Journal of Engineering Science 02(1&2), 2011, 97-106

JES
an International Journal

VIEWING OF SEVERE CYCLONIC STORM "AILA" THROUGH MM5 WITH DIFFERENT PARAMETERIZATION SCHEMES

Md. A. E. Akhter[1*], Md. Mahbub Alam[1] and M. Arif Hossain[2]

[1]*Department of Physics, Khulna University of Engineering & Technology, Khulna-9203, Bangladesh*
[2]*Department of Mathematics, Khulna University of Engineering & Technology, Khulna-9203, Bangladesh*

Received: 19 June 2011 Accepted: 19 October 2011

ABSTRACT

In this paper, results of the experiments to simulate the severe cyclonic storm Aila with two different planetary boundary layer (PBL) in combination with two convection schemes, with the aim to identify a better combination by using the non hydrostatic mesoscale model version 3.7 (MM5V3) is presented. Several sets of numerical experiments have been performed with 90 km and 30 km horizontal resolutions. The dimension of the coarse domain, which is mother domain, is taken as 34x41 and that for the nested one as 49x52. Two convection schemes (Grell and Kain Fritsch) with two planetary boundary layer (PBL) parameterization schemes (Blackadar and MRF) are used. Model simulated track and sea level pressure are compared with that obtained from observation. The model predicted pressure drops for all combinations are less than observed upto 0300 UTC of May, 2009. The simulated minimum central pressure were found 966, 971, 975 and 976 hPa for M-GR, M-KF, B-GR and B-KF respectively and that for observed one was 968 hPa. The model simulated horizontal wind and vertical cross section of temperature are also presented. The Medium Range Forecast (MRF) PBL scheme in combination with Grell cumulus convection scheme is found to perform better than the other combinations used in this study.

Keywords: *Convective system, Mesoscale model, Planetary boundary layer, Tropical cyclone.*

1. INTRODUCTION

The Bay of Bengal is potentially energetic region for the development of tropical cyclone and accounts for about 7% of the global annual total number of tropical storms (Neumann, 1993). These storms, in particular the post-monsoon storms, are highly devastating causing loss of life and damage to property, especially when they cross the coastal states of India and Bangladesh (Angelis, 1976). Therefore, reasonably accurate prediction of the Bay of Bengal cyclone is of great importance to avoid or reduce the loss of life and damages to property.

There have been considerable improvements in the field of prediction by numerical models during last two decades. High-resolution limited area models as well as global models are now being extensively used by most of the leading operational numerical weather prediction (NWP) centers of the world. With increasing computer resources, in the last decade, many of these NWP centers started using higher resolution models for tropical cyclone prediction to reduce errors associated with finite differencing (Dudhia, 1993) and for better representation of topographical features and sub-grid scale physical processes (Mandal *et al.,* 2003).

Cumulus convection, surface fluxes of heat, moisture and momentum and vertical mixing in the Planetary Boundary Layer (PBL) and radiative heating and cooling play important roles in the development of tropical cyclones (Anthes, 1982). Convection has long been recognized as a process of central importance in the development of tropical cyclones. The scales of convective clouds are too small to be resolved by numerical models and hence need to be parameterized in terms of variables defined at the grid points. A number of parameterization schemes (Frank, 1983; Molinari and Dudek, 1992; Emanuel and Raymond, 1993; Zhang *et al*., 1994; Kuo *et al.,* 1997) have been developed over the years but all of them have certain limitations. Performance of a numerical model in tropical cyclone forecast depends on how good the convection is parameterized in the model. Wang and Seaman (1997) conducted a comparison study of four convection schemes towards simulation of six precipitation events over continental United States. Tsutsui *et al.* (1998) made a study evaluating Kuo and Relaxed Arakawa-Schubert (RAS) schemes in simulating hurricanes using their regional atmospheric model.

Surface fluxes of latent heat and sensible heat energy play a vital role in the development and maintenance of tropical cyclones (Bayers, 1944). Emanuel (1986) and Rotunno and Emanuel (1987) further demonstrated the importance of surface fluxes. They showed that the hurricane can develop and be maintained as a result of energy supplied from the surface fluxes of latent heat and sensible heat energy even if there is no initial convective potential energy in the environment. Anthes and Chang (1978) showed the sensitivity of PBL parameterization in the simulation of hurricanes. Braun and Tao (2000) presented a comparison study of four PBL parameterization schemes in simulation of hurricane Bob (1991) using MM5 model. The model already

* Corresponding author: aeakhter@phy.kuet.ac.bd

showed its skill in simulating hurricanes (Karyampudi *et al.,* 1998; Liu *et al.,* 1997 and 1999; Braun and Tao, 2000).

In this paper, results of the experiments to simulate the severe cyclonic storm Aila with two different planetary boundary layer (PBL) in combination with two convection schemes, with the aim to identify a better combination by using the non hydrostatic mesoscale model version 3.7 (MM5V3) is presented. Two cumulus parameterization schemes namely Grell (1993), and Kain–Fritsch (1993) and two PBL parameterization schemes Blackadar (Blackadar, 1976 and 1979; Zhang and Anthes, 1982) and Hong–Pan (1996) as implemented in NCEP MRF model, are used to find the best combination in simulation of severe cyclonic storm Aila.

