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Track, intensity and few dynamical aspects of 'AILA' as simulated by operational NWP model of the IAF

T. P. SRIVASTAVA[†] and ANIL DEVRANI*

Met Faculty, Air Force Administrative College, Red Fields, Coimbatore, India

**Air Force Centre for Numerical Weather Prediction, Subroto Park, New Delhi, India*

e mail : tarendrasrivastava@gmail.com

सार – इस शोध पत्र में भारतीय वायु सेना के प्रचालनात्मक एन. डब्ल्यू. पी. मॉडल की क्षमता का मई 2009 में बंगाल की खाड़ी में बने और पश्चिम बंगाल को प्रभावित करने वाले प्रचंड चक्रवातीय तूफान 'आयला' के कुछ गत्यात्मक पहलुओं, उसके मार्ग, तीव्रता एवं स्थल प्रवेश के पूर्वानुमान का विश्लेषण करने का प्रयास किया गया है। इस मॉडल को 6 कि. मी. के छोटे भाग में कपासी प्राचलीकरण योजना के साथ और उसके बिना इस योजना का प्रयोग करके देखा गया है। बारी बारी से किए गए दोनों प्रयोगों के सेट में डी–2 पर तैयार किए गए पूर्वानुमान की तुलना में डी–1 के पूर्वानुमान अपेक्षाकृत बेहतर और आधिक सही पाए गए। कपासी प्राचलीकरण के पैटर्न्स विलंब से संवहन पैदा करते हैं परन्तु इस पैटर्न्स के बिना तैयार किए परिणाम की तुलना में अधिक सही है। 6 कि.मी. के छोटे भाग में कपासी प्राचलीकरण योजना के बिना रेडार की परावर्तिता डी. डब्ल्यू. आर. कोलकाता के वास्तविक परावर्तिता समय और स्थान दोनों की तुलना में अधिकतम देखी गई है।

ABSTRACT. An attempt has been made in this study to analyse the efficacy of operational NWP Model of the IAF in predicting the track, intensity, landfall and few dynamical aspects of 'AILA' a Severe Cyclonic Storm that formed over the Bay of Bengal and affected West Bengal during May 2009. Model runs were done with and without employment of cumulus parameterisation scheme in the finer domain of 6 km. The forecasts of D-1 were relatively better and more realistic in comparison to the one generated on D-2, in both sets of experiment, respectively. Patterns with cumulus parameterisation produced delayed convection but with finer details in comparison to the patterns generated without it. Maximum radar reflectivity without using cumulus parameterisation scheme in the finer domain of 6 km, compared well with the actual reflectivity of Kolkata DWR both in time and space.

Key words – Tropical cyclone, Rapid intensification, Probability, Vorticity, Divergence, Vertical wind shear, Bay of Bengal.

1. Introduction

Recent study (Osuri *et al.*, 2012) has revealed that convection and planetary boundary layer (PBL) processes play significant role in the genesis and intensification of tropical cyclones (TCs). Several convection and PBL parameterization schemes incorporate these processes in the numerical weather prediction models. Therefore, a systematic inter-comparison of performance of parameterization schemes is essential to customize a model. In this context, six combinations of physical parameterization schemes (2 PBL Schemes, YSU and MYJ and 3 convection schemes, KF, BM, and GD) of WRF-ARW model were employed to obtain the optimum combination for the prediction of TCs over North Indian Ocean. Five cyclones were studied for sensitivity experiments and the out-coming combination was tested on real-time prediction of TCs during 28. The tracks were compared with those provided by the operational centers like NCEP, ECMWF, UKMO, NCMRWF and IMD. It is found that the combination of YSU PBL scheme with KF convection scheme (YKF) provides a better prediction of intensity, track, and rainfall consistently.

Indian Air Force (IAF) has also entered the era of Numerical Weather Prediction (NWP) since 2004. With the installation of High Performance Computing System, Air Force Center for Numerical Weather Prediction (AFCNWP) is independently generating its own NWP guidance which is both area and location specific. Operational NWP Model of the IAF uses ARW core of WRF (Version 3.1.1) in a two way nested configuration at

[†]*Present affiliation* : Group Captain at H.Q., CAC, Allahabad, India

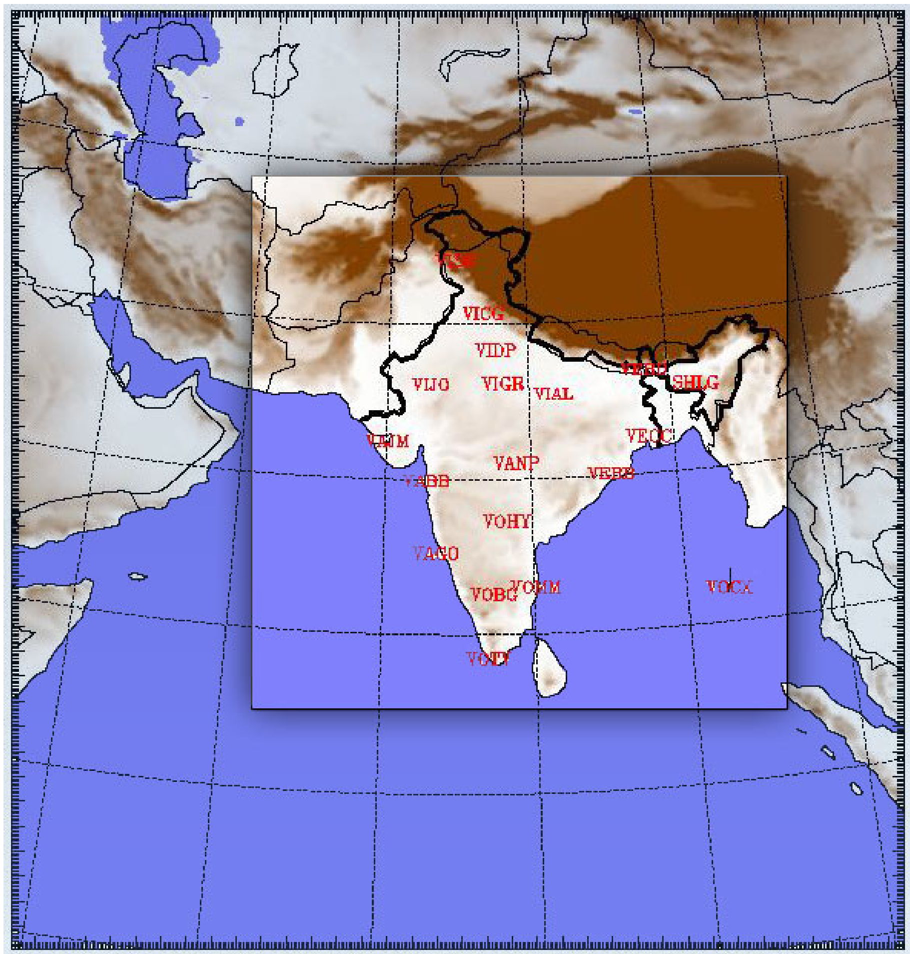


Fig.1. IAF Model - WRF Version 3.1.1 (ARW), Resolution : 18 km, 6 km (Double Nested)

resolutions of 18 and 6 km as per the domains shown in Fig. 1. Summary of the WRF characteristics is shown in Table 1. Initial and boundary conditions of 0000 UTC and 1200 UTC from NCEP GFS are used for model integration of 75 and 66 hours, respectively. The products of these two operational runs are made available to the field forecasters daily by 1600 hrs (IST) and 0400 hrs (IST). The guidance from these products is effectively integrated into the forecasting system for timely dissemination of meaningful weather prediction to all the users.

During May 2009 a Severe Cyclonic Storm 'AILA' had formed over the Bay of Bengal, moved northwards and affected West Bengal coast. The NWP Model of the IAF proved useful in providing sufficient warning time on its formation, intensity and movement. It helped the users in taking preventive measures to safeguard their assets on ground and evacuation of moveable property to safer locations. This study attempts to highlight the effectiveness of product generated from operational NWP Model of the IAF based on the initial conditions at 0000 UTC of 23 and 24 May 2009. Outcome of employing cumulus parameterisation in the finer domain of 6 km (and without it) has also been discussed for better appreciation of its effect.

2. History of 'AILA'

Under the influence of an upper air cyclonic circulation, a low pressure area formed over the southeast Bay of Bengal during the morning hours of 22nd May 2009. It subsequently concentrated into a depression and lay centered at 1130 hrs (IST) of 23rd May 2009 near 16.5º N / 88.0º E about 600 km south of Sagar Island. The depression moved northwards, intensified into a deep depression and lay centred at 0830 hrs (IST) of 24th May 2009 near 18.0° N / 88.5° E. It further intensified into a cyclonic storm 'AILA' at 1730 hrs (IST) of 24th May 2009

TABLE 1

Summary of characteristics of the WRF model

Characteristic Features	WRF Ver 3.1.1 (ARW)
Nesting option used	Two way nested: 6 km inner & 18 km outer
Vertical Co-ordinate	σ_p terrain-following mass vertical co-ordinate, dry hydrostatic-pressure, with vertical grid stretching permitted. Top of the model is a constant pressure surface (Laprise 1992)
Horizontal Grid	Arakawa C-grid staggering
Time Integration Scheme	Third-order Runga-Kutta scheme
Microphysics	New Thompson *et al*. scheme with ice, snow and graupel processes suitable for high-resolution simulations, adds rain number concentration [Thompson, *et al*., (2008, MWR)] in both domains
Convection	Grell-Devenyi Ensemble Scheme (Grell & Devenyi, 2002) in both domains
Radiation	RRTMG scheme that includes the MCICA method of random cloud overlap
Planetary Boundary Layer	MYJ TKE [Hong, *et al*., (2006, MWR)] in outer & YSU [Janjic (1994, MWR)] in inner domain
Land Surface Model	Unified Noah land-surface model (Chen and Dudhia, 2001) in both domains

TABLE 2

Experimental design

	First Set		Second Set	
	Exp - 1	Exp - 2	Exp - 3	Exp - 4
Start-Date	23 May 2009 (0000UTC)	24 May 2009 (0000UTC)	23 May 2009 (0000UTC)	24 May 2009 (0000UTC)
End Date	26 May 2009 (0000UTC)	27 May 2009 (0000UTC)	26 May 2009 (0000UTC)	27 May 2009 (0000UTC)
Cumulus Parameterization (Outer Domain)	Grell-Devenyi Ensemble	Grell-Devenyi Ensemble	Grell-Devenyi Ensemble	Grell-Devenyi Ensemble
Cumulus Parameterization (Inner Domain)	Grell-Devenyi Ensemble	Grell-Devenyi Ensemble	Nil	Nil

and lay centred near 18.5° N / 88.5° E. It continued to move northwards and intensified into a severe cyclonic storm at 1130 hrs (IST) of 25th May 2009 with centre over northwest Bay of Bengal near 22.0° N / 88.0° E close to Sagar Island. The system crossed West Bengal coast close to the east of Sagar Island by 1430 hrs (IST) as a Severe Cyclonic Storm with maximum estimated 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 lay centred at 2030 hrs (IST) of 25th May 2009 over Gangetic West Bengal, close to Kolkata. It continued its northerly movement, weakened into a deep depression and lay centred at 0830 hrs (IST) of 26th May 2009 over Sub-Himalayan West Bengal & Sikkim, close to Malda. It weakened into a depression and lay centred at 1130 hrs (IST) of 26th May 2009 over the same region close to Bagdogra. By 1430 hrs (IST) of 26th May 2009, it weakened further and was seen as a well marked low pressure area over Sub-Himalayan West Bengal and became less marked by 27th May 2009.

