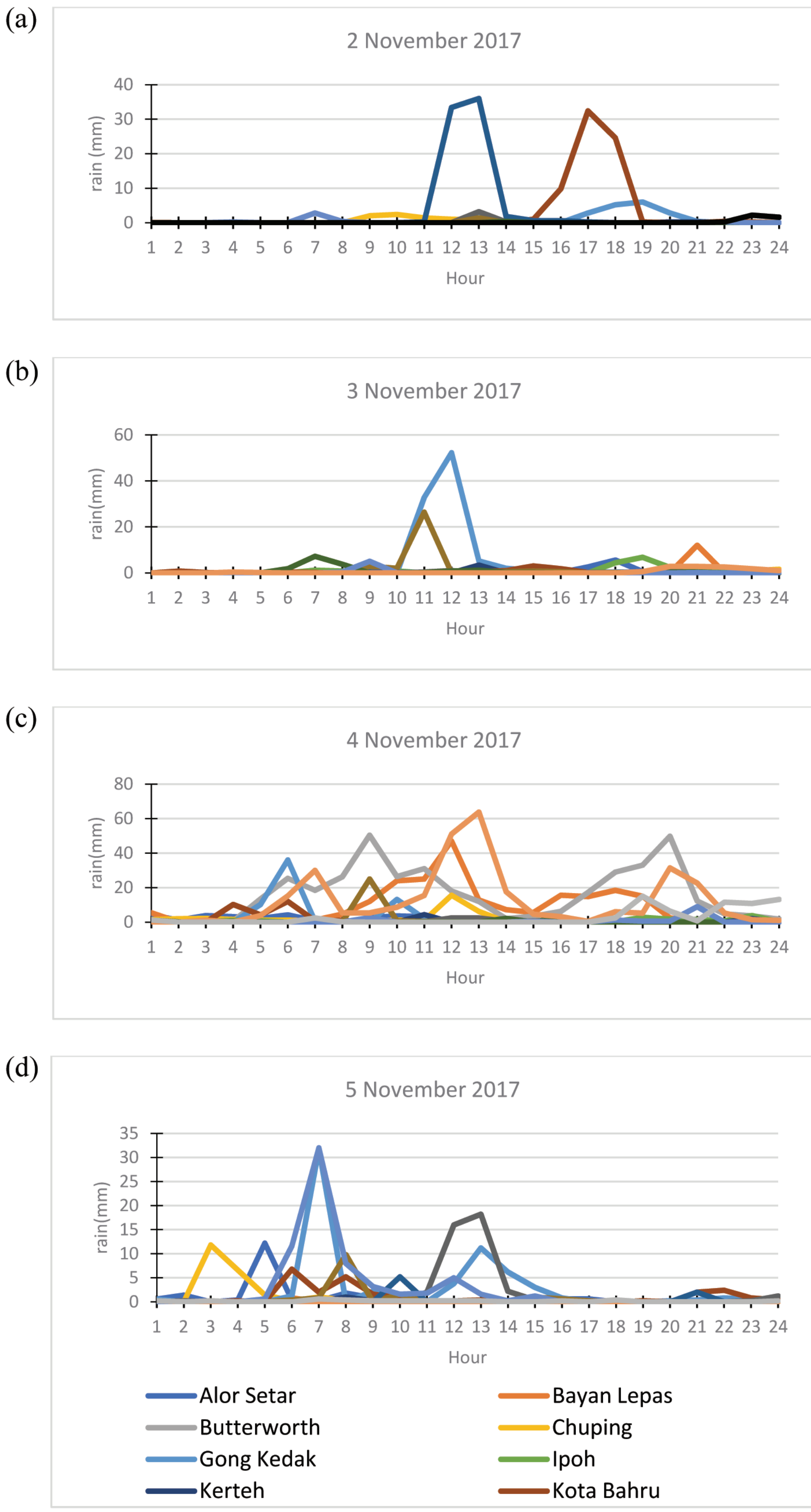

FIG. 4. Rainfall variations at selected station.

