Numerical Modeling of Extreme Marine Meteorological Events in Malaysia

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ABSTRACT

The paper described the implementation of the 5th generation mesoscale model (MM5) of Pennsylvania State University and National Center of Atmospheric Research at the Climate and Ocean Analysis Laboratory, National University of Malaysia. The capability of this limited area model in Malaysia region is demonstrated based on the simulations of two extreme cases which effected the country. The cases selected are the storm effected the east coast of Peninsular in December 2004 and the rare near-equatorial typhoon Vamei, which occurred in December 2001. It is shown that the model can simulate these events to a reasonable accuracy. The simulated 3-days accumulated rainfall for the 2004 storm case compares well with the observation in term of rainfall amount as well as the location of storm center. The reproduced synoptic wind patterns during the episode also compare favorably to the National Center of Environmental Prediction final analyses product. Using the grid analysis nudging algorithm in the first model domain, MM5 reproduced the evolution of typhoon Vamei accurately in the inner domain of 15 km resolution. Both the strength and the storm track of the system is reasonably simulated. The hydrometeor characteristic of the simulated typhoon is also shown to have close proximity to the visible satellite imagery.

ABSTRAK

Kertas kerja ini menghuraikan perlaksanaan model atmosfera mesoskala generasi ke-5 (MM5) Pennsylvania State University (PSU) dan National Center of Atmospheric Research (NCAR) oleh Makmal Analisis Iklim dan Lautan (MAIL) di Universiti Kebangsaan Malaysia. Keupayaan model rantauan ini unruk kegunaan di kawasan Malaysia didemostrasikan melalui simulasi dua kes cuaca ekstrim yang melanda negara ini. Kes-kes yang dipilih ini adalah kes ribut yang melanda pantai timur Semenanjung Malaysia pada Disember 2004 dan kes taufan Vamei yang berlaku pada Disember 2001. Model MM5 boleh mensimulasikan peristiwa-peristiwa ini dengan kejituan yang *berpatutan. Hujan kumulatif 3 hari simulasi bagi ribut 2004 adalah setanding dengan data cerapan dari segi nilai jumlah hujan serta pusat ribut tersebut. Corak angin sinoptik yang disimulasikan adalah setanding dengan produk analisis National Center of Environmental Prediction (NCEP). Dengan menggunakan algoritma tolakan bergrid untuk domain pertama, MM5 mensimulasikan evolusi taufan Vamei secara tepat dalam domain dalaman yang beresolusi 15 km. Kedua-dua kekuatan serta jejakan ribut dapat disimulasikan dengan minasabah. Ciri-ciri hidrometeor taufan simulasi adalah juga setanding dengan imej satelit.*

Keywords: 5th generation mesoscale model (MM5); typhoon Vamei; Malaysia

Introduction

Numerical modeling provides an effective tool in the study of important physical processes associated with various marine meteorological phenomenon. The approach is remarkably important especially in the tropical maritime continent where the scarcity of observation stations hinder understanding of these phenomenon. It is hence important to increase the capability of local scientists in Malaysia to develop relevant skills in modeling and understanding these physical processes, which usually associated with disastrous meteorological events.

The east coast of Peninsular Malaysia is prompt to such events. During the northeast monsoon, which usually commence in November and retreat in the coming March, prevailing low level northeasterlies bring large amount of precipitation to the coastal area (Cheang 1987). Frequently, the northeasterlies interacted with synoptic disturbances (Chang et al. 2003) formed within the near equatorial trough and catalyzed the intensification of the system. The associated torrential precipitation (usually in the magnitude > 200 mm) causes disastrous flood in the coastal area as well as result in perturbation in the hydrodynamic characteristic near shore (waves, storm surge (Loy et al. 2006) which affected the near shore ecosystems as well as the economic activities.

In the National University Malaysia, Climate and Ocean Analysis Laboratory (COAL) have adopted the 5th generation mesoscale model (MM5) developed by the Pennsylvania State University (PSU) and National Center of Atmospheric Research (NCAR) to facilitate research on the marine meteorological processes. To date, our modeling effort focuses mainly on the east coast of Peninsular Malaysia. In this paper, it is of our intention to describe our current implementation of the PSU/NCAR MM5 modeling system and to demonstrate the capabilities of this model in simulating two different extreme cases affected the east coast Peninsular Malaysia. The first case is associated with a propagating Borneo vortex (Chang et al. 2005) which interacted with the local topography (Juneng & Tangang 2006) and brought torrential rainfall to the east coast area. The later is the famous equatorial typhoon which form just about 1.5°N of the equator and affected the southern tips of Johor in December 2001. The model and its implementation is discussed in the next section. Section 3 discussed the result of the simulation of the two selected extreme cases. Section 4 summarized the paper.

The 5th Generation Mesoscale Model

A Brief Overview

The PSU/NCAR MM5 implemented in COAL is the version 3.6 codes. The model is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate mesoscale atmospheric circulation. Its characteristic include (i) a multiple-nest capability, (ii) multitasking capability on shared- and distributed-memory machines, (iii) a four-dimensional data-assimilation capability, and (iv) more physics options. The model is supported by several pre- and post- processing programs (i.e TERRAIN, REGRID, LITTLE_R, INTERPF and INTERPB) which are referred to collectively as the PSU/NCAR MM5 modeling system.