2. MODEL DESCRIPTION AND INITIAL CONDITIONS

The non-hydrostatic version of the MM5 modeling system, developed at Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) by Anthes, Warner, Ying-Hwa, Kuo and their colleagues, is used in this study. MM5 is a primitive equation hydrostatic/non-hydrostatic limited area model.

Pressure perturbation p', three velocity components (u, v, w), temperature T, specific humidity q are the prognostic variables in non-hydrostatic version of the model. Model equations in the terrain following sigma co-ordinate are written in flux form and solved in 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 with longer time step and the terms giving rise to fast moving waves are integrated with shorter time step. The most useful feature of MM5 model is its flexibility in terms of many options that are user specified and by setting these parameters to appropriate values, the model can be used for a wide range of applications. These include number of nests, type of convection, PBL and radiation parameterization schemes etc. A detailed description of the model is provided by Dudhia (1993) and Grell *et al*., (1995). A short overview of the model set up for our present study is provided in Table 1.

A series of four experiments are carried out using four possible combinations of two convection and two PBL parameterization schemes along with three common physics options. The three common physics options are cloud for radiation scheme, simple ice for microphysics and 5-layer soil model for soil model. The two convection schemes are Grell (1993) and Kain–Fritsch (1993), which are referred as GR and KF respectively. Two PBL schemes are Blackadar (Blackadar, 1976 and 1979; Zhang and Anthes, 1982) and Hong–Pan (1996) as implemented in NCEP MRF model, which are referred as B and M respectively. The experiments using MRF PBL scheme in combination with GR and KF convection schemes are referred as experiments M–GR and M–KF respectively. Similarly experiments using Blackadar PBL scheme in combination with GR and KF convection schemes are referred as experiments B–GR and B–KF respectively. Results obtained from these experiments are examined by simulated output with observed to find the best combinations towards forecasting the track and intensity of the severe cyclonic storm AILA. The initial and boundary conditions for model integration are obtained from NCEP FNL one degree data set.

Table 1: Design for fifth generation Penn State/NCAR Mesoscale Model (MM5) Version 3.7

Dynamics	Non-hydrostatic with three-dimensional Coriolis force
Main prognostic variables	u, v, w, T, p' *and* q
Map projection	Lambert conformal mapping
Central point of the domain	20° N, 88° E
Horizontal grid distance	90 km and 30 km (Mother& Nested)
Number of vertical levels	23 half sigma levels
Horizontal grid system	Arakawa B grid
Time integration scheme	Leapfrog scheme with time-splitting technique
Radiation parameterization scheme	Cloud
PBL parameterization scheme	MRF, Blackadar
Cumulus parameterization schemes	Grell, Kain-Fritisch
Microphysics	Simple Ice
Soil model	5-layer soil model
Time step	240 seconds

Table 2: Observed central position, pressure, maximum sustained surface wind and other parameters for Severe Cyclonic Storm "AILA" over the Bay of Bengal during 23-26 May, 2009

Date	Time (UTC	Central Lat ^{0}N/ Long ^{0}E	Estimated		Grade
			Central pressure (hPa)	Maximum sustained surface wind (Kt)	
23-05-2009	0600	16.5/88.0	998	25	D
	1200	16.5/88.0	994	25	D
	1800	17.0/88.5	996	25	D
24-05-2009	0000	17.0/88.5	996	25	D
	0300	18.0/88.5	992	30	DD
	0600	18.0/88.5	988	30	DD
	0900	18.0/88.5	986	35	DD
	1200	18.5/88.5	986	35	CS
	1500	19.0/88.5	986	35	CS
	1800	19.0/88.5	986	35	CS
	2100	20.0/88.0	984	40	CS
25-05-2009	0000	20.0/88..0	980	40	CS
	0300	20.5/88.0	978	50	CS
	0600	21.5/88..	974	55	SCS
	The system crosses West Bengal coast close to Sagar Island between 0800 and 0900 UTC and lay centered over Gangetic West Bengal close to Diamond Horbour				
	0900	22.0/88.0	968	60	SCS
	1200	22.5/88.0	970	50	SCS
	1500	23.0/88.0	978	45	CS
	1800	23.5/88.0	980	40	CS
	2100	24.0/88.0	981	35	CS
26-05-2009	0000	25.0/88.0	982	30	CS
	0300	25.5/88.0	988	25	DD
	0600	27.0/88.5	992	20	D
	0900	The system weakened into a well marked low pressure area over Sub-Himalayan West Bengal and neighborhood			