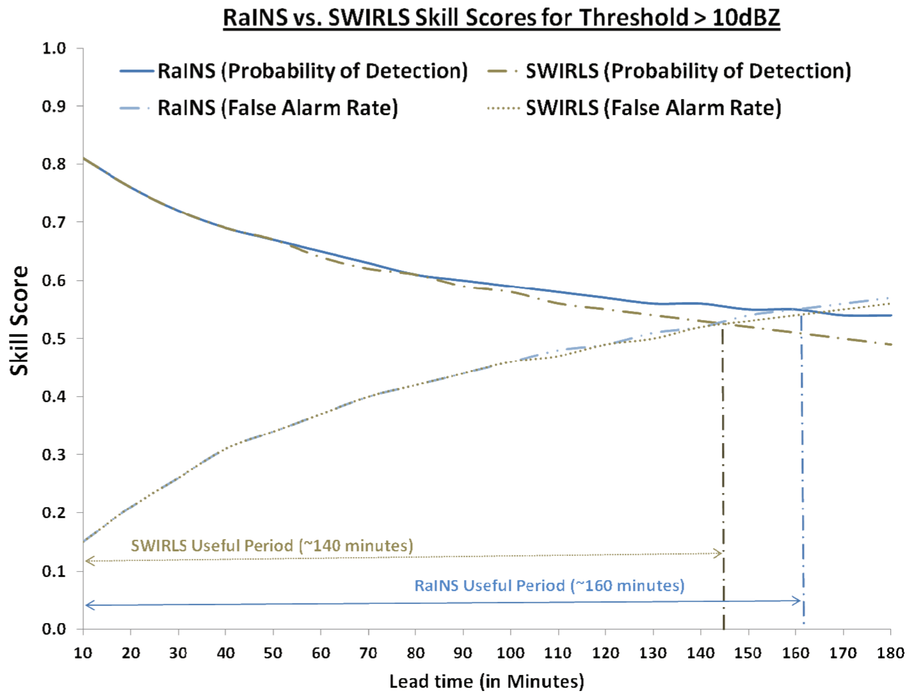

FIG. 5. RaINS versus SWIRLS verification results

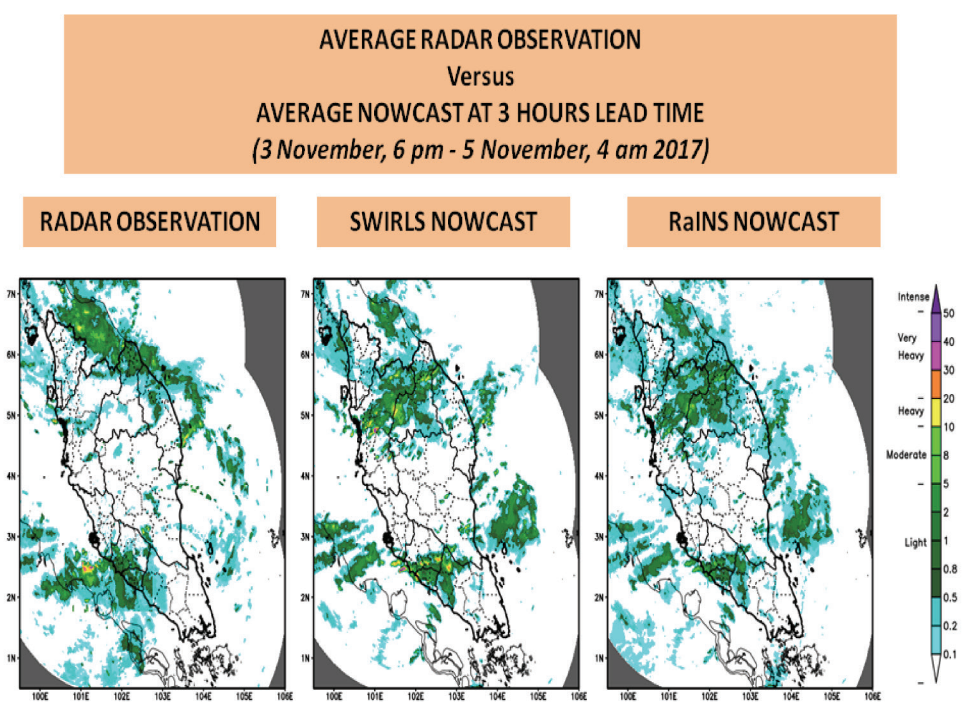

FIG. 6. Average of Radar Observation, SWIRLS and RaINS nowcast