Since MM5 is a regional model, it requires an initial condition as well as lateral boundary condition to run. To produce lateral boundary condition for a model run, one needs gridded data to cover the entire time period that the model is integrated. Terrestrial and isobaric meteorological data are horizontally interpolated (programs TERRAIN and REGRID) from a latitude-longitude mesh to a variable high-resolution domain on either a Mercator, Lambert conformal, or polar stereographic projection. The interpolated first guess field can then be enhanced (LITTLE_R) with conventional observations from the network of surface and upper air stations to provide mesoscale information. Program INTERPF performs the vertical interpolation from pressure levels to the sigma coordinate system of MM5. Sigma surfaces near the ground closely follow the terrain, and the higher-level sigma surfaces tend to approximate isobaric surfaces.

The main prognostic variables in the model are pressure perturbation *p*ô, three velocity components (*u, v, w*), temperature *T* and specific humidity *q*. Model equations are written in flux form and solved numerically using Arakawa B grid. Leapfrog time integration scheme with time splitting technique is used in model integration. In time splitting technique, the slowly varying terms are integrated in time with longer time step and the terms giving rise to fast moving gravity waves are integrated with shorter time step. The most useful feature of PSU/NCAR MM5 model is its flexibility in the sense that many options are user specified. The model can be used in various applications by simply setting these parameters to appropriate values. These include number of nests, type of convection, PBL, radiation parameterization schemes and many other options. Another advantage of this modeling system is that it is a state-of-the-art model and is under continuous development and well documented. A detailed description of the model is provided by Grell et al. (1995).

Hardware and Compilation Configuration

Depending on the resolution setup, running PSU/NCAR MM5 codes could take a good amount of computing resources. However the integration of Massive Parallel Processing (MPP) options into the MM5 version 2.8 in 1998 has enabled the codes to run on distributed memory parallel machines such as the Beowulf clusters. The PSU/NCAR MM5/MPP modeling system can now be implemented in a more cost effective way. At the Climate and Ocean Analysis Laboratory, National University of Malaysia, a Linux based SMP Beowulf cluster (christened Phyton) has been developed to run the MM5/MPP codes. The system consists of 8 AMD Athlon MP 2400++ processors on 4 SMP nodes connected by 100 Mbps Fast Ethernet. The inter-process programming environment is carried out with MPICH, a public implementation of Massage Passing Interface (MPI), which is freely available. Portland group of compilers were used to compile the MM5/MPP codes since it consists of a fully functional Fortran 90 compiler and supports Cray-style pointer which is essential to compile the MM5/MPP codes. The MM5 codes were originally developed on big-endian processors and running the codes on little-endian processors requires the compilers to provide the ï *byteswapio* option. The Portland Group of compilers provide all the necessary features.

Simulation Result

Synoptic Overview of the Event

9-11 December 2004 case

The first extreme case considered in this paper occurred during 9-11 December 2004. The event was associated with the development of mesoscale convective system that may have a complex interaction with the local topography structure. Satellite imageries show that thick cloud bands were located over the east of Peninsular Malaysia as well as the eastern coast of northern Sumatra. The Tropical Rainfall Measuring Mission (TRMM) 72-hour accumulated precipitation product indicates more than 600 mm of rain fell in regions along the east coast of the Peninsular Malaysia with a maximum peak occurred in the vicinity of 103ºE 4ºN (Figure 1). Also, over the eastern coast of northern Sumatra, moderate accumulated rainfall amount of 200-250 mm had been recorded.

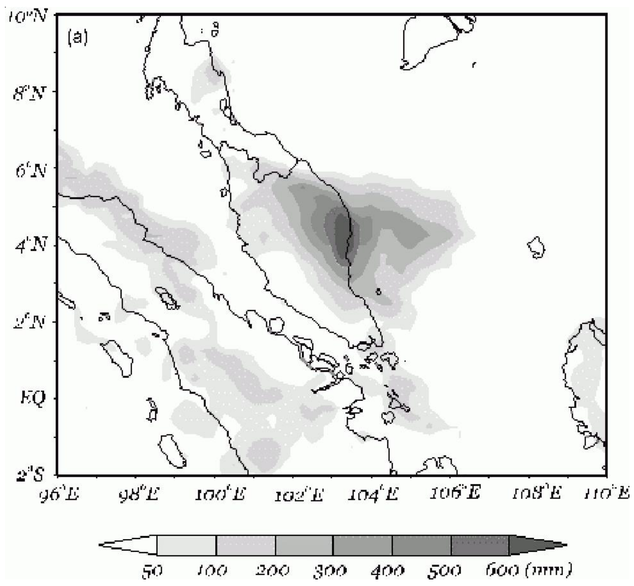

FIGURE 1: The Spatial Distribution of the 72 hours Accumulated Rainfall (mm) from 00 UTC 09/12/2004 to 00 UTC 12/12/2004

Prior to the event initialization, the lower troposphere levels were dominated by persistently strong northeasterly cold surge wind with speed exceeding ~18 m/s (Figure 2). The northeasterly monsoon flow is usually associated with heavy rainfall in the east coast of Peninsular Malaysia during northeast monsoon season due to its transport of moist air as it crosses the South China Sea (SCS) before reaching the coastal area (Cheang 1987). Also noted is the existence of a remarkable tropical depression located east of the coast at 00 UTC 09 December 2004 (Figure 2a). The formation of this depression took place around 05 December 2004 in the vicinity of western Borneo (not shown). Due to the formation nature of this disturbance, it is usually referred to as Borneo vortex (Chang et al. 2005). A Borneo vortex is a common low-level quasi-stationary feature during the northeast monsoon period. However, the depression in this case tracked westward and head to the coastal region of Peninsular Malaysia. At 00 UTC 10 December, close to the maximum recorded rainfall period, the vortex was located inland with the center slightly south of the area of rainfall maxima (Figure 2b).