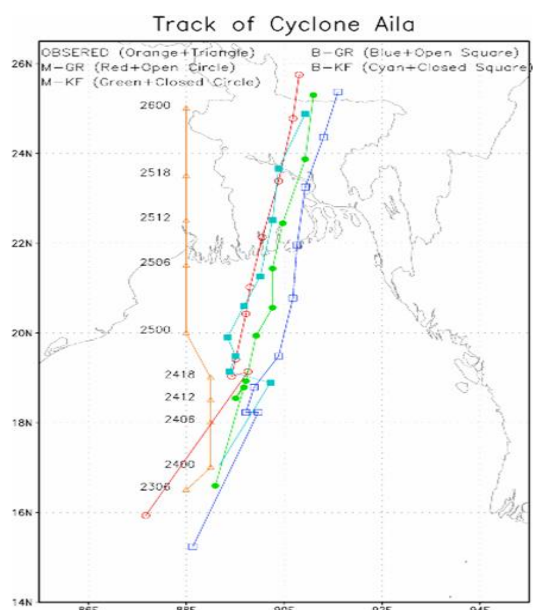

Figure 1: Observed and simulated tracks of the severe Cyclonic storm 'Aila' (location identified with date and time; 2306 means 0600 UTC of May 23, 2009) that formed in the Bay of Bengal 23 – 25 May, 2009 and crossed Bangladesh – India coast.

3. DESCRIPTION OF THE SYSTEM

The MM5 model described in section 2 is used to simulate severe cyclonic storm AILA. The observed track of the system, according to IMD, is shown in Fig.1. The observed central lat ^{0}N/Long ^{0}E, pressure, maximum sustained surface wind of the system as provided by IMD, are tabulated in Table 2. At 06 UTC of May 23 the system was in the state of depression and was centered near 16.5^0 N, 88 ^{0} E i.e. about 600 km south of Sagar Island. The depression moved in northerly direction and intensified into deep depression and at 03 UTC of 24 May was near 18.0^0 N, 88.5^0 E. At 12 UTC of 24 May it was intensified into a cyclonic storm and named as AILA and was centered near 18.5^0 N, 88.5^{0}E. It continued to move in northerly direction and intensified into a severe cyclonic storm at 06 UTC of 25 May and was centered over northwest Bay of Bengal near 21.5^0 N 88.0^{0}E close to the Sagar Island. The system crossed West Bengal of India and Khulna of Bangladesh coast close to the east of Sagar Island between 0800 to 0900 UTC as a severe cyclonic storm with wind speed of 100 to 110 kmph. The lowest estimated central pressure was about 967 hPa at the time of landfall. After the landfall, the system continued to move in a northerly direction, gradually weakened into a cyclonic storm and at 1500 UTC of 25 May was centered over Gangetic West Bengal, close to Kolkata. While it continued its northerly movement, it further weakened into a deep depression and at 0300 UTC of 26 May was over Sub-Himalayan west Bengal close to Malda. It weakened into a depression and at 0600 UTC of 26 May was close to Bagdogra. It weakened further and became less marked on 27 May (Fig.1).

4. RESULTS AND DISCUSSIONS

Four experiments are performed to examine the performance of the two convection and two PBL schemes mentioned in section 2. The model is integrated from 00 UTC of 23 May to 00 UTC of 27 May 2009 (i.e. 96 hrs) with the time step 240 seconds and their outputs are compared with those reported by (IMD). Outputs of all four combinations have been produced at three hours interval and processed using Grid Analysis and Display system (GrADS) at different interval of time (three hours or more). Using GrADS, the model simulated track along with observed track provided by IMD, mean SLP, wind at 850 hPa and vertical cross section of temperature of 12 and 18 UTC of May 24, 00 and 03 UTC of May 25, 2009 using M-GR and B-GR are presented and are been discussed. On the other hand, the model simulated track along with observed track provided by IMD, mean SLP, wind at 850 hPa and vertical cross section of temperature of 12 and 18 UTC of May 24, 00 and 06 UTC of May 25, 2009 using M-KF and B-KF are presented and are been discussed. The times 03 and 06 UTC of 25 May are just the available time before landfall. These are different because different combinations have different landfall time. Track is drawn from 0600 UTC of May 23 to 0000 UTC of May 26, 2009. In this paper we discuss the track, sea level pressure, wind at 850 hPa level and vertical cross section of temperature of the cyclone AILA.

4.1 TRACK OF THE SEVERE CYCLONIC STORM AILA

The observed track of the cyclone and that obtained from model simulation, using four possible combinations, are presented as in Fig. 1. Figures show the track of the cyclone from 0006 UTC of May 23 to 0000 UTC of May 26, 2009. The time for the data point are shown in figure and these are 2306, 2400, 2406, 2412, 2418, 2500, 2506, 2512, 2418 and 2600. 2306 means 0600 UTC of May 24, 2009. The landfall time and position are tabulated in the Table 3. It is seen from Table 3 that the model simulated landfall time and position differ from those provided by IMD but all are close.

Table 3: Model simulated and observed landfall position, time and central pressure

	M-GR	M-KF	B-GR	B-KF	IMD(observed)
Landfall position	89.5544 21.6786	89.8465 21.8178	90.2639 21.7830	89.5961 21.7134	88.0 21.5
Landfall time	04 UTC of 25 May	08 UTC of 25 May	05 UTC of 25 May	08 UTC of 25 May	08 UTC of 25 May
Pressure before landfall	966 hPa at 04 UTC of 25 May	972 hPa at 06 UTC of 25 May	977 hPa at 03 UTC of 25 May	976 hPa at 06 UTC of 25 May	968 hPa at 09 UTC of 25 May

The model-simulated track of the storm is almost parallel to the IMD observed track in the whole path with deviation mostly in the longitudinal position. The positional error may have occurred due to the initial positional error. Landfall positions predicted by Grell convective scheme (89.5544^{0}E and 21.6786^{0}N) and landfall time predicted by KF Scheme (08 UTC of 25 May) are close to observed landfall position (88^{0}E and 21.5^{0}N) and landfall time (08 UTC of 25 May). Finally, both landfall position and time predicted by M-GR are relatively close to observed one.