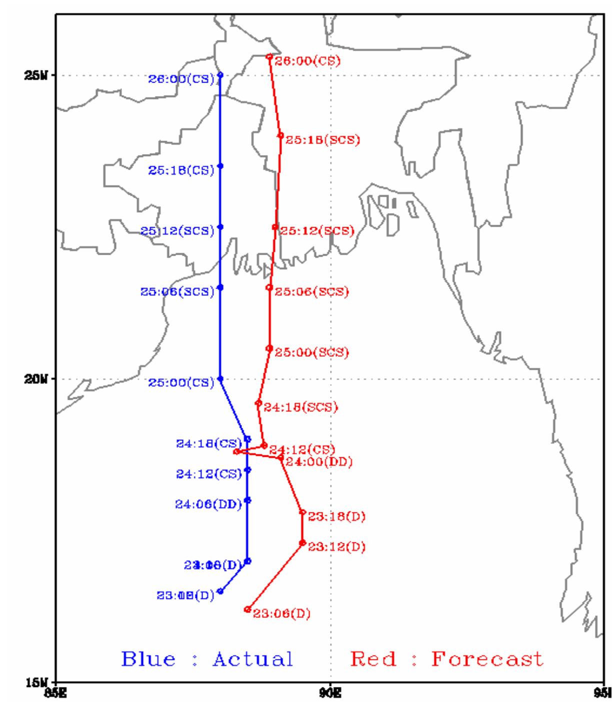


Fig. 2(a). Track & Intensity : Based on initial conditions of 23 May 2009 / 0000 UTC (With Cu Parameterization)

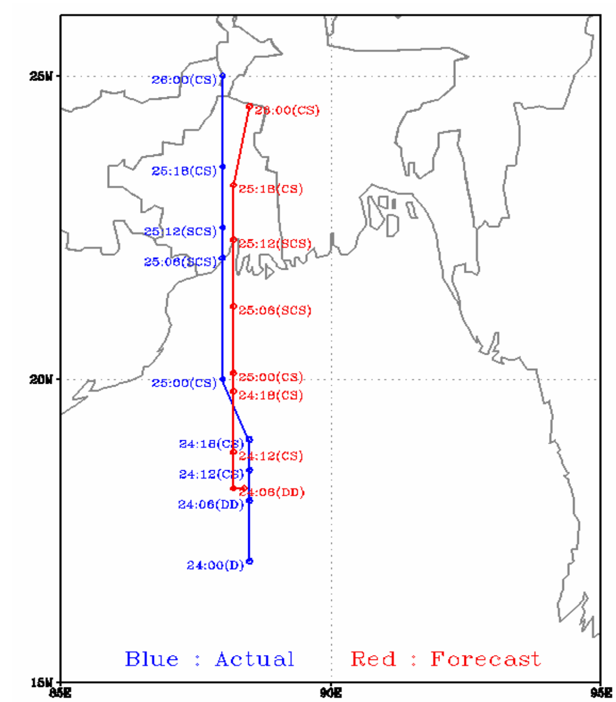


Fig. 2(b). Track & Intensity : Based on initial conditions of 24 May 2009 / 0000 UTC (With Cu Parameterization)

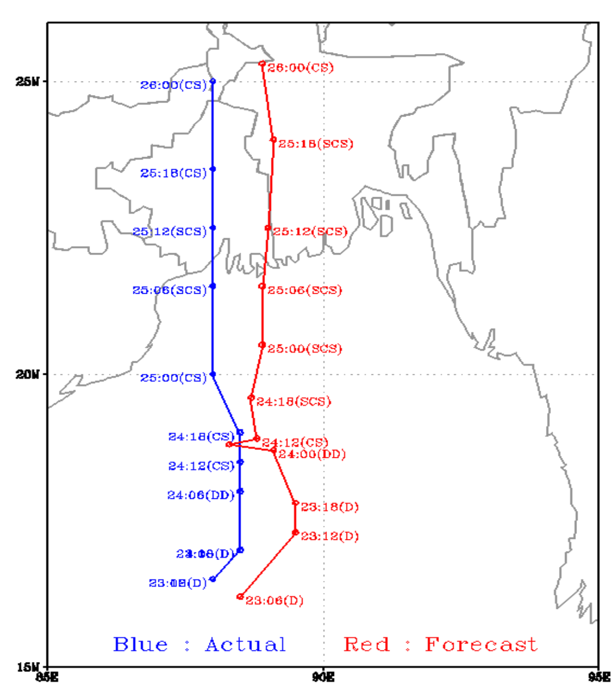


Fig. 2(c). Track & Intensity : Based on initial conditions of 23 May 2009 / 0000 UTC (Without Cu Parameterization)

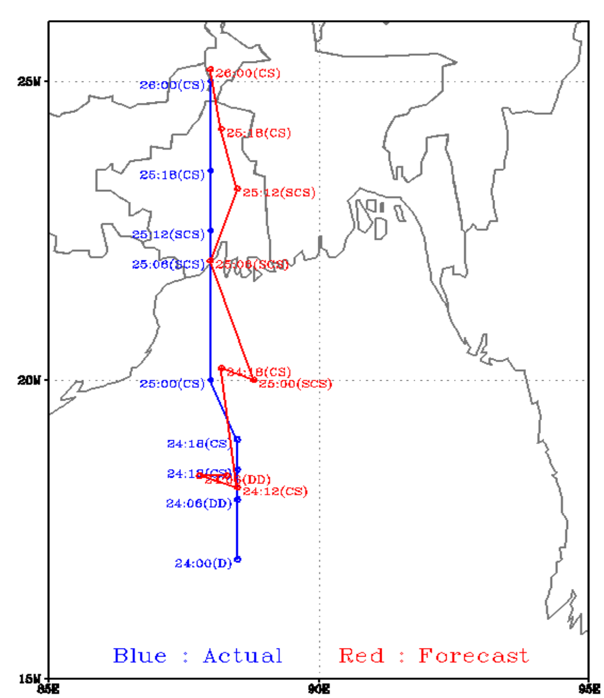


Fig. 2(d). Track & Intensity : Based on initial conditions of 24 May 2009 / 0000 UTC (Without Cu Parameterization)

TABLE 3

Observed and Predicted Track (centre of the system) and intensity Central Pressure Values (CPV) from the initial conditions of 23 & 24 May 2009 (0000 UTC) with cumulus parameterization (Grell-Devenyi Ensemble) scheme both in outer & inner domains

Observed values					Predicted values													
Actual data					Initial conditions: 23 May 2009 (0000 UTC)							Initial Conditions: 24 May 2009 (0000 UTC)						
Date/Time	Lat.(N)	Long.(E)	CPV (hPa)	Grade	Forecast hours	Lat.(N)	Long.(E)	CPV (hPa)	Grade	Distance Error (km)	CPV Error	Forecast hours	Lat.(N)	Long.(E)	CPV (hPa)	Grade	Distance Error (km)	CPV Error
23/0600	16.50	88.00	998	D	06 hrs	16.50	88.50	997.4	L	55	-0.6							
23/1200	16.50	88.00	994	D	12 hrs	18.00	90.00	994.1	D	275	0.1							
23/1800	17.00	88.50	996	D	18 hrs	18.00	89.00	993.1	D	123	-2.9							
24/0000	17.00	88.50	992	D	24 hrs	18.50	88.50	992.1	D	165	0.1							
24/0600	18.00	88.50	988	DD	30 hrs	18.00	89.00	990.9	DD	55	2.9	06 hrs	18.2	88.20	991.0	DD	40	3.0
24/1200	18.50	88.50	986	CS	36 hrs	18.20	88.80	987.4	CS	47	1.4	12 hrs	18.8	88.20	988.4	CS	47	2.4
24/1800	19.00	88.50	986	CS	42 hrs	18.80	89.10	987.2	CS	70	1.2	18 hrs	19.8	88.20	986.8	CS	94	0.8
25/0000	20.00	88.00	980	CS	48 hrs	19.10	88.90	984.0	CS	140	4.0	24 hrs	20.1	88.20	984.1	CS	25	4.1
25/0600	21.50	88.00	974	SCS	54 hrs	20.20	89.50	981.4	SCS	218	7.4	30 hrs	21.2	88.20	982.6	SCS	91	8.6
25/1200	22.50	88.00	970	SCS	60 hrs	21.20	89.50	979.5	SCS	218	9.5	36 hrs	22.3	88.20	982.5	SCS	31	12.5
25/1800	23.50	88.00	980	CS	66 hrs	22.10	89.50	978.30	SCS	226	-1.7	42 hrs	23.2	88.20	983.0	CS	40	3.0

Note : Highlighted cells depict values at the observed & predicted landfall time

TABLE 4

Observed and predicted track (centre of the system) and intensity Central Pressure Values (CPV) from the initial conditions of 23 & 24 May 2009 (0000 UTC) with cumulus parameterization (Grell-Devenyi Ensemble) scheme in outer domain and without cumulus parameterization in inner domain