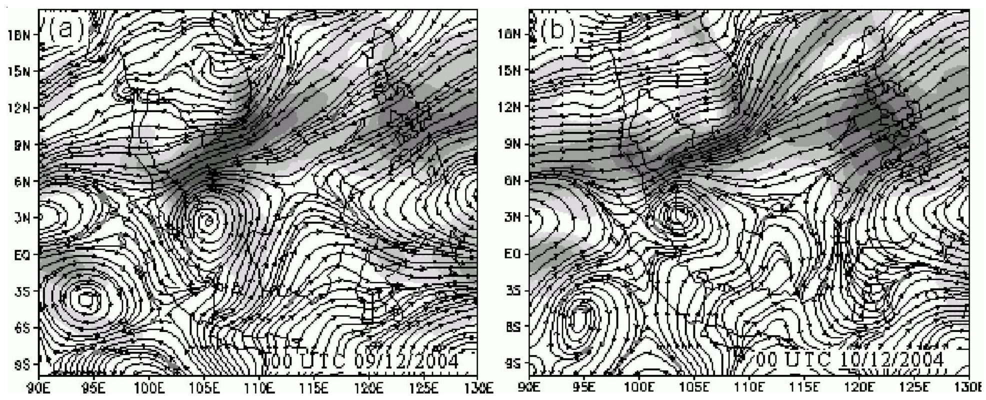

FIGURE 2: 850 hPa Streamline and the Quantities (shaded, interval 2 ms^{-1}) from the NCEP Global Analyses Valid at (a) 0000 UTC 09 December 2004, (b) 0000 UTC 10 December 2004

Typhoon Vamei 2001

Begining 19 December 2001, a cold surge developed rapidly over the SCS while the Borneo vortex was established at the northwest coast of Borneo approximately 3°N. The vortex moved southwestward along the Borneo coast toward the equator and by 21 December 2001, it drifted off the coast to be located over the narrow part of the southern SCS i.e. the region between western Borneo and eastern Peninsular Malaysia. Chang et al. (2003) argued that the vortex persisted in the area for several days while the strong northeasterly surge was slightly deflected to the northwest of the vortex causing the cross-equatorial flow to wrap around the vortex resulting in a spinning up of a rapid counter-clockwise circulation. At 0600 UTC 25 December a weak LLCC disturbance was located approximately 200 nm east of Singapore and by 0600 UTC 26 December it moved closer to about 130 nm northeast of Singapore. By late on the 26 December, the disturbance began to strengthen rapidly and at 0000 UTC 27 December JWTC issued their first warning on system by upgrading it to a 45-kts tropical storm located approximately 75 nm east of Singapore (Joint Typhoon Warning Center, 2002) (Figure 3a). By 0600UTC 27 December, the center was located at about 35 nm northeast of Singapore and the JMA upgraded it to a 40-kts tropical storm. At the same time JWTC, based on the observed wind speed of 75 kts from US naval ship located within the eyewall, upgraded the storm to a typhoon Joint Typhoon Warning Center, 2002). Another ship reported wind gusts up to 105 kts within the southern portion of the eyewall.

Typhoon Vamei made a landfall in the southeastern tip of the Peninsular Malaysia at about 0830 UTC 27 December and by 1200 UTC the storm was in land at about 20 nm north of Singapore (Figure 3b). The storm weakened rapidly after it made a landfall and continued its westward propagation and by 0000 UTC 28 December it was over the Sumatra Island (Figure 3c). Both JWTC and JMA downgraded the system to a 30-kts tropical depression. JWTC issued a final warning on the depression with the center still located over Sumatra. By 1800 UTC 29 December, the remnants of Vamei was already off the Sumatra Island into the eastern Indian Ocean where it continued its westward propgation until 1800 UTC 31 December when JWTC made their final warning on the system.