4.2 CENTRAL PRESSURE OF THE CYCLONE AILA

Fig. 2 show the SLP distribution and in table 2 that provided by IMD is tabulated. Simulated mean SLP of 12 and 18 UTC of May 24, 00 and 03 UTC of May 25, 2009 using M-GR and B-GR are presented. On the other hand, simulated mean SLP of 12 and 18 UTC of May 24, 00 and 06 UTC of May 25, 2009 using M-KF and B-KF are presented. At the initial time (00 UTC of May 24, 2009) model simulated mean SLP is 999 hPa for all the four combinations and that for observed one is 998 hPa at 06 UTC of May 24, 2009. From Fig.'s 2, it is seen that after 48 hours (at 00 UTC of 25 May, 2009), the model predicted central pressure with the combinations M-GR, M-KF, B-GR and B-KF of cyclone AILA were 967, 974, 975 and 978 hPa respectively and observed one is 980 hPa. Starting from the beginning up to 48 hours Model predicted central pressure drops for all combinations are more than those observed. The observed pressure drop and model predicted pressure drop upto 72 hours are presented in Fig. 3.

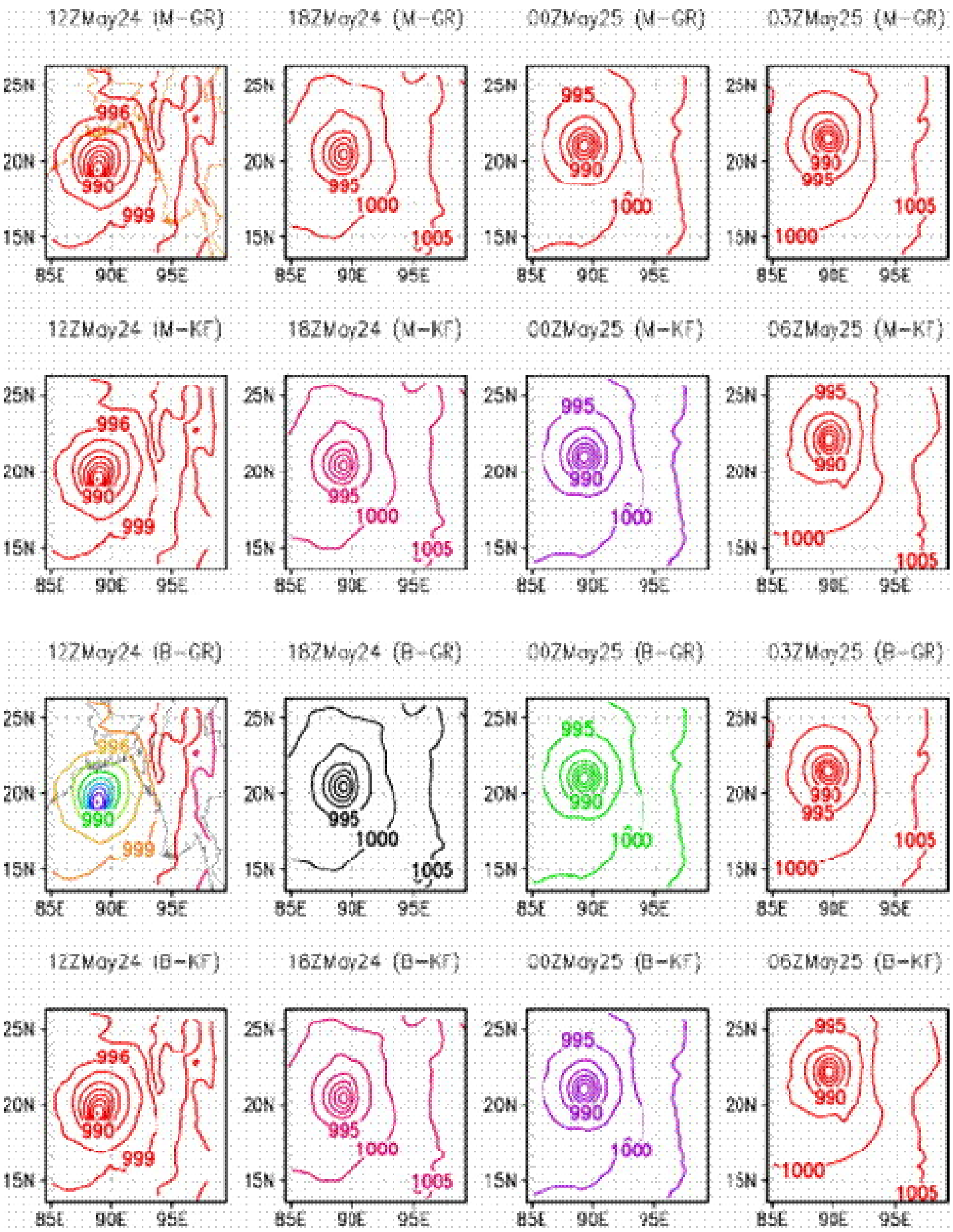

Figure 2: Simulated Mean Sea Level Pressure of the severe Cyclonic storm 'Aila' at different time with different combinations (figure identified with date, time and combination: 12ZMay24 (M-GR) means 1200 UTC of May 24, 2009 with MRF PBL and Grell convection scheme).