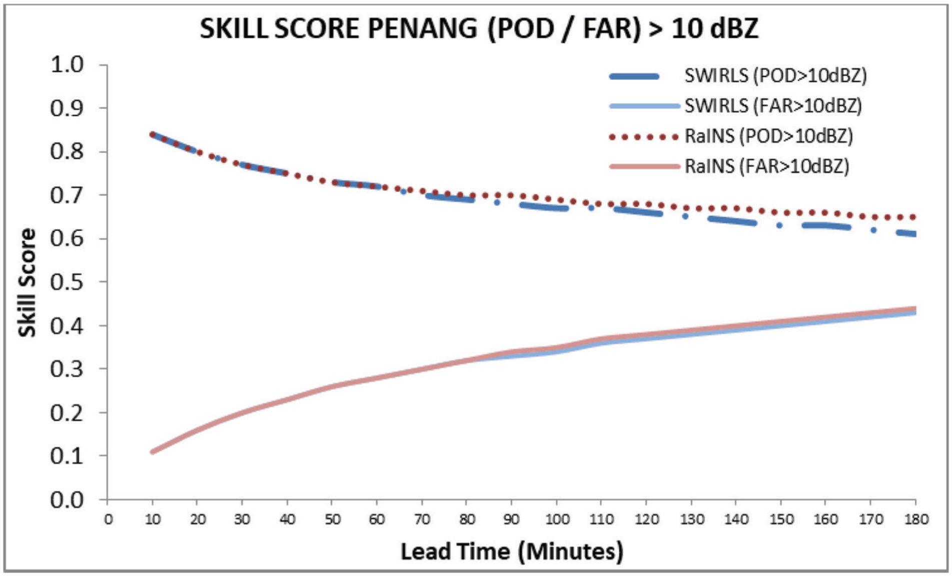

FIG. 7. Regional scale skill score

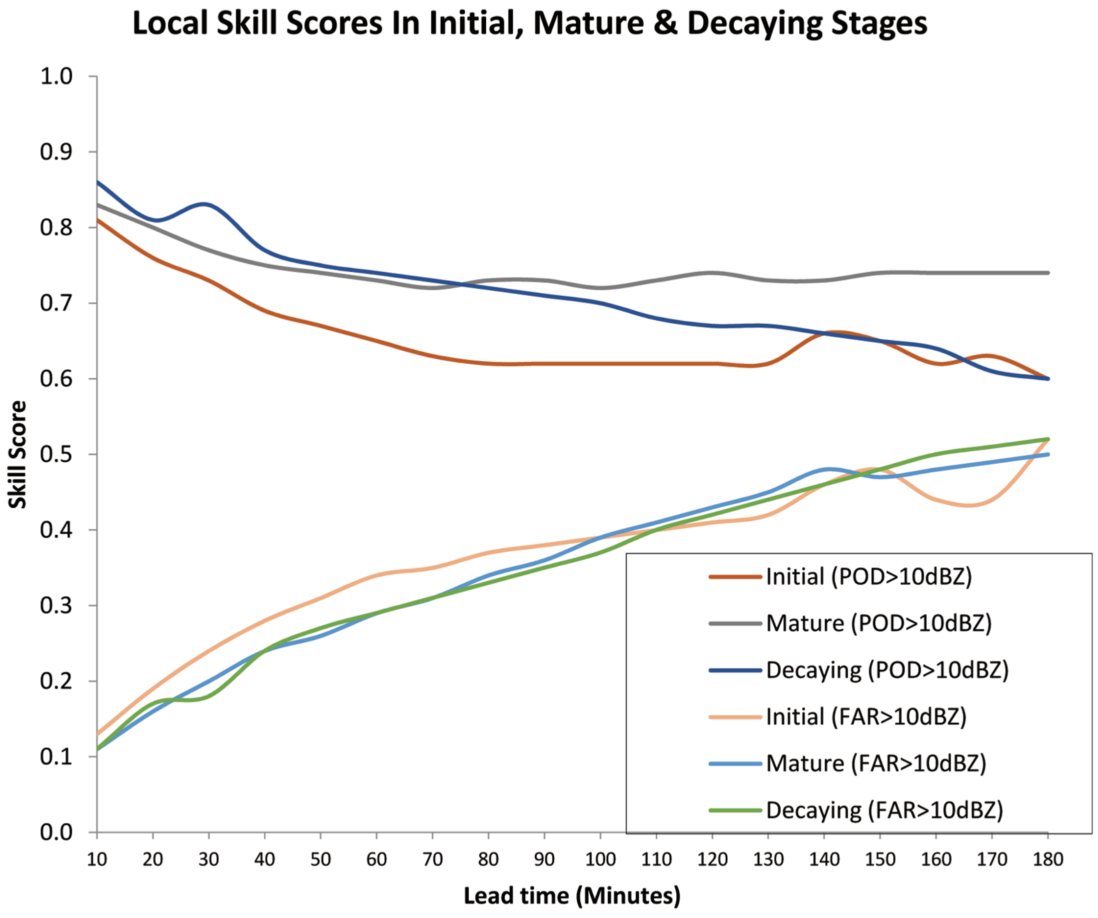

FIG. 8. Temporal scale skill scores