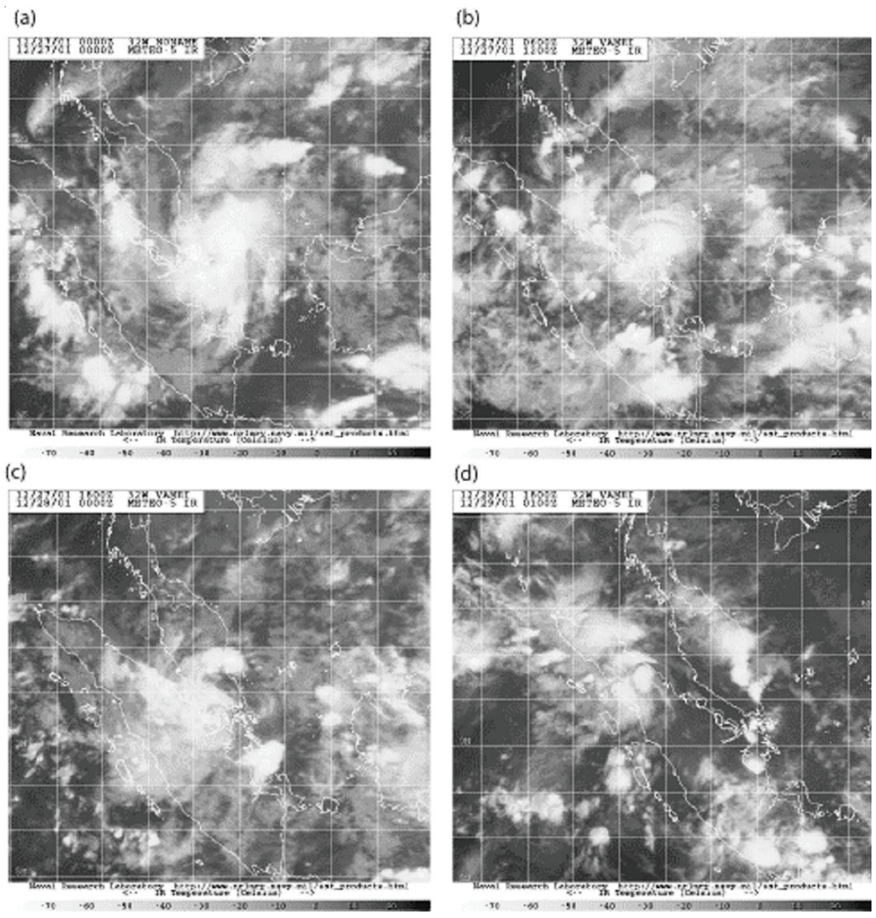

FIGURE 3: SSM/I Imegery of IR Temperature Taken at (a) 0830 UTC 27 December, (b) 1200 UTC 27 December, (c) 00 UTC 28 December and (d) 1800 UTC 29 December.

The system brought heavy rainfall as it crossed the southern tip of the Peninsular Malaysia into the Starit of Malacca and Sumatra. Several hours before it made a landfall, the southeastern part of the Peninsular Malaysia received substaintial amount of rain as indicated by the TRMM rain rate snapshot (Figure 4a). Substaintial rainfall was also indicated over a region in SCS i.e. north of 5^{o}N. During 1200 UTC 28 December, when the system was over the Sumatra Island i.e. at approximately 3^{o}N and 100^{o}E, heavy precipitation was indicated in the vicinity (Figure 4b). Heavy precipitation was also indicated in northern part of the Peninsular Malaysia.

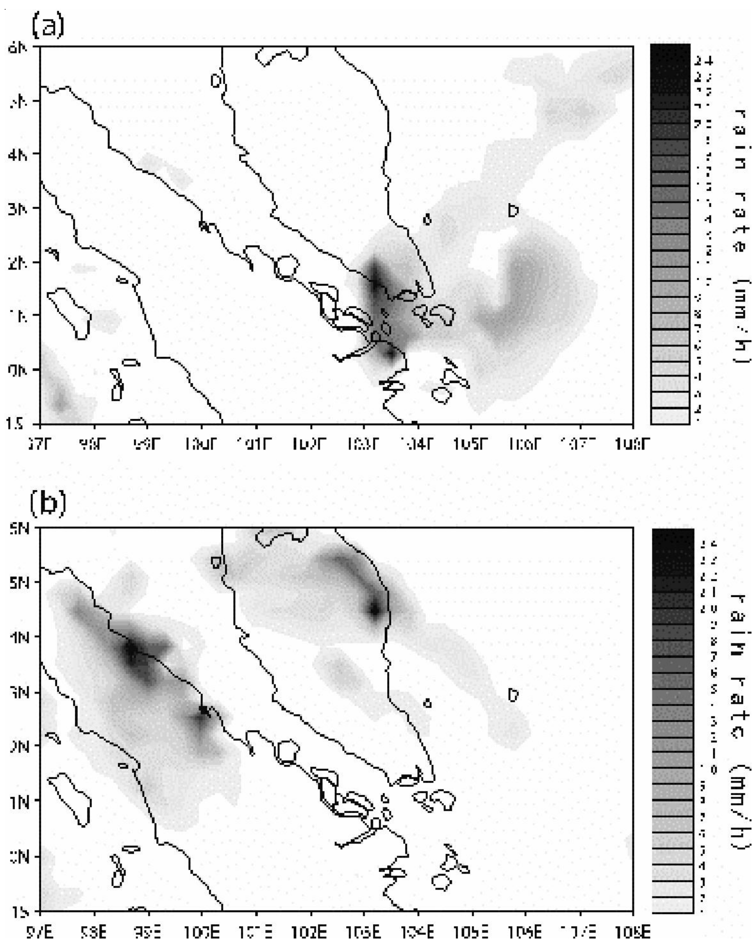

FIGURE 4: Surface Rainrate (unit in mm/hour) at (a) 0000 UTC - 0300 UTC 27 December 2001 and (b) 1200 UTC -ï 1500 UTC 27 December 2001 from TRMM 3 Hourly Product

MM5 Simulation Result and Discussion

9-11 December 2004 Case

The model configuration for simulating this extreme rainfall case is summarized in Table 1. Attention was focused on the capability of the model to simulate accurate characteristic of the precipitation. The model reasonably simulated the spatial pattern of the 72-hr accumulated (from 00 UTC 09/12/2004 to 00 UTC 12/12/2004) rainfall during the episode, with correct location of the rainfall maxima in the eastern coast of Peninsular Malaysia at ~4ºN latitude (Figure 5a). The simulated total values of the 72-hr accumulated rainfall also compared favorably to the TRMM estimation. The simulation reproduced about 70% of the observed rainfall. It is noted that the band of moderate rainfall in the east coast of northern Sumatera also simulated well by the model. However, the magnitude of simulated rainfall in the region was slightly higher than the TRMM estimation (Figure 1b).