Observed values					Predicted values													
Actual data					Initial Conditions: 23 May 2009 (0000 UTC)							Initial Conditions: 24 May 2009 (0000 UTC)						
Date/ Time	Lat. (N)	Long. (E)	CPV (hPa)	Grade	Forecast Hours	Lat. (N)	Long. (E)	CPV (hPa)	Grade	Distance Error (km)	CPV Error	Forecast Hours	Lat. (N)	Long. (E)	CPV (hPa)	Grade	Distance Error (km)	CPV Error
23/0600	16.50	88.00	998	D	06 hrs	16.2	88.5	994.0	D	64	4.0							
23/1200	16.50	88.00	994	D	12 hrs	17.3	89.5	993.6	D	187	-0.4							
23/1800	17.00	88.50	996	D	18 hrs	17.8	89.5	989.8	D	141	-6.2							
24/0000	17.00	88.50	992	D	24 hrs	18.7	89.1	985.7	DD	198	-6.3							
24/0600	18.00	88.50	988	DD	30 hrs	18.8	88.3	981.7	CS	91	-6.3	06 hrs	18.4	87.8	990.0	DD	89	2.0
24/1200	18.50	88.50	986	CS	36 hrs	18.9	88.8	977.4	CS	55	-8.6	12 hrs	18.2	88.5	986.9	CS	33	0.9
24/1800	19.00	88.50	986	CS	42 hrs	19.6	88.7	975.0	SCS	70	-11.0	18 hrs	20.2	88.2	983.1	CS	136	-2.9
25/0000	20.00	88.00	980	CS	48 hrs	20.5	88.9	970.2	SCS	113	-9.8	24 hrs	20	88.8	976.8	SCS	88	-3.2
25/0600	21.50	88.00	974	SCS	54 hrs	21.5	88.9	967.4	SCS	99	-6.6	30 hrs	22	88	975.3	SCS	0	1.3
25/1200	22.50	88.00	970	SCS	60 hrs	22.5	89	970.1	SCS	110	0.1	36 hrs	23.2	88.5	974.6	SCS	95	4.6
25/1800	23.50	88.00	980	CS	66 hrs	24	89.1	975.5	SCS	133	-4.5	42 hrs	24.2	88.2	978.3	CS	80	-1.7

Note : Highlighted cells depict values at the observed & predicted landfall time

TABLE 5

Prediction errors in landfall distance & time and CPV error (Actual Landfall: 22° N / 88° E on 25 May 2009 at 0900 UTC)

Initial Conditions	Landfall (Lat./Long.)	Landfall (Date/Time)	Error Distance/Time	CVP Error (hPa)
23 May 2009 (With Cu Para)	22.1° N / 89.50° E	25 May 2009 /1800 UTC	165 km / 9 hours (Late)	-1.7
24 May 2009 (With Cu Para)	21.75° N / 88.20° E	25 May 2009 / 0900 UTC	35 km / 0 hours (In Time)	8.6 to 12.5
23 May 2009 (Without Cu Para)	22.00° N / 88.95° E	25 May 2009 / 0900 UTC	105 km / 0 hours (In Time)	-6.6 to 0.1
24 May 2009 (Without Cu Para)	22.00° N / 88.00° E	25 May 2009 / 0600 UTC	0 km / 3 hours (Early)	1.3

TABLE 6

Predicted maximum values of few NWP products from the initial conditions of 23 & 24 May 2009 (0000 UTC) with cumulus parameterization Scheme both in outer & inner domains with actual maximum values of 3 hourly TRMM rainfall and reflectivity of DWR Kolkata

Initial Conditions : 23 May 2009 (0000 UTC)										Initial Conditions : 24 May 2009 (0000 UTC)								
Forecast Hours	Date/Time	Vorticity at 850 hPa ($1x10^{-5}$/sec)	Max Divergence at 200 hPa (1×10^{-5}/sec)	Vertical Velocity at 500 hPa (cm/sec)	Max Moisture Convergence at 850 hPa (1×10^{-5} g/sec)	Max Predicted 3 hrly Rainfall (mm)	Max 3 hrly TRMM Rainfall (mm)	Max Predicted Radar Reflectivity (dBz)	Max Actual Radar Reflectivity (DWR Kolkata)	Forecast Hours	Vorticity at 850 hPa (1×10^{-5}/sec)	Max Divergence at 200 hPa (1×10^{-5}/sec)	Vertical Velocity at 500 hPa (cm/sec)	Max Moisture Convergence at 850 hPa (1×10^{-5} g/sec)	Max Predicted 3 hrly Rainfall (mm)	Max 3 hrly TRMM Rainfall (mm)	Max Predicted Radar Reflectivity (dBz)	Max Actual Radar Reflectivity (DWR Kolkata)
06 hrs	23/0600	75.44	34.15	148.65	-9.45	49.26	85.14	40.85										
12 hrs	23/1200	86.85	40.77	119.23	-10.16	44.41	59.79	40.67										
18 hrs	23/1800	79.13	37.86	142.95	-12.70	42.51	108.23	29.80										
24 hrs	24/0000	72.10	42.83	207.38	-13.72	77.27	156.39	39.61										
30 hrs	24/0600	100.04	51.91	153.38	-18.16	56.10	149.52	37.88		06 hrs	76.03	33..86	182.19	-9.61	45.72	149.52	39.30	
36 hrs	24/1200	113.83	42.96	167.31	-9.45	44.54	133.38	36.71		12 hrs	72.08	58.39	168.98	-15.54	44.25	133.38	43.62	
42 hrs	24/1800	106.23	43.73	135.78	-12.00	49.01	128.58	39.95		18 hrs	98.33	60.22	159.65	-14.49	85.77	128.58	42.18	
48 hrs	25/0000	161.21	48.28	180.38	-16.83	84.97	90.60	40.86	46.00	24 hrs	139.59	55.12	209.10	-17.82	75.34	90.60	41.34	46.00
54 hrs	25/0600	167.68	68.02	145.81	-11.59	62.94	109.11	42.36	>50.00	30 hrs	119.72	73.34	166.72	-11.65	71.36	109.11	44.84	>50.00
60 hrs	25/1200	152.15	68.70	302.98	-14.58	65.35	100.47	49.20	>50.00	36 hrs	123.69	75.43	316.57	-22.20	81.46	100.47	52.80	>50.00
66 hrs	25/1800	238.92	88.00	642.92	-17.14	97.12	90.57	55.34		42 hrs	133.8	86.51	228.49	-13.40	86.99	90.57	42.73	
72 hrs	26/0000	188.99	90.03	280.08	-16.81	84.55	130.70	45.11		48 hrs	109.77	75.87	242.34	-23.90	70.51	130.70	54.50	

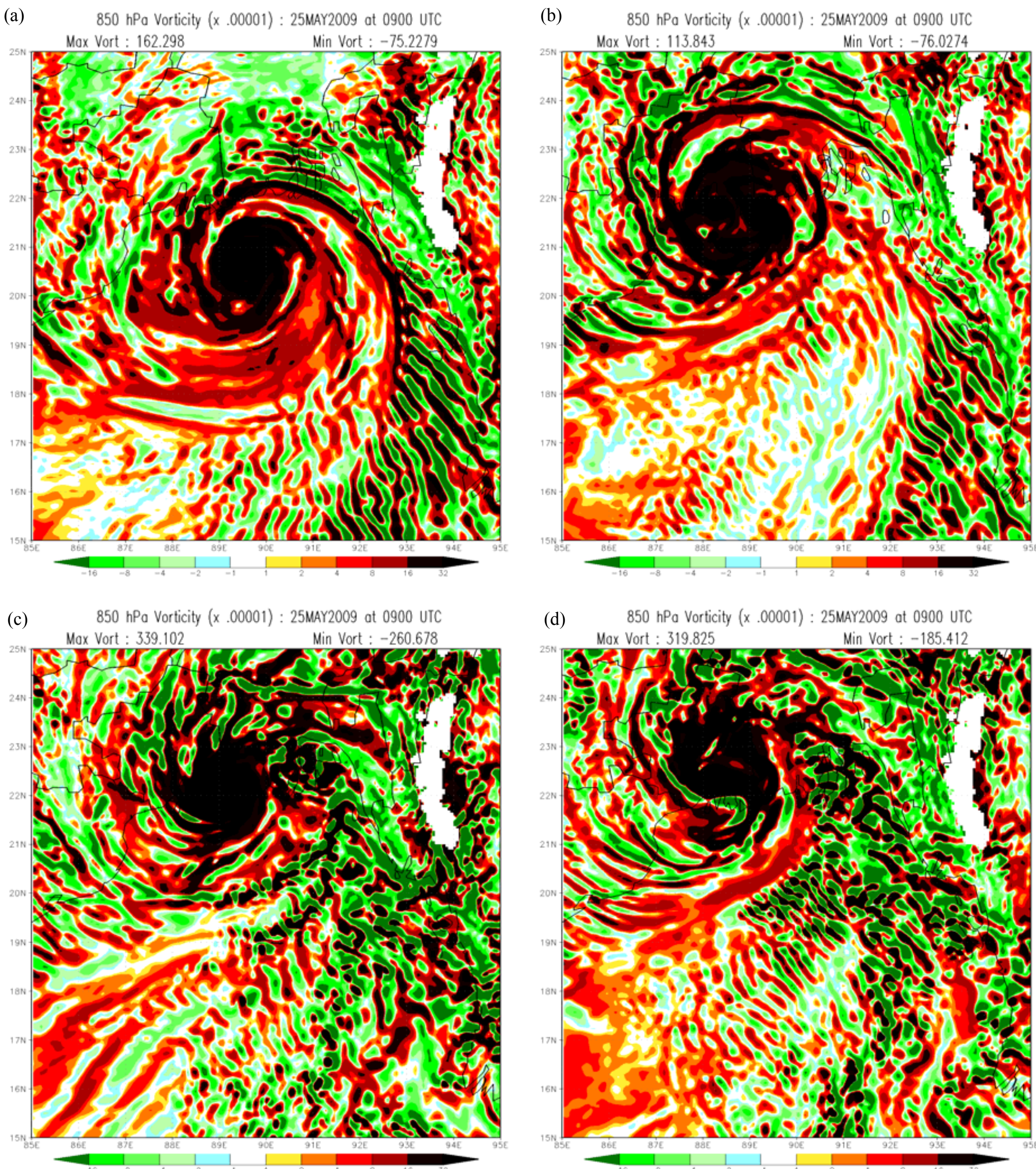
Note : Highlighted cells depict values at the predicted landfall time

TABLE 7

Predicted maximum values of few NWP products from the initial conditions of 23 & 24 May 2009 (0000 UTC) with without cumulus parameterization scheme in inner domain with actual maximum values of 3 hourly TRMM rainfall and reflectivity of DWR Kolkata