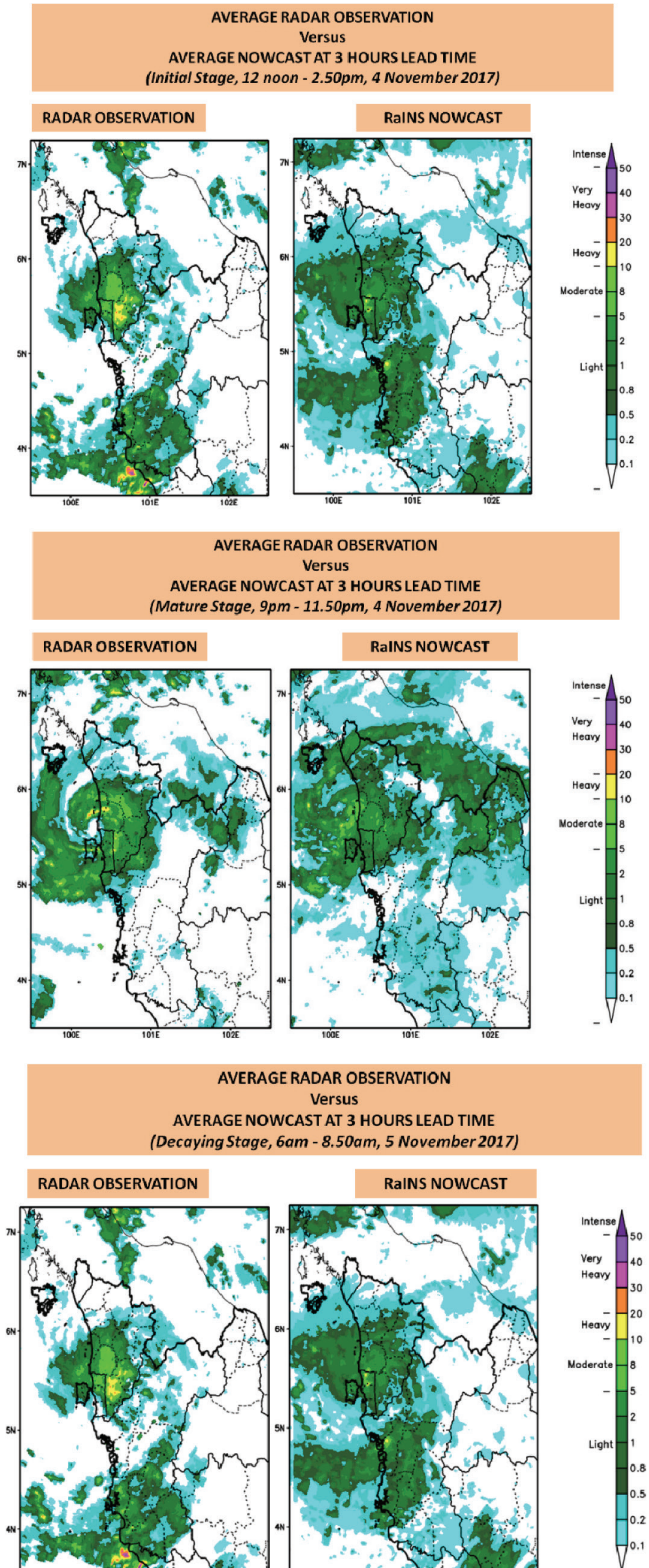

FIG. 9. Average of Radar Observation vs. RaINS nowcast according the stages of storm.

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