TABLE 1: PSU/NCAR MM5 Setup in the Simulation of December 2004 Storm Case

Description	Options
Horizontal Resolution	Domain 1: 45 km / Domain 2: 15 km
Vertical Resolution	23 half sigma levels
Radiation parameterization	CCM2 schemes
PBL parameterization	Blackadar schemes
Cumulus parameterization	Betts-Miller schemes
Microphysics	Schulz schemes
Lateral boundary updating interval	6 hours

The simulation also reproduced the low-level monsoon circulation reasonably with the formation of low-level cyclonic vortex in the vicinity of South China Sea (SCS) at ~105ºE after 12 hours simulation. The remarkably strong surface northeasterlies to the northwest quadrant of the vortex was correctly simulated despite stronger wind intensity. At 24-hr model forecast, the low level vortex was already located at about ~104ºE indicating rapid westward propagation toward the coastal region. The surface wind intensity to the north of the vortex strengthens and resulting in enhanced advection of moisture air toward the coastal region (Figure 5b).

It is instructive and crucial to investigate the associated moist convective process, in order to understand the factor contributing to the notable rainfall amount near the vicinity of rainfall maxima shown in Figure 1b. Figure 6 shows considerable precipitable water over the off-coast region collocated with the northwest quadrant of the low-level vortex center at 00 UTC 10/12/2004. In addition, an impinging of moist air from east and northeast directions passing through the area of convectively unstable air is also apparent in Figure 6. Note also that there are moisture flux vectors joining the easterlies water vapor fluxes from southeast quadrant of the cyclonic center passing through area of high potential instability (~10ºC). It is essential to investigate the origin of moisture

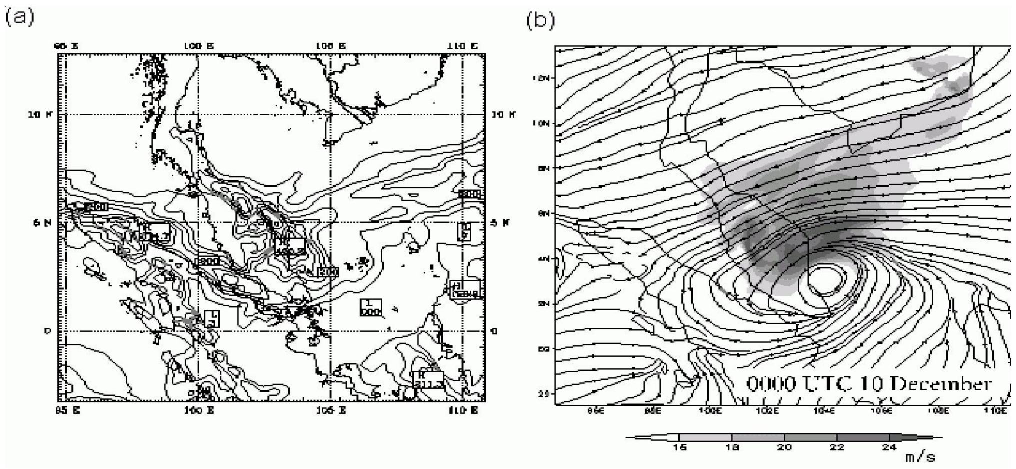

FIGURE 5: (a) 72 h (00 UTC 09/12/2004 ï 00 UTC 12/12/2004) Accumulated Rainfall and (b) 850 hPa Streamline (valid at 00 UTC 10/12/2004) and the Quantities (shaded, interval 2 ms^{-1}) simulated by the PSU/NCAR MM5