Initial Conditions: 23 May 2009 (0000 UTC)										Initial Conditions: 24 May 2009 (0000 UTC)								
Forecast Hours	Date/Time	Vorticity at 850 hPa (1×10^{-5}/sec)	Max Divergence at 200 hPa (1×10^{-5}/sec)	Vertical Velocity at 500 hPa	Max Moisture Convergence at 850 hPa (1×10^{-5} g/sec)	Max Predicted 3 hrly Rainfall (mm)	Max 3 hrly TRMM Rainfall (mm)	Max Predicted Radar Reflectivity (dBz)	Max Actual Radar Reflectivity (DWR Kolkata)	Forecast Hours	Vorticity at 850 hPa (1×10^{-5}/sec)	Max Divergence at 200 hPa (1×10^{-5}/sec)	Vertical Velocity at 500 hPa	Max Moisture Convergence at 850 hPa (1×10^{-5} g/sec)	Max Predicted 3 hrly Rainfall (mm)	Max 3 hrly TRMM Rainfall (mm)	Max Predicted Radar Reflectivity (dBz)	Max Actual Radar Reflectivity (DWR Kolkata)
06 hrs	23/0600	266.57	347.22	1429.24	-38.16	189.08	85.14	62.23										
12 hrs	23/1200	213.87	312.67	1188.20	-24.67	240.65	59.79	60.92										
18 hrs	23/1800	254.26	276.36	1406.77	-25.56	116.67	108.23	61.06										
24 hrs	24/0000	243.33	290.02	1445.27	-26.27	134.32	156.39	58.18										
30 hrs	24/0600	384.37	244.55	1663.22	-35.87	401.24	149.52	60.86		06 hrs	254.54	289.07	1157.31	-33.63	307.61	149.52	59.63	
36 hrs	24/1200	448.22	262.71	1473.93	-27.22	160.43	133.38	59.81		12 hrs	291.47	296.18	1169.6	-26.28	238.46	133.38	58.93	
42 hrs	24/1800	304.32	331.96	1664.28	-36.21	126.25	128.58	62.73		18 hrs	371.72	309.91	1347.8	-32.64	193.68	128.58	59.13	
48 hrs	25/0000	361.77	325.39	1828.38	-44.67	200.65	90.60	62.71	46.00	24 hrs	320.66	345.18	1336.03	-39.60	249.01	90.60	63.10	46.00
54 hrs	25/0600	289.09	251.14	1509.00	-35.13	232.85	109.11	60.19	50.00	30 hrs	287.9	219.45	1678.77	-35.10	148.86	109.11	59.98	50.00
60 hrs	25/1200	246.29	181.99	1016.63	-30.16	232.60	100.47	61.44	50.00	36 hrs	251.95	297.39	1791.97	-32.27	235.12	100.47	60.36	50.00
66 hrs	25/1800	256.86	379.23	1369.84	-46.67	104.52	90.57	62.15		42 hrs	221.12	312.87	1318.63	-40.55	112.72	90.57	62.05	
72 hrs	26/0000	234.27	357.64	1446.54	-37.09	266.46	130.70	60.62		48 hrs	200.64	250.44	1474.69	-30.26	168.08	130.70	58.23	

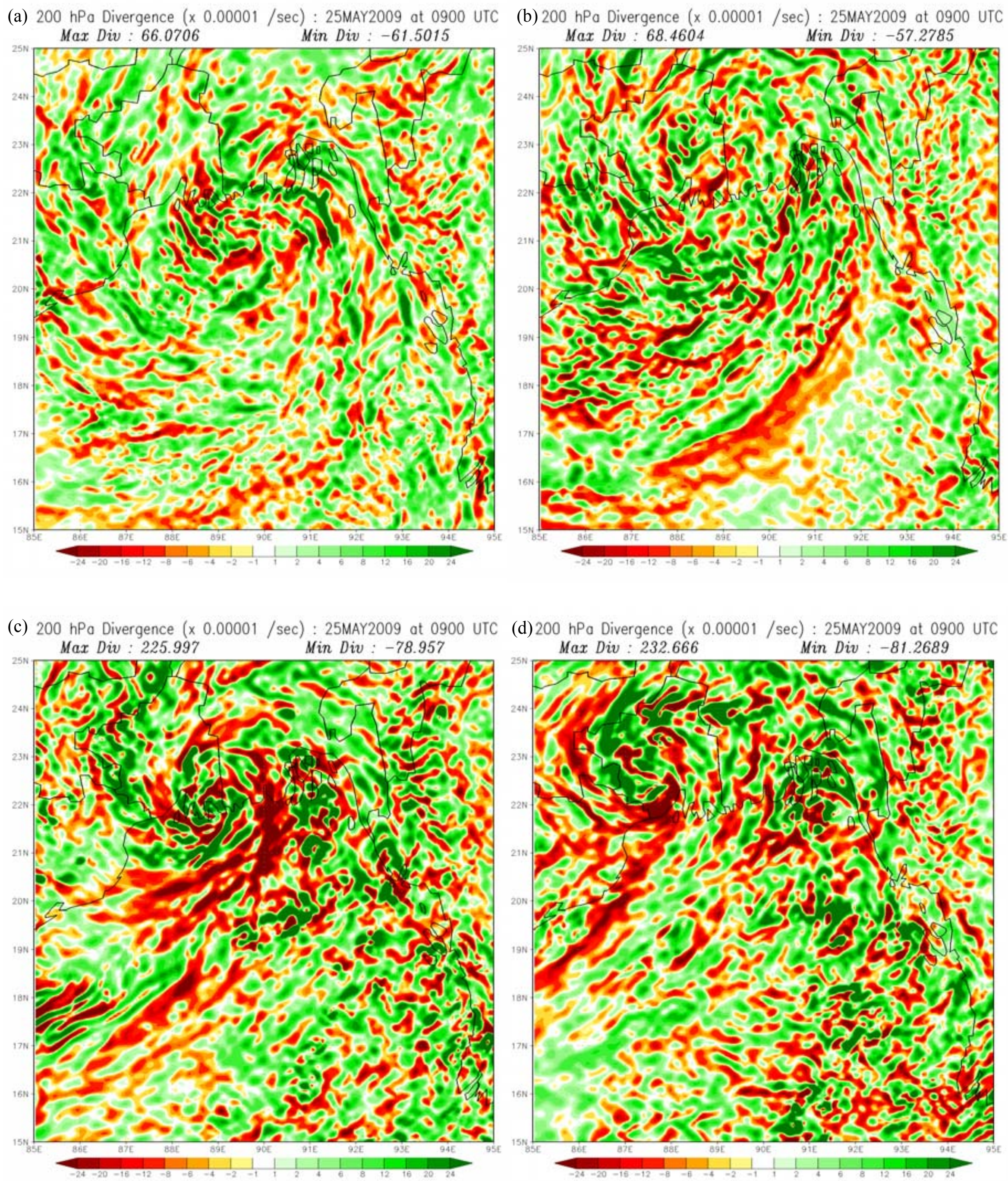
Note : Highlighted cells depict values at the predicted landfall time



Figs. 3(a-d). Vorticity at 850 hPa, based on initial conditions of (a) 23 May 2009 / 0000 UTC valid for 25 May 2009 / 0900UTC, (b) 24 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC, (c) 23 May 2009 / 0000 UTC valid for 25 May 2009 / 0900UTC and (d) 24 May 2009 / 0000 UTC valid for 25 May 2009 / 0900UTC (Without Cu Parameterisation)

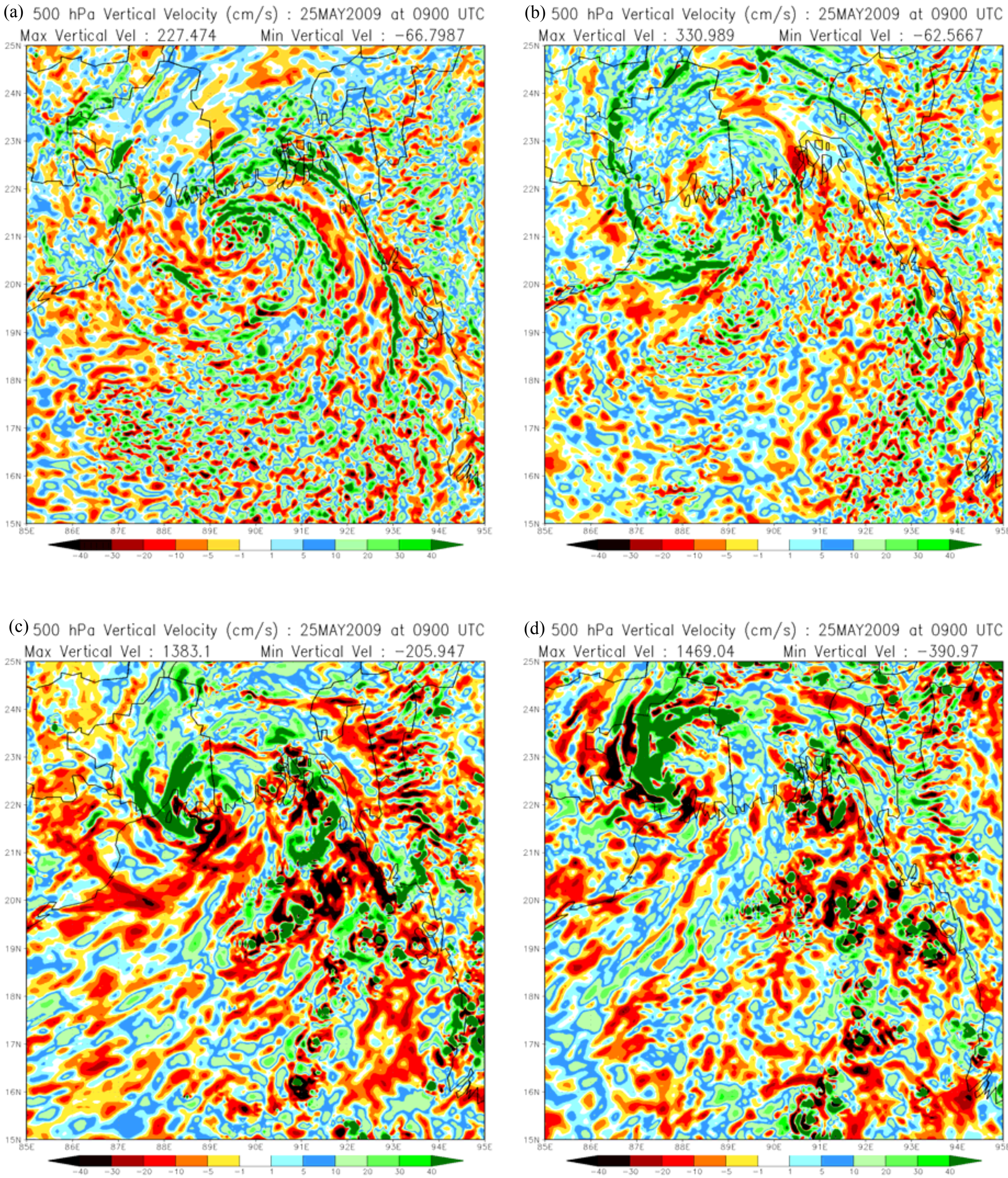
3. Data and methodology

Track, intensity and few other products generated through the finer domain of 6 km by using the 0000 UTC initial conditions of 23rd May 2009 (D-2) and 24th May 2009 (D-1), have been studied. To understand the efficacy of the IAF model towards enhancing advance warning of the impending adverse weather, IR imagery of Kalpana-I, merged rainfall dataset from TRMM 3B42V6 and Maximum Radar Reflectivity as given by the DWR of