It is found that, after 48 hrs, the model predicted pressure drops for all combinations are less than those of the observed. Finally just before landfall the simulated minimum central pressure are 966, 971, 975 and 976 hPa for M-GR, M-KF, B-GR and B-KF respectively and that for observed one was 968 hPa. These simulated and observed minimum mean sea level pressures are obtained at different time and different position by different combinations. Model predicted pressure drop from Figs. 2 show that the large-scale pressure distribution pattern among the simulations by MRF PBL scheme in combination with the Grell convection scheme is in close agreement with the observed pressure drop reported by IMD. The better simulated results obtained using the MRF PBL scheme is probably due to stronger vertical mixing allowed in this scheme, which facilitates convection and hence development of the storm.

4.3 WIND AT 850 HPA DURING THE MOVEMENT OF TROPICAL CYCLONE "AILA"

Model simulated wind using four possible combinations using convection and two PBL parameterization schemes at 850 hPa level at different time are presented as in Fig.'s 4. The 850 hPa level wind was simulated well by the model. It is seen from the model simulated wind that maximum wind speed is generated in the right front side (eastern side) of the system. It is due to the fact that the motion of the cyclone also contributes to its swirling winds. In addition, the model simulates stronger vortex for all combinations compared to the observed one. Again, GR convection schemes with both PBL simulates strong wind vector earlier than the KF convective schemes with both PBL.

Maximum anemometer height wind using combination M-GR, M-KF, B-Gr and B-KF are 31 m/s, 28 m/s, 26 m/s and 25 m/s respectively at time 03 UTC of 25 May, 2009 (not shown). On the other hand, the maximum anemometer height wind provided by IMD is 31 m/s (60 Kt) at time 09 UTC of 25 May, 2009. So, maximum anemometer height wind by Grell cumulus convection scheme with MRF PBL (M-GR) has matched with the observed.

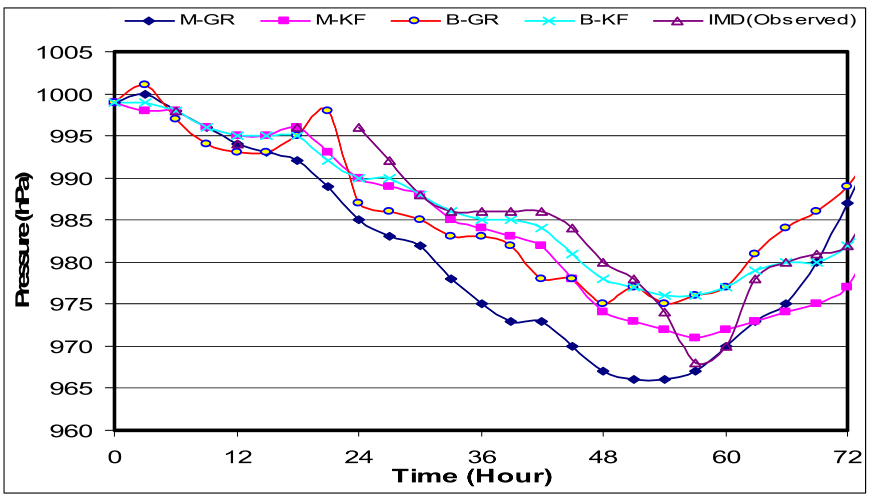

Figure 3: Comparison between simulated and observed central pressure of the severe Cyclonic storm 'Aila' at different Physics and PBL combinations with different time.

4.4 VERTICAL CROSS SECTION OF TEMPERATURE PROFILE

Fig. 5 illustrates the model simulated vertical cross section of temperature profile from 850 hPa to 200 hPa at different time and at different latitude shown in Table 4. From the Figures, we see that the thermal influence is extended up to 200 hPa level. Maximum temperature profile at different levels satisfied the warm core of the cyclone. Table 4 shows also the increase of temperature at the core from the surrounding at different time for different combination of physics at 400 hPa. M-GR, B-GR, M-KF, M-GR and M-KF combinations show the maximum temperature at the core at time 12, 18 UTC of 24 May, 00, 03 and 06 UTC of 25 May, 2009 respectively. The variations of maximum temperature are more systematic in M-GR and M-KF than the other two.