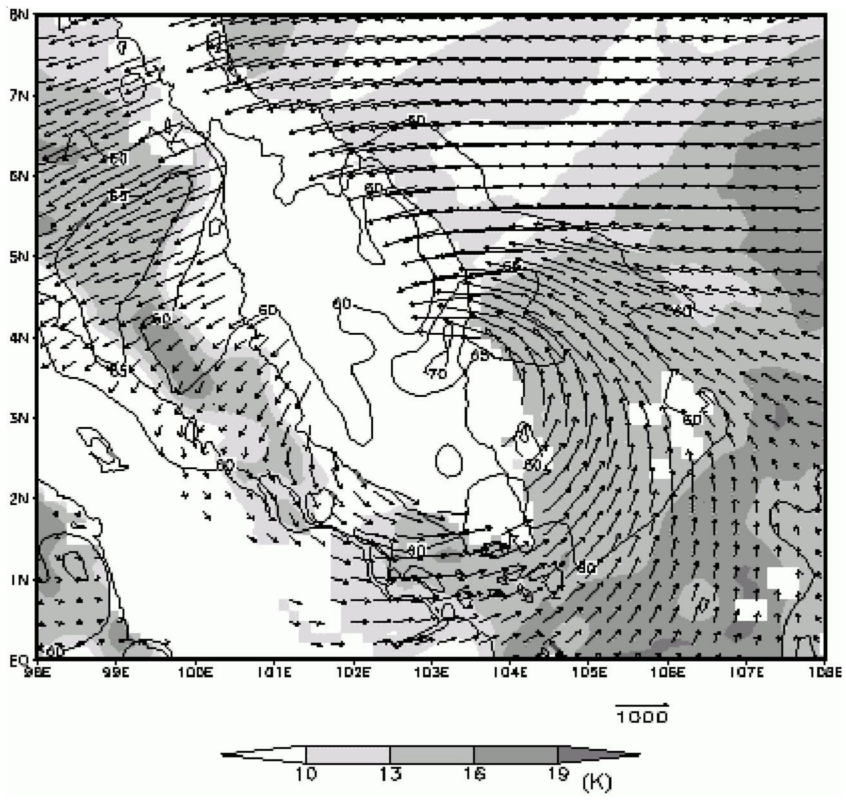

FIGURE 6: Vertically Integrated (1000 hPa ï 300 hPa) Water Vapor Flux (Vectors), the Convective Instability Computed from the Difference in Equivalent Potential Temperature Between the 1000 hPa and 500 hPa Levels (shades: interval 3 K) and the Precipitable Water Greater than 60 mm (contours) from the PSU/NCAR MM5 Simulation

transport associated with the atmospheric circulation during the episode. Figure 7 depicts the 24-hr backward trajectories of air parcel arriving at 103.2°; 3.9°N at various altitudes computed from the MM5 simulated meteorological fields. It is noticed that there were two origins of air parcel arriving at the area of maximum rainfall. At lower altitudes, the air parcels travel from the northeast direction while at higher altitudes of > 2000 m the air parcels were mainly from the southeast regions and traveled a curve trajectories passing through the area of intense potential instability before heading towards the coastal region. This further contributed to the enhanced moisture convergence along the coastal area where the maximum accumulated rainfall was recorded. All the trajectories traveled at low levels and the strong convection took place when the air parcel approaching the vortex center before landfall, indicating that the vorticity advection was likely to be the main governing factor for the moist air convection near the vicinity of the rainfall maxima area. It is suggested that there was a strong association between the low-level vortex and the extreme precipitation episode with vigorous moist convection in the wind shear region to the northwest quadrant of the vortex center. It is appropriate to conclude that the positioning of the vortex was an important factor in determining the location of the precipitation maxima and presumably its strength determined the intensity of the accumulated rainfall.

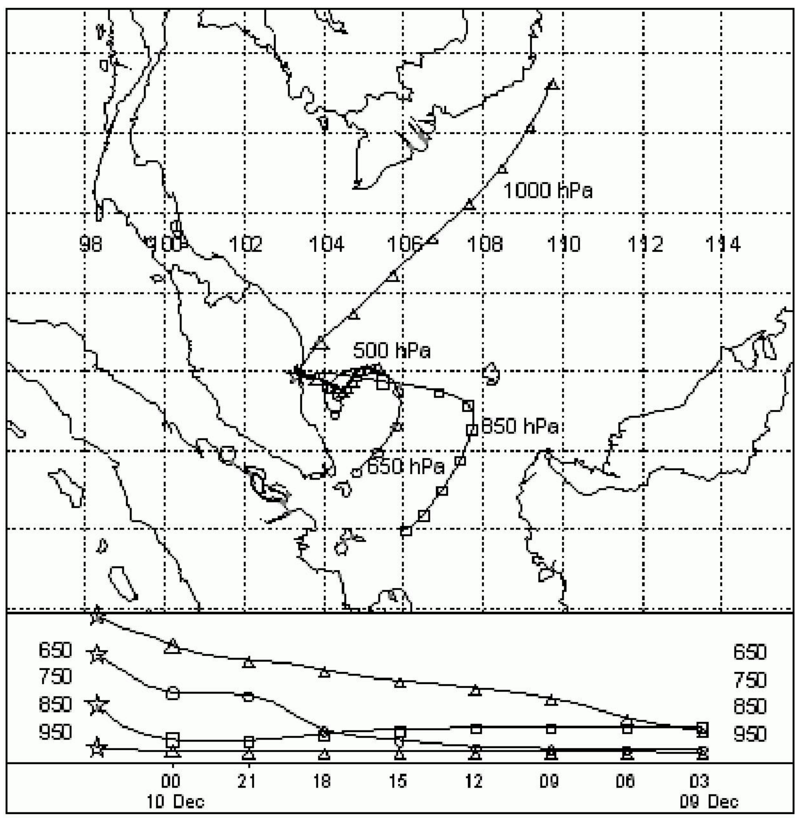

FIGURE 7: 24 h Backward Trajectories of Air Parcels Released at 0300 UTC 10 December 2004 at 100 m, 2000 m and 4200 m and 6000 m Above Ground Level. The Bottom Panel Indicates the Altitude Along Time of the Air Parcels

Typhoon Vamei

The model configuration to simulate typhoon Vamei is summarized in Table 2. The first domain which is of 45 km resolution is used for grid analysis purpose to provide the consistent boundary forcings to the child domain of 15 km grids. A comparison between the predicted and observed storm track (Figure 8) and intensity (Figure 9) revealed a reasonable accuracy of the simulation, especially considering that no initial bogus vortex is inserted during the model initialization. However the track appear to be less well consistent with the observation during the initialization period and it is consistently slightly northward of the JTWCôs best track database. This is partly due to fact that the vortex is weak during the model initialization. Given that no extra observation data assimilation in the first domain grid analysis nudging, there are some uncertainties to the location and strength of the incipient cyclone when the simulation starts. As the simulated and observed cyclone intensified, the error became progressively small, less than 60 km at 0600 UTC 27 2001 before the landfall of the system at the eastern coast Johor.