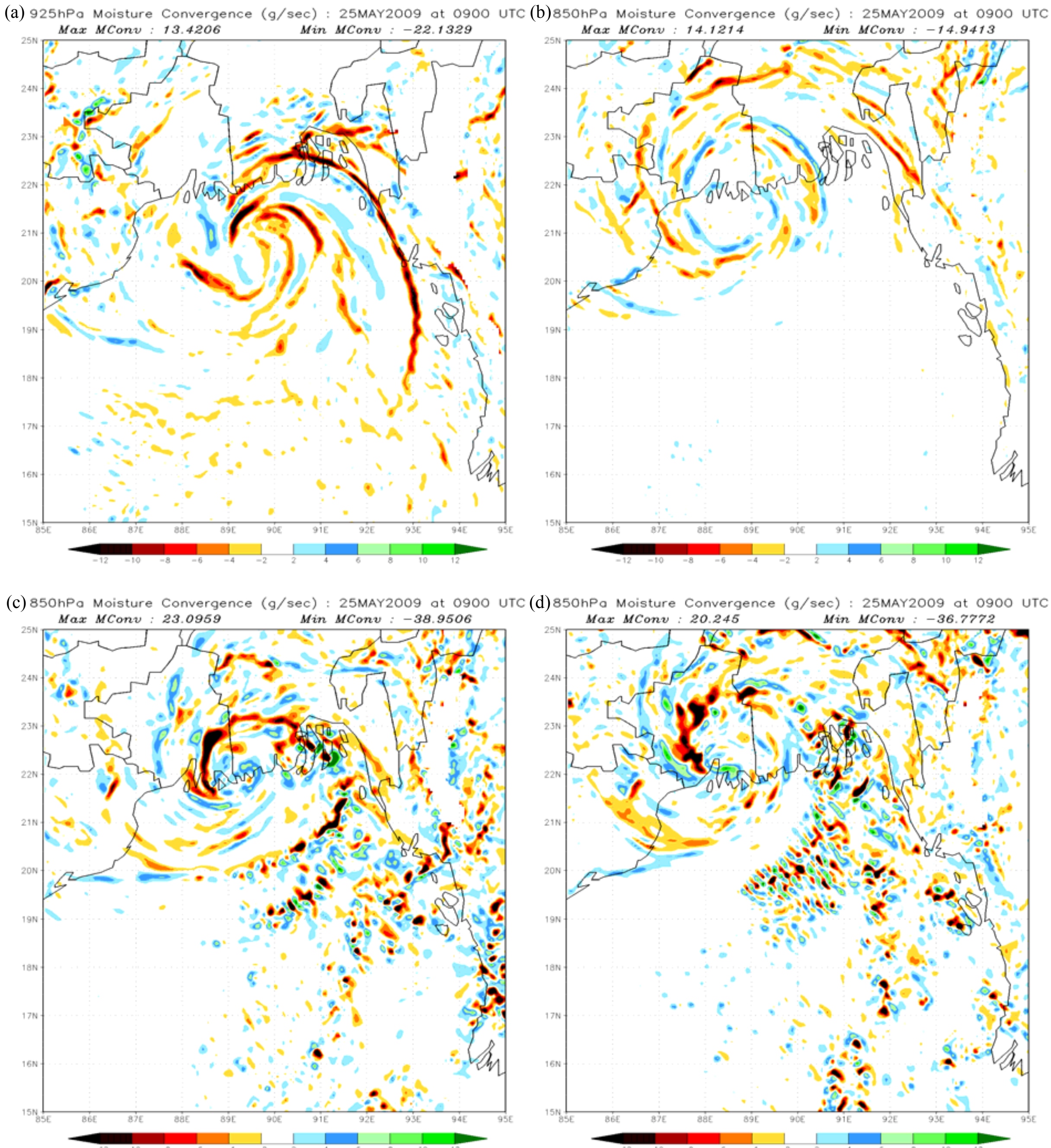
Figs. 4(a-d). Divergence at 200 hPa, based on initial conditions of (a) 23 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC, (b) 24 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC, (c) 23 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC and (d) 24 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC (With Cu Parameterization)

Kolkata has been compared with the model generated total cloud cover, rainfall and radar reflectivity. Two sets of model runs were done. First set consisted of the default runs with cumulus parameterization in the finer domain of 6 km. To study the effect of removing the cumulus parameterization at 6 km, second set of experiments were designed without cumulus parameterization in the finer domain. Details of the experimental designs are shown in



Figs. 5(a-d). Vertical Velocity at 500 hPa, based on initial conditions of (a) 23 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC, (b) 24 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC, (c) 23 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC and (d) 24 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC (With Cu Parameterisation)

Table 2. For better appreciation of predicted patterns, products were generated for the region within longitude 15° N to 25° N and latitude 85° E to 95° E. Detailed discussion is done for six hourly products from the two set of experiments for predicted time period valid from 23 May 2009 / 0600 UTC to 25 May 2009/1800 UTC and from 24 May 2009/0600 UTC to 25 May 2009/1800 UTC.



Figs. 6(a-d). Moisture Convergence at 850 hPa, based on initial conditions of (a) 23 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC, (b) 24 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC, (c) 23 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC and (d) 24 May 2009 / 0000 UTC valid for 25 May 2009 / 0900 UTC (Without Cu Parameterization)

4. Results and discussions

4.1. *Predicted track and intensity of 'AILA'*

As shown in the Figs. 2(a-d), a general northerly track was predicted by the initial conditions of D-2 and D-1 in the two sets of experiments. Deviations in predicted track from that observed had more eastward bias from the initial conditions of D-2 than that of D-1. Eastward bias reduced in the set of experiments without cumulus parameterization in the finer domain. Predicted and observed track (centre of the system) and

Comparison of Products From Exp-1 & 2: Initial Conditions of 23 May 2009 / 0000 UTC

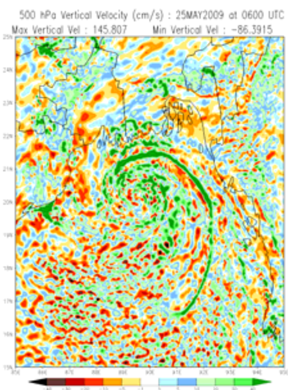


Fig. 7(a). Vertical Velocity at 500 hPa valid for 25 May 2009 / 0600 UTC (With Cu Para)

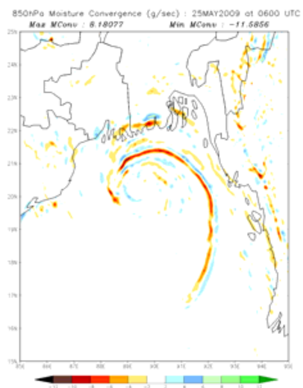


Fig. 7(b). Moisture Convergence at 850 hPa valid for 25 May 2009 / 0600 UTC (With Cu Para)

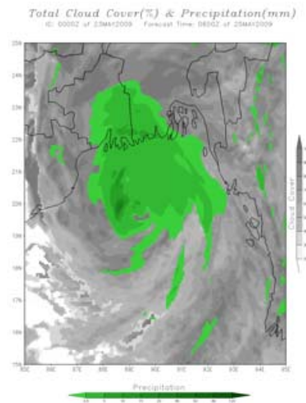


Fig. 7(c). Total Cloud Cover & 6 hrly Pptn valid for 25 May 2009 / 0600 UTC (With Cu Para)

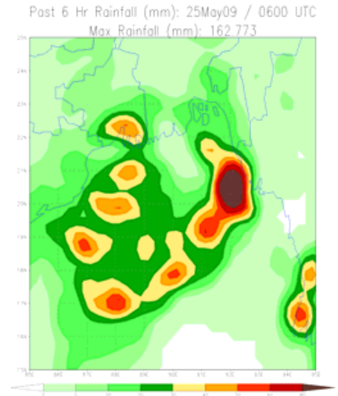


Fig. 7(d). TRMM 3B42V7 6h Rainfall valid at 0600 UTC / 25 May 2009

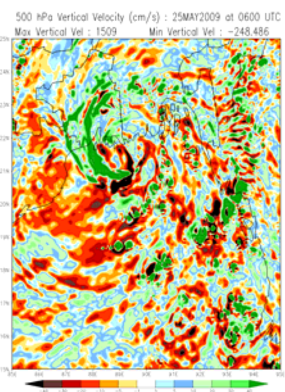


Fig. 7(e). Vertical Velocity at 500 hPa valid for 25 May 2009 / 0600 UTC (Without Cu Para)

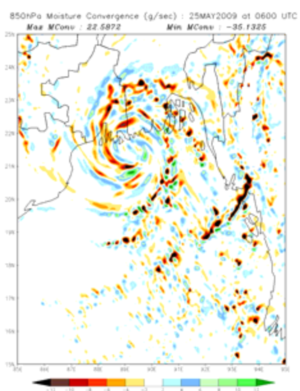


Fig. 7(f). Moisture Convergence at 850 hPa valid for 25 May 2009 / 0600 UTC (Without Cu Para)

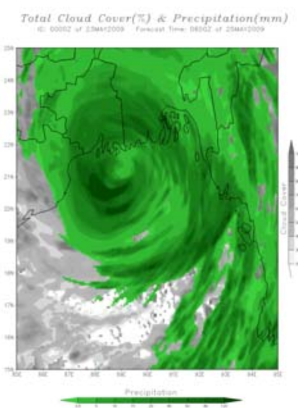


Fig. 7(g). Total Cloud Cover & 6 hrly Pptn valid for 25 May 2009 / 0600 UTC (Without Cu Para)

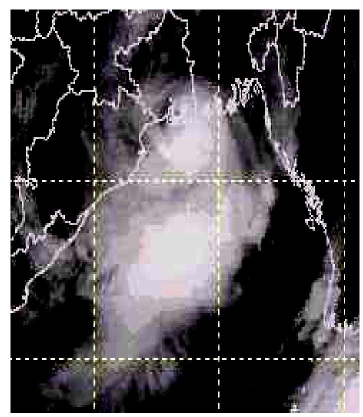


Fig. 7(h). Kalpana-I, IR Image valid at 25 May 2009 / 0600 UTC

intensity (central pressure values) from the different initial conditions are summarized in Tables 3 & 4. Table 5 shows the prediction errors in distance and time of landfall. On D-2 the landfall was predicted 165 km East and nine hours later in Exp. 1 which reduced to 104 km East and at the same time in Exp. 3, in comparison to the actual location and time. D-1 had relatively better prediction as Exp. 2 predicted landfall 35 km East with no error in time where as the error reduced to nil though the landfall time was three hours early in Exp. 4. The isobaric patterns confirmed well with the actual pattern throughout the predicted period however the forecast values of central pressure were higher in the first set of experiment and generally lower in the second set. Values were nearly realistic in Exp. 4.