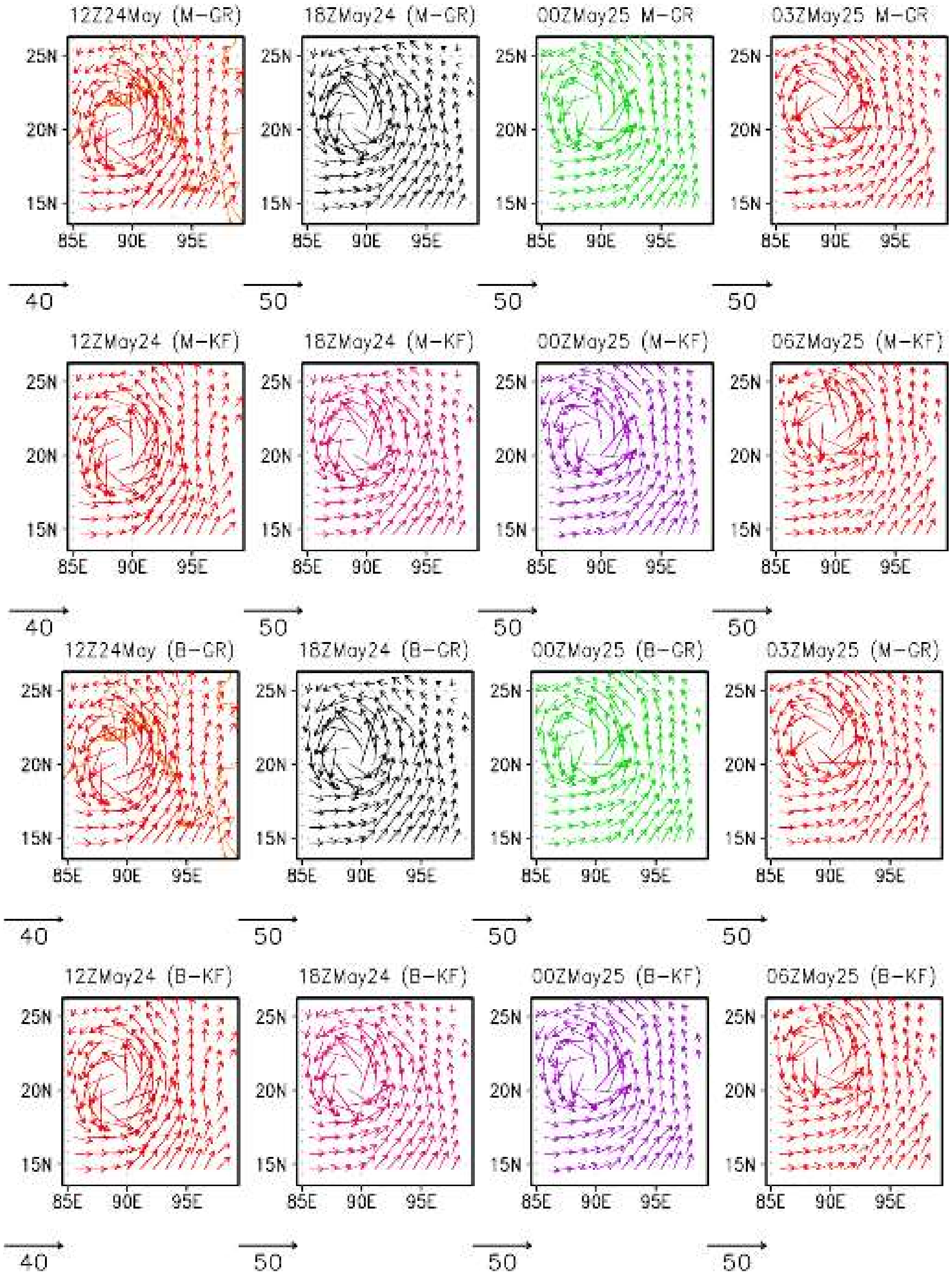

Figure 4: Simulated wind at different time with different Physics and PBL combinations (figure identified with date, time and combination: 12ZMay24 (M-GR) means wind at 1200 UTC of May 24, 2009 with MRF PBL and Grell convection scheme)

Table 4: The model simulated vertical cross section of temperature profile from 850 hPa to 200 hPa at different time and at different latitude

Time	Latitude, Longitude and Increase of Temperature at the core (T) in degree											
	M-GR			M-KF			B-GR			B-KF		
	lat	lon	T^0C	lat	Lon	T^0C	Lat	Lon	T^0C	lat	lon	T^0C
12 UTC of 24 May	19.38	88.97	6.7	18.58	89.26	4.0	18.79	89.26	4.9	19.48	88.89	4.75
18 UTC of 24 May	20.35	89.26	6.0	19.48	90.43	5.7	19.52	89.93	6.65	19.87	88.76	5.0
00 UTC of 25 May	20.98	89.35	6.0	20.67	90.81	7.5	20.81	90.22	7.0	20.53	89.09	5.8
03 UTC of 25 May	21.40	89.51	6.1				21.25	90.25	5.2			
06 UTC of 25 May			__	21.16	90.81	7.25				21.26	89.55	4.8