TABLE 2: PSU/NCAR MM5 Setup in the Simulation of Typhoon Vamei 2001

Description	Options
Horizontal Resolution	Domain 1: 45 km / Domain 2: 15 km
Vertical Resolution	23 half sigma levels
Radiation parameterization	CCM2 schemes
PBL parameterization	Blackadar schemes
Cumulus parameterization	Kain-Fritch schemes
Microsphysics	Schulz schemes
Lateral boundary updating interval	12 hours

Figure 9 compares the simulated typhoon intensity to the observed. Both simulation and observation are in general agreement but differ in details during the 36-hours model integration. Initially, the deepening of the storm is less prominent in the model simulation. The simulated cyclone deepened to the minimum central pressure intensity (981 hPa) around 15-h into model integration time which is about 3 hours behind that of the observed. After reaching the maximum intensity, the system approached the land in the next 3-4 hours and filled up rapidly. The simulated intensity appear to be well corresponded to the observation during the weakening phase of the system. Consistent with the less well simulated storm track, this is partly due to the fact that there are some uncertainties in the initial condition that cannot be resolved without a proper and sophisticated observational data assimilation treatment. The comparison between simulated and the observed maximum sustained wind suggest a more consistent and accurate reproduction of the surface wind characteristic.

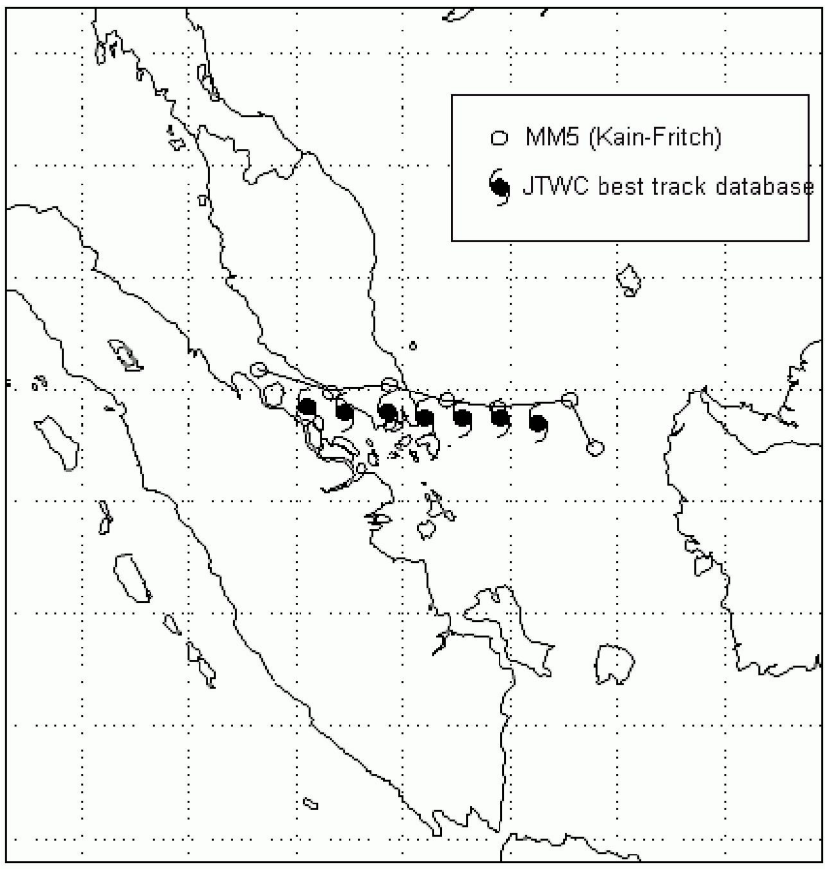

FIGURE 8: The Propagation Track of Typhoon as Suggested in the JTWCǒs Best Track Database and that Simulated by the PSU/NCAR MM5

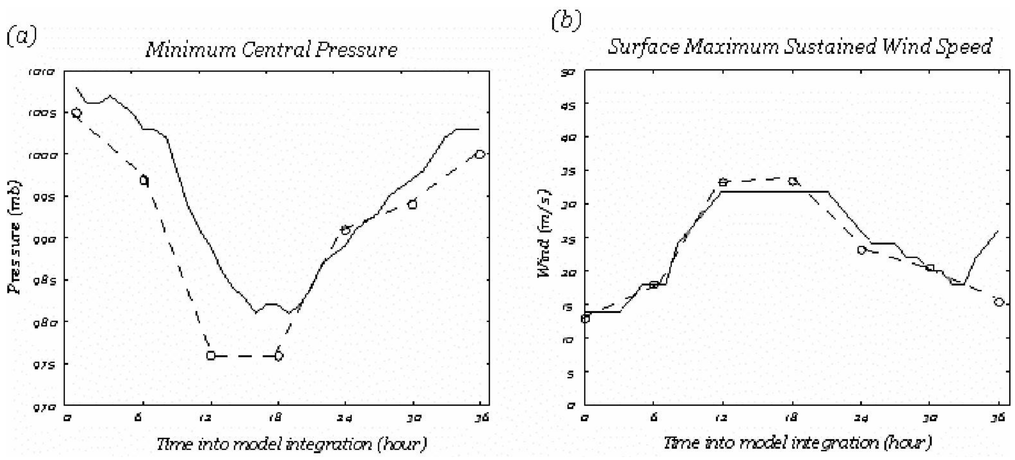

FIGURE 9: The Simulated (solid) and the JTWC Estimated (dotted) (a) Storm Central Pressure and (b) the Surface Maximum Sustained Wind