4.2. *Vorticity at 850 hPa and divergence at 200 hPa*

After the onset of South West Monsoon over Andaman Sea and adjoining south Bay of Bengal by 20th May 2009, increase in the southerly surge resulted in increase in relative vorticity over the South East Bay of Bengal. It led to the formation of a low pressure area over the region on 22nd May 2009. Due to presence of high magnitude of the low level relative vorticity that was commensurate with the values of upper level divergence

Comparison of Products From Exp-3 & 4: Initial Conditions of 24 May 2009 / 0000 UTC

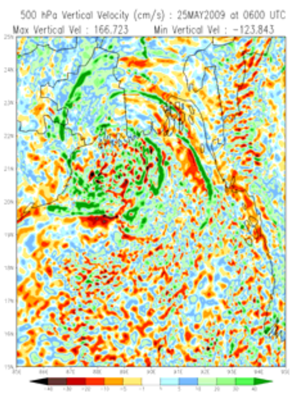


Fig. 8(a). Vertical Velocity at 500 hPa valid for 25 May 2009 / 0600 UTC (With Cu Para)

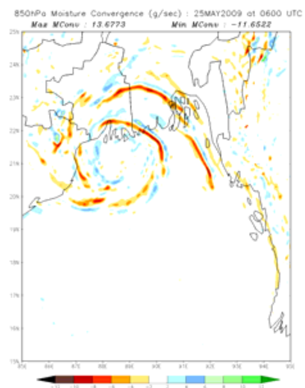


Fig. 8(b). Moisture Convergence at 850 hPa valid for 25 May 2009 / 0600 UTC (With Cu Para)

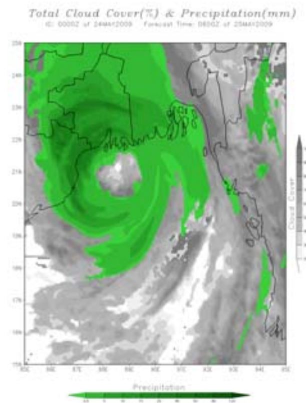


Fig. 8(c). Total Cloud Cover & 6 hrly Pptn valid for 25 May 2009 / 0600 UTC (With Cu Para)

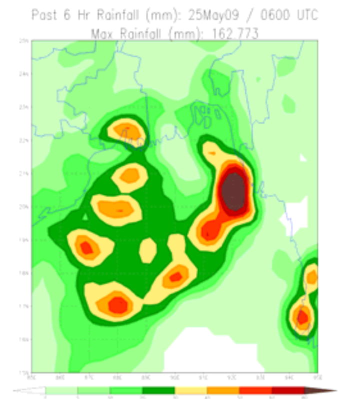


Fig. 8(d). TRMM 3B42V7 6h Rainfall valid at 0600 UTC / 25 May 2009

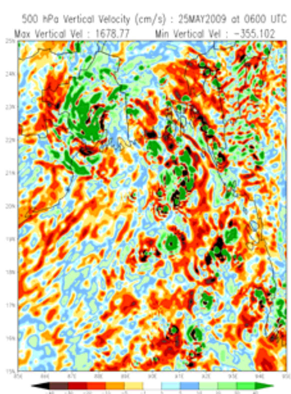


Fig. 8(e). Vertical Velocity at 500 hPa valid for 25 May 2009 / 0600 UTC (Without Cu Para)

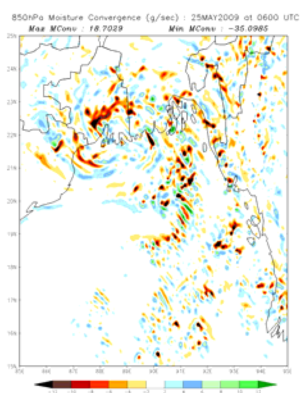


Fig. 8(f). Moisture Convergence at 850 hPa valid for 25 May 2009 / 0600 UTC (Without Cu Para)

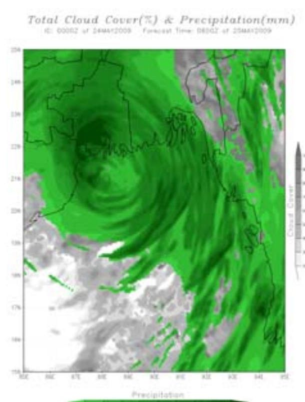


Fig. 8(g). Total Cloud Cover & 6 hrly Pptn valid for 25 May 2009 / 0600 UTC (Without Cu Para)

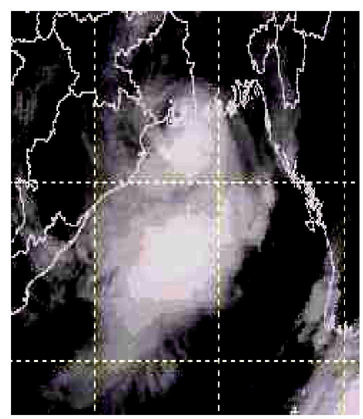


Fig. 8(h). Kalpana-I, IR Image valid for 25 May 2009 / 0600 UTC

around the centre of the system, intensification of the system continued. By 1730 hrs (IST) of 24th May 2009 it intensified into a cyclonic storm 'AILA' and lay centred at 18.50º N / 88.50º E. Juxtaposition of higher values of low level convergence and upper level divergence maintained the strength of the system before it started weakening after 0000 UTC of 26th May 2009. Figs. 3(a-d) & 4(a-d) show the pattern of vorticity at 850 hPa and divergence at 200 hPa valid for 0900 UTC of 25th May 2009. It clearly highlights high magnitude of low level relative vorticity with commensurating values of upper level divergence. The pattern brings out the low level convergence juxtaposed by upper level divergence and further the values are apparently more realistically predicted by the model on D-1. As seen in Tables 6 & 7, predicted values of maximum vorticity at 850 hPa and divergence at 200 hPa were relatively lower in the first set of experiments with cumulus parameterization in both the domains in comparison to the second set of experiments where these values were significantly higher.

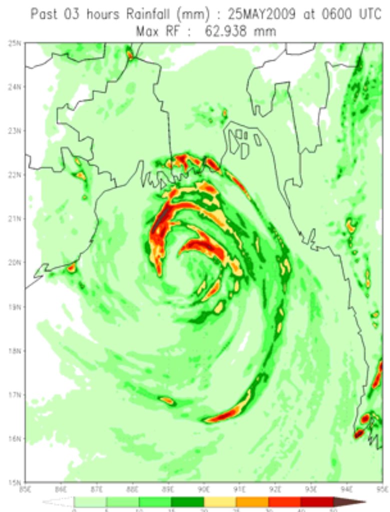


Fig. 9(a). Rainfall based on IC of 23 May 2009 / 0000 UTC (With Cu Para)

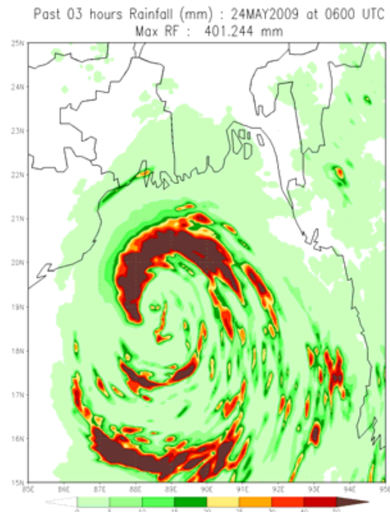


Fig. 9(b). Rainfall based on IC of 23 May 2009 / 0000 UTC (Without Cu Para)

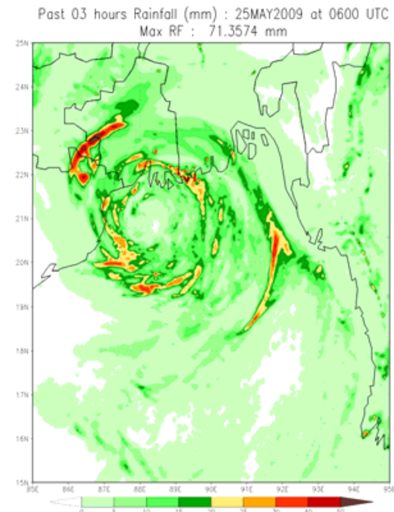


Fig. 9(c). Rainfall based on IC of 24 May 2009 / 0000 UTC (With Cu Para)

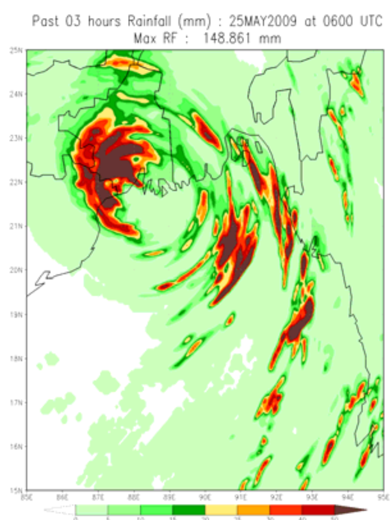


Fig. 9(d). Rainfall based on IC of 24 May 2009 / 0000 UTC (Without Cu Para)

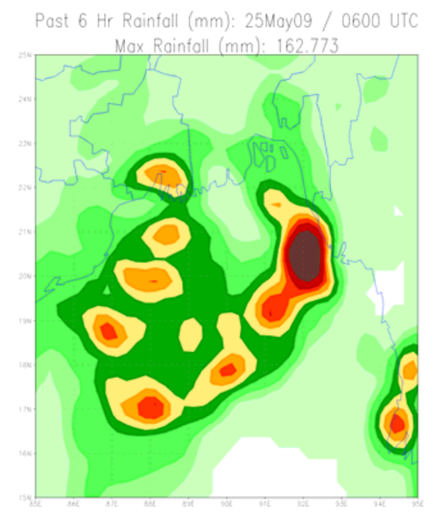


Fig. 9(e). TRMM 3B42V6 6h Rainfall valid at 0600 UTC / 25 May 2009

4.3. *Vertical velocity at 500 hPa*

Low level convergence if overlaid by upper level divergence will lead to higher positive values of upward vertical velocity at the level of no-divergence (LND). Shown in Figs. 5(a-d) is the predicted pattern of vertical velocity at 500 hPa valid for 25th May 0900 UTC, using initial conditions of D-2 and D-1 with and without cumulus parameterization in the inner domain of 6 km. Higher positive values of the vertical velocity at 500 hPa predicted by the model, match well with the convective cloud patterns as shown by the imageries of Kalpana-I, of similar times. It is also noticed that the patterns are better defined with cumulus parameterization than without it. The maximum values of vertical velocity are relatively lower in the first in the first set of experiments with cumulus parameterization in both the domains in comparison to the second set of experiments where these