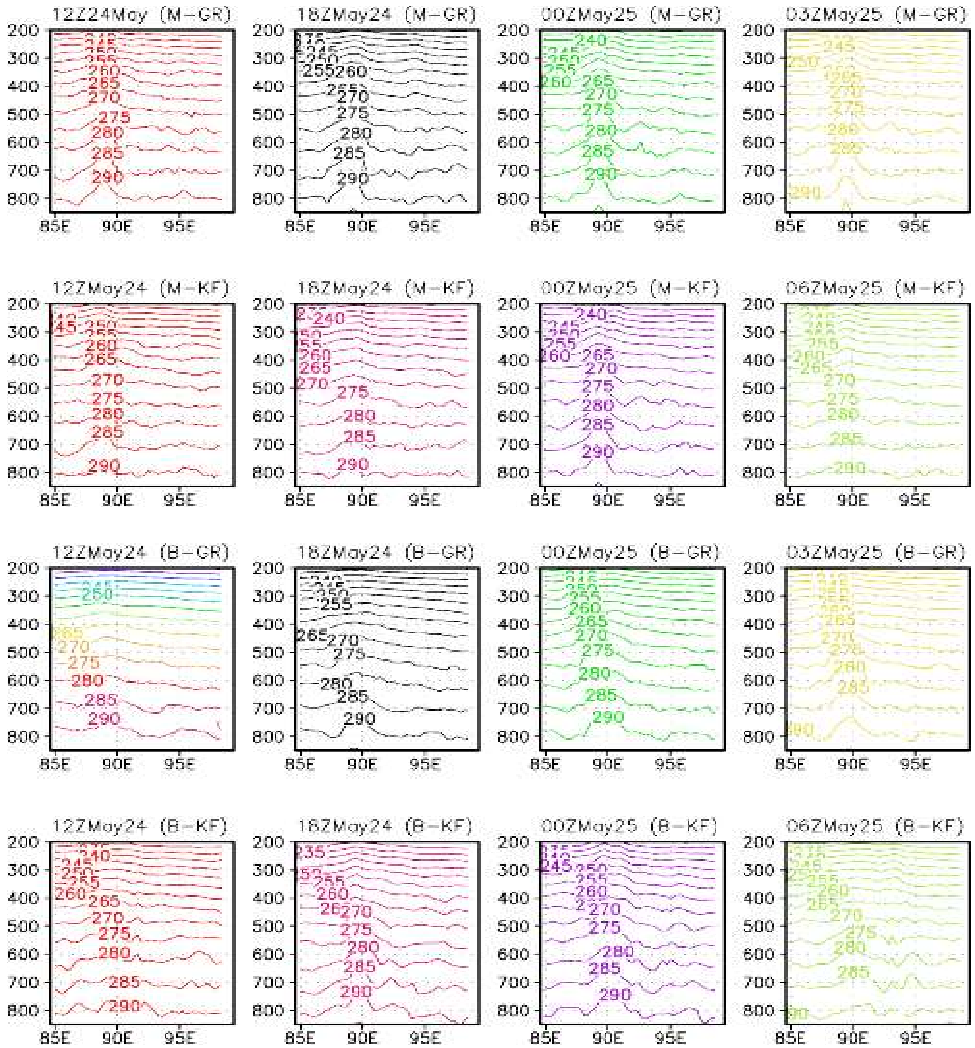

Figure 5: Vertical cross section of Temperature profile between 850-200 hPa levels with different time and different combinations (12ZMay24 (M-GR) means vertical cross of temperature profile between 850 - 200 hPa levels at time 1200 UTC of May 24, 2009 with MRF PBL and Grell convection scheme)

5. CONCLUSIONS

This paper presents the results obtained from four experiments with different cumulus convection and PBL towards simulation of cyclone Aila. Some broad conclusions that can be drawn out are as follows.

i) The model has successfully simulated the cyclonic events with all four chosen combination of physics options with the NCEP FNL data.

ii) Grell cumulus convection scheme with MRF PBL has shown better performance in term of central pressure (simulated 966 hPa, observed 968 hPa).

iii) The landfall time is predicted with close accuracy by Grell convective scheme with both MRF and Blackadar PBL schemes.

iv) Grell cumulus convection scheme with MRF PBL has better performed to give the landfall position. The positional error may have occurred due to the initial positional error.

v) Anemometer height wind by Grell cumulus convection scheme with MRF PBL has matched well with the observed.

Thus we may conclude that Grell cumulus convection scheme along with MRF PBL is the better combination to simulate the severe cyclonic storm Aila.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the NCEP/NCAR for their reanalysis data sets used for the present study. The Ministry of Science and Information & Communication Technology, Bangladesh is gratefully acknowledged for providing financial support to the authors.

REFERENCES

Anthes, R. A., 1982. Tropical cyclones: Their evolution, structure and effects, Meteorol. Monogr. Ser. 19(41), 208.

Anthes, R. A., and Chang, S. W., 1978. Response of the hurricane boundary layer to changes of sea surface temperature in a numerical model, J. Atmos. Sci., 35, 1240–1255.

Bayers, H. R., 1944. *General Meteorology*, McGraw-Hill, 645.

Betts, A. K., 1986. A new convective adjustment scheme, Part I: Observational and theoretical basis, Quart. J. Roy. Meteorol. Soc. 112, 677–691.