The quality of the simulation is further demonstrated by comparing the hydrometeor characteristic at the system scale of the simulated storm and that captured by the satellite. Figure 10a displays the visible satellite imagery of the cloud at 0400 UTC 27 December 2001 while Figure 10b shows a top view of the hydrometeor of the storm delineated by the 0.02 g kg^{-1} isosurfaces of the cloud water and ice, rain-water, snow and graupel. It is interesting to see that there is a remarkable similarity between the simulated and observed storm in term of general cloud distribution as well as the location of the system. Although it is not possible to predict the detailed distribution of convective cells along the spiral bands, the model does simulate well the cellular convection at the outer edge and the intense and organized (convective and stratiform) clouds in the eyewall. Both the model and the observations show the development of organized spiral cloud bands and a relatively dry zone to the southeast quadrant of the vortex.

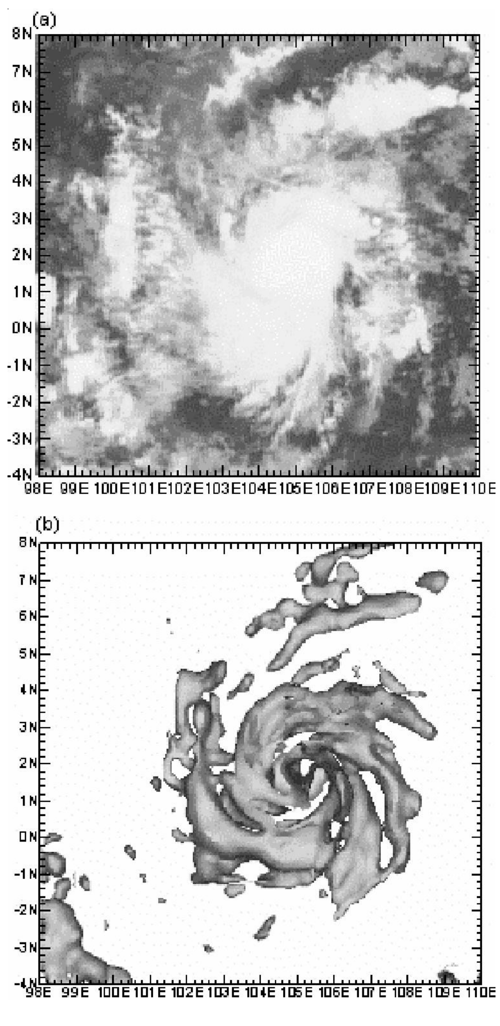

FIGURE 10: (a) Visible Satellite Imagery Taken at 04 UTC 27/12/2001 and (b) the Top View of the Model Simulated Hydrometeor as Determined by the 0.02 g kg-1 Isosurface for Cloud Water and Ice, Rain-water, Snow and Graupel Valid at 04 UTC 27/12/2001

Summary & Conclusion

The paper examined the capability and suitability of the PSU/NCAR MM5 modeling system in the Malaysia regions. The skill of this model in simulating meteorological processes is demonstrated through simulation of two extreme weather cases that effected the east coast Peninsular Malaysia. Firstly, the extreme episode of 9-11 December 2004 is successfully simulated at a resolution of 15 km by the PSU/NCAR MM5 model, initialized and bounded by the NCEP final global analyses. The model is able to reproduce the important features associated with the event, which include the formation and westward propagation of a low-level vortex as well as high wind speeds over the northwest quadrant of the vortex center. The simulated precipitation also compares favorably to the observation in term of spatial and total accumulated amount.

Secondly, we simulated near-equatorial typhoon Vamei 2001 at 15 km resolution. Both the simulated storm center pressure and surface maximum sustained wind are generally in good agreement with the JTWCÕs estimation. Also, the model predicted the storm track well compare to the archived database. In addition, the simulation captured the hydrometeor characteristic at the system scale as compared to the visible satellite imagery. However the simulation output during the initial model run is generally less consistent with the observation as there is no fine scale information provided. Recent advancement in tropical cyclone prediction has suggested the importance of vortex bogussing in the model first guess field (Kurihara *et al* 1993; Zou and Qingnong, 2000) in order to obtain less erroneous storm track and intensity forecast. However, in the current simulation, the bogussing process is omitted due to inaccessible information of the vortex structure during the initial time.

While Malaysia is frequently affected by extreme weather events associated with synoptic scale disturbances during the winter monsoon season, the scarcity of observation stations in the maritime equatorial region hinders understanding of these severe weather systems. It is encouraging that the results present in this study showed that the PSU/NCAR MM5 model, driven by coarser global analyses is capable of simulating events such as the 9-11 December heavy rainfall episode as well as the rare typhoon effected our region. Therefore, model studies such as this one can be very useful for local research to compliment conventional analysis.

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