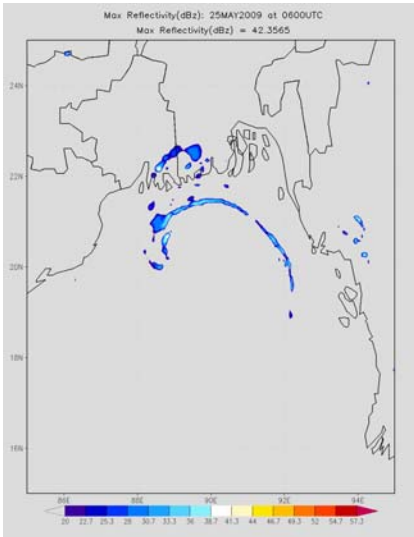


Fig. 10(a). Model Predicted Max Reflectivity 0600 UTC / 25 May 2009 IC : 23 May 2009 / 0000 UTC (with CP)

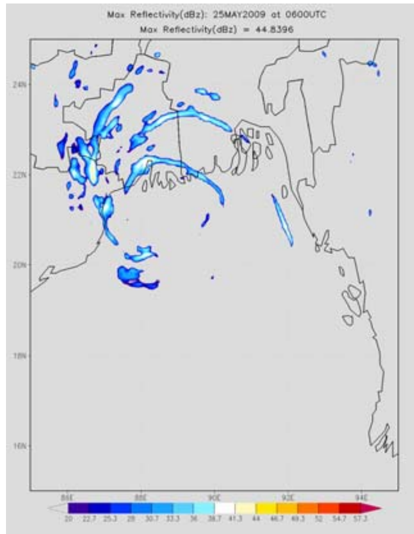


Fig. 10(b). Model Predicted Max Reflectivity 0600 UTC / 25 May 2009 IC : 24 May 2009 / 0000 UTC (with CP)

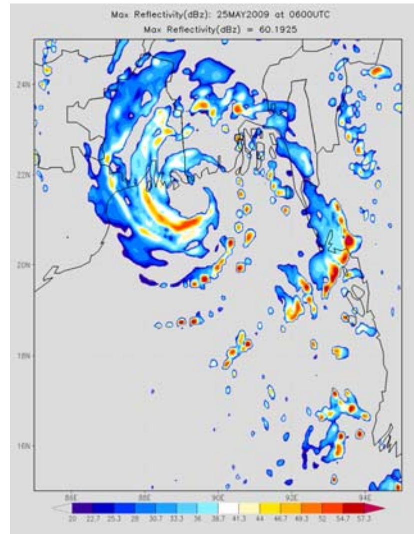


Fig. 10(c). Model Predicted Max Reflectivity 0600 UTC / 25 May 2009 IC : 23 May 2009 / 0000 UTC (without CP)

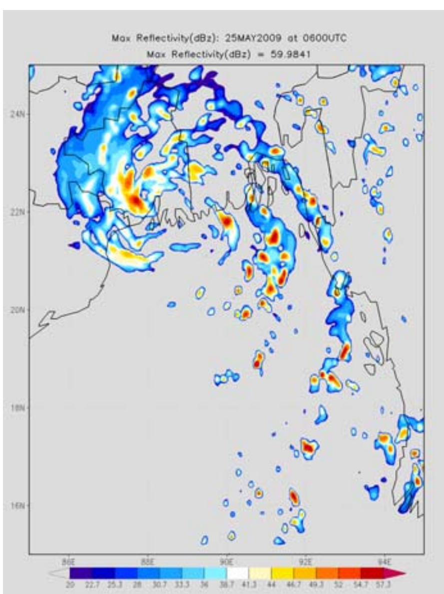


Fig. 10(d). Model Predicted Max Reflectivity 0600 UTC / 25 May 2009 IC : 24 May 2009 / 0000 UTC (without CP)

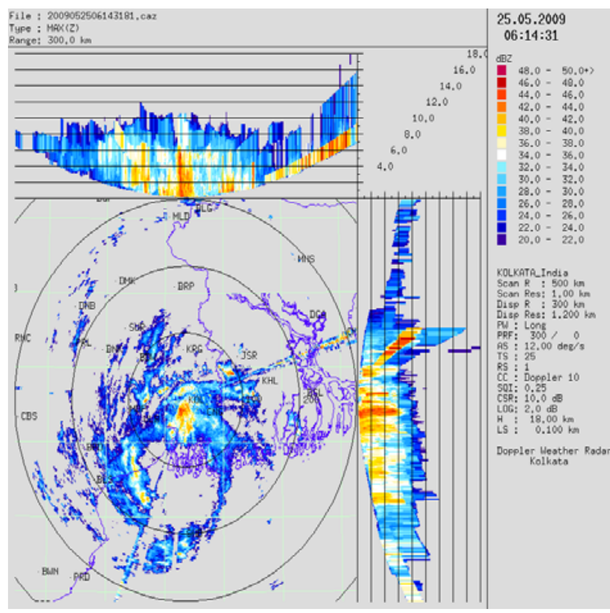


Fig. 10(e). Max Reflectivity by Kolkata DWR at 0614 UTC / 25 May 2009

values were significantly higher. It could be because at resolution of 6 km cloud resolving methodology may not function as well as compared to its performance in relatively finer resolution (say at 1-3 km) where the results may apparently be better.

4.4. *Moisture convergence at 850 hPa*

Moisture advection is horizontal transport of moisture, which plays a very important role in the development of precipitation. If little moisture is

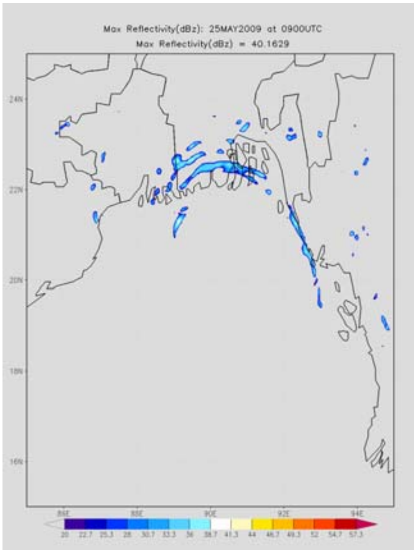


Fig. 11(a). Model Predicted Max Reflectivity 0900 UTC / 25 May 2009 IC : 23 May 2009 / 0000 UTC (with CP)

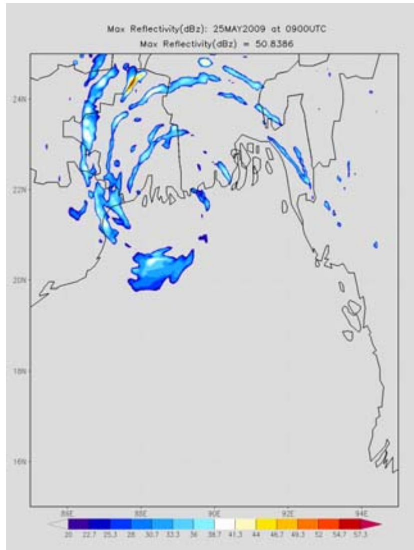


Fig. 11(b). Model Predicted Max Reflectivity 0900 UTC / 25 May 2009 IC : 24 May 2009 / 0000 UTC (with CP)

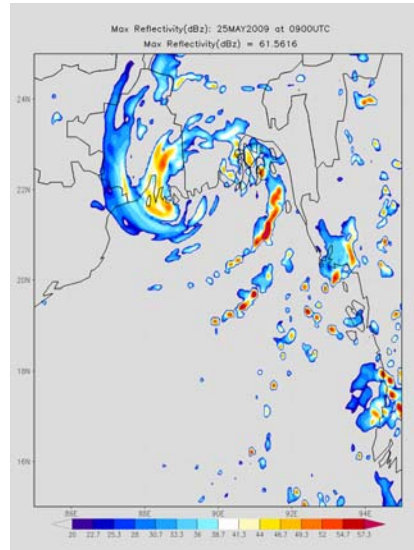


Fig. 11(c). Model Predicted Max Reflectivity 0900 UTC / 25 May 2009 IC : 23 May 2009 / 0000 UTC (without CP)

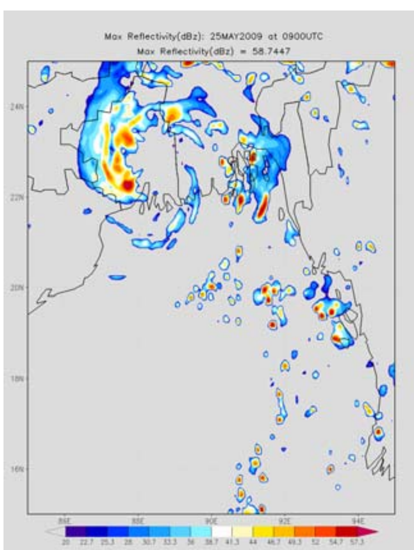


Fig. 11(d). Model Predicted Max Reflectivity 0900 UTC / 25 May 2009 IC : 24 May 2009 / 0000 UTC (without CP)

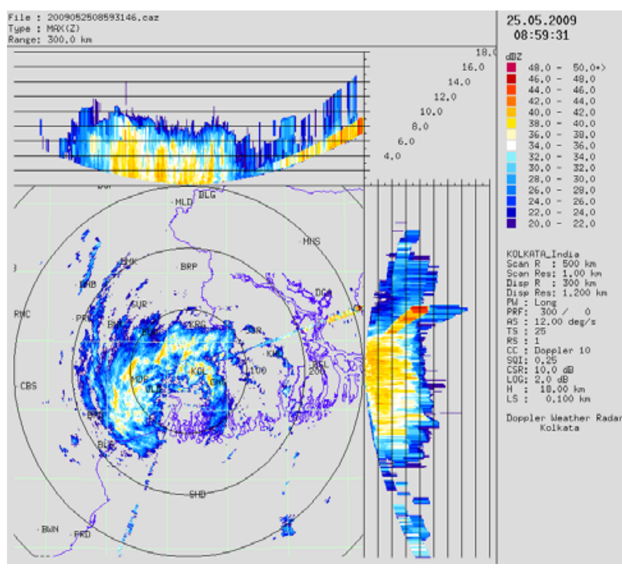


Fig. 11(e). Max Reflectivity by Kolkata DWR at 0859 UTC / 25 May 2009

available, it is unlikely that precipitation will occur. However, if any system is supplied with an abundance of moisture, there is an increased likelihood that heavy precipitation will be realized. Shown in Figs. 6(a-d) is the predicted pattern of moisture convergence at 850 hPa valid for 25th May 0900 UTC, using initial conditions of D-2 and D-1 with and without cumulus parameterization in the inner domain of 6 km. As in the case of vertical