Blackadar, A. K., 1976. Modeling the nocturnal boundary layer, Preprints, Third Symposium on Atmospheric Turbulunce, Diffusion and Air quality, Raleigh, NC, Amer. Meteor. Soc. 46–49.

Blackadar, A. K., 1979. High-resolution models of the planetary boundary layer in Pfafflin and Ziegler (eds.), Advances in Environmental Science and Engineering, Gordon and Briech Sci. Publ., New York 1(1), 50–85.

Braun, S. A., and Tao, W. K., 2000. Sensitivity of high-resolution simulations of hurricane Bob (1991) to planetary boundary layer parameterizations, Mon. Wea. Rev., 128, 3941–3961.

De Angelis, D., 1976. World of tropical cyclones – North Indian Ocean, Mar. Weather Log, 20,191–194.

Dudhia, J., 1993. A non-hydrostatic version of Penn State – NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front, Mon. Wea. Rev., 121(1), 1493–1513.

Emanuel, K. A., and Raymond, D. J., 1993. The representation of cumulus convection in numerical models, Meteorol. Monogr. Ser., 46, 246.

Emanuel, K.A., 1986. An air sea interaction theory for tropical cyclones. Part I: Steady-state maintenance, J. Atmos. Sci., 43,585–604.

Frank, W.M., 1983. The cumulus parameterization problem, Mon. Wea. Rev., 111, 1859–1871.

Gray, W.M., 1968. Global view of the origin of tropical disturbances and storms, Mon. Wea. Rev., 96, 669–700.

Grel, G., Dudhia, J., and Stauffer, D. R., 1995. A description of the fifth generation Penn State/NCAR Mesoscale Model (MM5), NCAR Tech. Note NCAR/TN-398 + STR, 122.

Grell, G., 1993. Prognostic evaluation of assumption used by cumulus parameterizations, Mon. Wea. Rev., 121, 764–787.

Hong, S. H., and Pan, H. L., 1996. Nonlocal boundary layer vertical diffusion in a medium range forecast model, Mon. Wea. Rev., 124, 2322–2339.

Kain, J. S., and Fritsch, J. M., 1993. Convective parameterization for mesoscale models: The Kain- Fritsch scheme. The representation of cumulus convection in numerical models, Meteor. Monogr., 46, 165–170.

Karyampudi V. M., Lai G. S. and Manobianco J., 1998. Impact of initial condition, rainfall assimilation and cumulus parameterization on simulation of Hurricane Florence, Mon. Wea. Rev., 126, 3077–3101.

Kuo, Y.H., Bresch, J.F., Cheng, M.D., Kain, J., Parsons, D.B., Tao, W.K. and Zhang, D.L., 1997. Summary of a mimiworkshop on cumulus parameterization for mesoscale models, Bull. Am. Meteorol. Soc., 78,475–491.

Liu, Y., Zhang, D.L. and Yau, M.K., 1997. A multi-scale numerical simulation of hurricane Andrew (1992): Part-I: Explicit simulation and verification, Mon. Wea. Rev., 125, 3073–3093.

Liu, Y., Zhang, D.L., and Yau, M.K., 1999. A multi-scale numerical simulation of hurricane Andrew (1992): Part-II: Kinematics and inner core structure, Mon. Wea. Rev. 127, 2597–2616.

Mandal, M., Mohanty, U.C., Potty, K.V.J. and Sarkar, A., 2003. Impact of horizontal resolution on prediction of tropical cyclones over Bay of Bengal using a regional weather prediction model, Proceedings Ind. Acad. Sci. (Earth and Planetary Sciences), 112(1), 79–93.

Mitra, A. K., Bohra, A. K., and Rajan, D., 1997. Daily rainfall analysis for Indian summer region, Int. J. of Climate 17, 1083–1092.

Molinari, J., and Dudek, M., 1992. Parameterization of convective precipitation in mesoscale numerical models, A critical review, Mon. Wea. Rev., 120, 326–344.

Neumann, C. J., 1993. Global overview: In Global Guide to Tropical Cyclone Forecasting, World Meteorological Organization: Geneva, 1(1-1), 56.

Rotunno, R., and Emanuel, A., 1987. An air sea interaction theory for tropical cyclones: Part-II: Evolutionary study using a non-hydrostatic axisymmetric numerical model, J. Atmos. Sci., 44, 542–561.

Tsutsui, J., Kasahara, A., and Hirakuchi, H., 1998. Impacts of diabatic initialization and cumulus parameterization on numerical typhoon prediction, Journal of Meteorol. Soc. Japan, 76(6), 889–907.

Wang, W., and Seaman, N. L., 1997. A comparison study of convective parameterization schemes in a mesoscale model, Mon. Wea. Rev., 125,252–278.

Zhang, Da-Lin and Anthes, R. A., 1982. A high-resolution model of the planetary boundary layer – sensitivity tests and comparisons with SESAME-79 data, J. Appl. Meteorol., 21, 1594–1609.

Zhang, Da-Lin, Kain, J. S., Fritsch, J. M., and Gao, K., 1994. Comments on Parameterization of convective precipitation in mesoscale numerical models: A critical review, Mon. Wea. Rev., 122, 2222–2231.