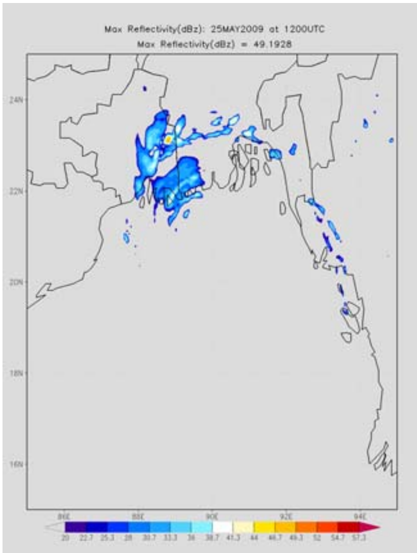


Fig. 12(a). Model Predicted Max Reflectivity 1200 UTC / 25 May 2009 IC : 23 May 2009 / 0000 UTC (with CP)

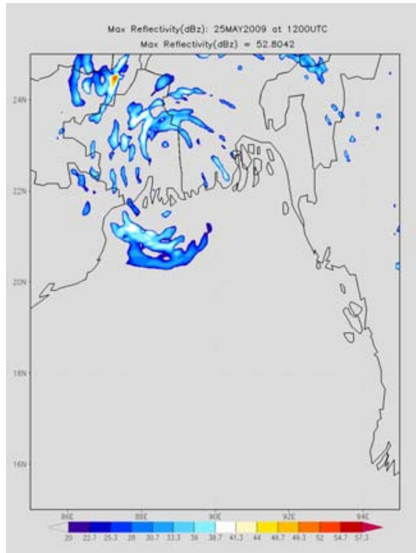


Fig. 12(b). Model Predicted Max Reflectivity 1200 UTC / 25 May 2009 IC : 24 May 2009 / 0000 UTC (with CP)

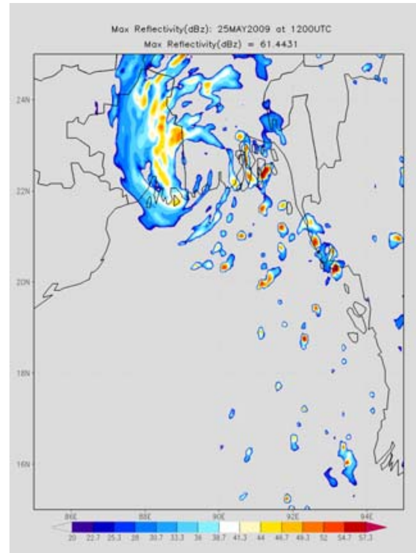


Fig. 12(c). Model Predicted Max Reflectivity 1200 UTC / 25 May 2009 IC : 23 May 2009 / 0000 UTC (without CP)

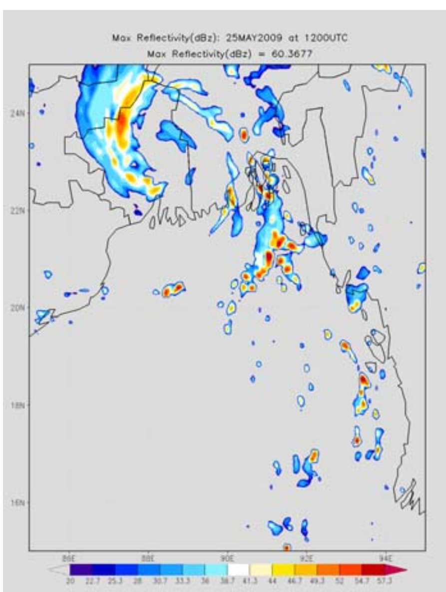


Fig. 12(d). Model Predicted Max Reflectivity 1200 UTC / 25 May 2009 IC : 24 May 2009 / 0000 UTC (without CP)

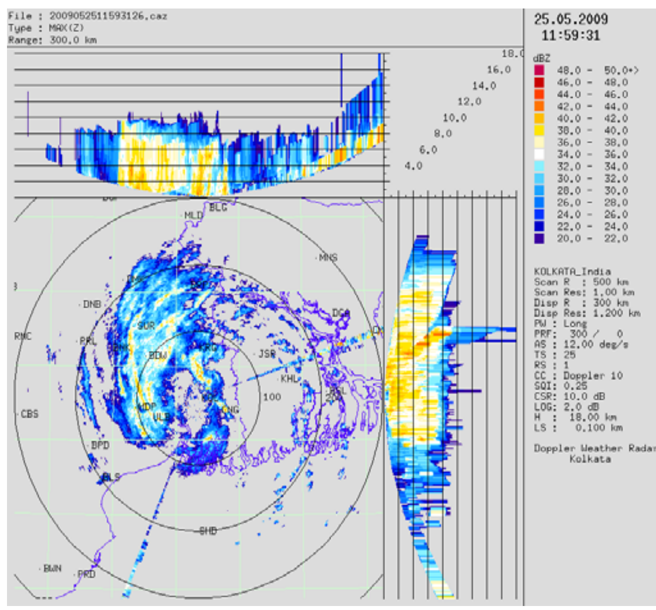


Fig. 12(e). Max Reflectivity by Kolkata DWR at 1159 / 25 May 2009

velocity the pattern of maximum moisture convergence is well defined when cumulus parameterization scheme is employed in the inner domain. The spread is relatively more in when no cumulus parameterization is used. It is noticed that the maximum moisture convergence as predicted on D-2 and D-1 match well with the areas of precipitation. To study the efficacy of predicted values of moisture convergence, its comparison was done with the IR images of Kalpana - I of the corresponding times. It was seen that the threshold values of moisture convergence (that corresponds to increasing convection and thereby production of convective clouds in the satellite imageries) achieved by the model was delayed when cumulus parameterization scheme was used in the inner domain. Subsequently on comparison, it is seen that three hourly rainfall patterns of TRMM 3B42V7 match well with the areas of high magnitude of moisture convergence. This rich moisture supply was enough for showers and thunderstorms to develop as indicated by the radar echoes of Kolkata DWR of similar times. It is to be noted that the precipitation was located in the region where the strongest moisture convergence was predicted.

4.5. *Total cloud cover*

This product is still in experimental mode. Modifications have been done for the display of predicted clouds by suppressing or enhancing the values of low, medium and high clouds to get the best possible realistic picture by comparing it with the Kalpana – I image of the same time, in the hind cast mode. To make the product more meaningful 6 hourly predicted rainfall patterns has been superimposed over the predicted total cloud cover. In the case discussed here, this product matched well with the corresponding actual Kalpana-I IR images of the similar times. Vertical velocity at 500 hPa, Moisture Convergence at 850 hPa, total cloud cover with 6 hourly precipitation predicted for 0600 UTC of 25th May 2009 along with IR imagery of Kalpana-I and 6 hourly rainfall given by TRMM 3B46V7 valid for same date and time are shown in Figs. 7(a-h) & Figs. 8(a-h). Its qualitative comparison brings out that predicted positive values of the vertical velocity at 500 hPa (LND) where the convective clouding may be expected, match well with actual cloud patterns shown by the Kalpana-I IR image. Further, predicted moisture convergence at 850 hPa where more convection and therefore the rainfall match well with areas of convection and precipitation shown by the Kalpana-I IR image and TRMM 3B46V7 product valid for the same time. Pattern of predicted rainfall matched well on D-1 with the TRMM rainfall in terms of its spread and intensity around the centre of AILA.

4.6. *3 Hourly rainfall pattern*

TRMM 3B42V7 products were used for qualitative validation of the model predicted rainfall. It is seen in Figs. 9(a-e) that three hourly pattern of rainfall predicted by the model in the first set of experiments, with cumulus parameterization in both the domains, had relatively lesser spread in comparison to the second set of experiments in which no cumulus parameterization was used in the finer domain. Spread and intensity of predicted rainfall increased on the D-1 runs. Pattern of predicted rainfall in Exp. 4 matched well with the TRMM rainfall in terms of its spread and intensity. Table 6 shows that in the vicinity of the system maximum amounts of 3 hourly predicted rainfalls by the model in the first set of experiments remains lower in comparison to the TRMM. Anomaly reduces marginally on D-1. Table 7 shows that in the second set of experiments, the anomaly reverses as the model over predicts the maximum 3 hourly rainfall amounts in comparison to the TRMM 3B47V7 particularly around the landfall time.

4.7. *Maximum radar reflectivity*

The predicted patterns of D-2 and D-1 (Figs. 10-12) matched well with the actual Maximum Reflectivity shown by the DWR of Kolkata. When compared to the moisture convergence at 850 hPa, the pattern matches well with the highly reflective clouds, representing relatively higher convection, predicted by the model for the similar time. This aspect was apparent both with and without employment of cumulus parameterization scheme in the inner domain of 6 km and the patterns corresponded well in both the cases. Comparison of this product was done both with and without cumulus parameterization scheme in the nested domain of 6 km. When critically analysed, akin to the patterns of moisture convergence, there was a delay in prediction of highly reflective clouds with cumulus parameterization scheme than without it. It was also seen that the patterns produced without employing cumulus parameterization scheme matched relatively better with the actual DWR products of similar times and hence were more realistic. The same is shown for 0600 UTC, 0900 UTC and 1200 UTC on 25th May 2009 in Figs. 10 (a-e), Figs. 11 (a-e) and Figs. 12 (a-e), respectively. Tables 6 & 7 show that the maximum values of model predicted radar reflectivity around the landfall time are apparently higher than the observed values as inferred from the available legend of the Radar images Kolkata DWR.

5. Limitations

The comparison of the model predicted rainfall has been done with TRMM 3B42V7 for the purpose of validation. It needs to be appreciated that the rainfall estimated by remote sensing show lower rain rate than ground-based point data hence the comparisons will apparently get biased. Further, spatial resolution of TRMM is 0.25° but convective clouds and precipitation are usually at a finer resolution hence enhancing the errors when a compared to rainfall predicted by the NWP Models at higher resolution. Therefore, for improving the quality of forecast verification, there is a need for a higher resolution rainfall data with adequate rain gauge observations to retain important aspects of the precipitation patterns.

6. Conclusion

Predictions pertaining to track, intensity and rainfall etc. of 'AILA' from the finer domain of 6 km of the Operational NWP Model of the IAF had provided sufficient warning time to the users in the affected areas. The forecasts of D-1 were relatively better and more realistic in comparison to the one generated on D-2, with advance warning of more than 20 hours and 40 hours for its landfall, respectively. Employing cumulus parameterization scheme in finer domains has its own implications. In this study it was seen that the patterns produced with cumulus parameterization produced finer details in comparison to the patterns generated without it. Albeit, as demonstrated by the model generated patterns of maximum radar reflectivity without using cumulus parameterization scheme in the finer domain of 6km, compared well with the reflectivity of Kolkata DWR.

Acknowledgments

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