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Impact of physical parameterization schemes on the numerical simulation of Orissa Super Cyclone (1999)

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सार – 29 अक्तूबर, 1999 को उड़ीसा में आए महाचक्रवात को प्रतिरूपित करने के लिए पेनसिलवेनिया स्टेट यूनिवर्सिटी के राष्ट्रीय वायुमंडलीय अनुसंधान केन्द्र के मेसोस्केल मॉडल (एम. एम. 5) के गैर–द्रवस्थैतिक रूपांतर का उपयोग किया गया है। चक्रवात के मार्ग और उसके विकास पर कैन–फ्रिश, बेट्स–मिलर, ग्रेल और एंथेस–कुओ नामक चार कपासी प्राचलीकरण स्कीमों तथा हाँग–पैन और बर्क थॉम्पसन नामक दो ग्रहीय परिसीमा स्तर प्राचलीकरण (पी. बी. एल.) स्कीमो के प्रभाव का अध्ययन करने के लिए प्रयोग किए गए है। चक्रवात की गति, न्यूनतम दाब का विकास, वर्षा का पैटर्न और तापमान के उर्ध्वाधर क्रॉस सेक्शन के संबंध में संवेदनशीलता की जाँच की गई है।

एंथेस–कुओ स्कीम को छोड़कर अन्य सभी प्रतिरूपण अति क्षीण परिसंचरण से अति प्रचंड चक्रवातीय तूफान विकसित करने में सक्षम हैं। न्यूनतम केन्द्रीय दाब का बनना विभिन्न कपासी स्कीमों में अधिक संवेदनशीलता दर्शाता है जिसमें समाकलन अवधि के 4 दिनों के दौरान कैन–फ्रिश स्कीम से 966 है. पा. और एंथेस–कुओ स्कीम से 1004 है. पा. रही। प्रतिरूपित चक्रवात की गति पर विभिन्न कपासी प्राचलीकरण स्कीमों का महत्वपूर्ण प्रभाव रहा है। इससे प्राप्त हुए परिणामों से पता चला है कि कैन–फ्रिश और हाँग–पैन की मिली जुली स्कीमों से चक्रवात के न्यूनतम केन्द्रीय दाब का विकास और पवनों की क्षैतिज एवं उर्ध्वाधर संरचनाओं, तापमान विसंगतियों और रेनबैंड लक्षणों को अच्छी तरह प्रदर्शित किया जा सकता है।

ABSTRACT. Non-hydrostatic version of Pennsylvania State University- National Center for Atmospheric Research mesoscale model (MM5) is used to simulate the super cyclonic storm that crossed Orissa coast on 29 October, 1999. Experiments are carried out with four cumulus parameterization schemes namely; Kain-Fritsch, Betts-Miller, Grell and Anthes-Kuo and two planetary boundary layer parameterization (PBL) schemes namely; Hong-Pan and Burk-Thompson to study their impact on the movement and development of the cyclone. The sensitivity is examined in terms of movement, evolution of minimum pressure, rainfall pattern and vertical cross section of temperature.

All the simulations are able to develop the very severe cyclonic storm from very weak circulation except with Anthes-Kuo scheme. The evolution of the minimum central pressure shows much sensitivity among the different cumulus schemes with Kain-Fritsch producing 966 hPa while Anthes-Kuo 1004 hPa during the 4 days of the integration period. Different cumulus parameterization schemes show significant impact on the simulated movement of the cyclone. The results reveal that the evolution of minimum central pressure and horizontal as well as vertical structures of winds, temperature anomalies and rainband characteristic to a cyclone are well brought out by the combination of Kain-Fritsch and Hong-Pan schemes.

Key words – Super cyclonic storm, Cumulus parameterization, PBL parameterization.

1. Introduction

The heat and moisture fluxes from the oceanic surface and latent heat release in cumulus cells are major driving forces for the development and maintenance of the tropical cyclones. These important physical processes are included in the model either explicitly or implicitly depending upon the model resolution. Since the convective elements range from 0.1 to 10 km, very fine resolution is required to resolve them. Most of the models use the cumulus parameterization in order to include the impact of convective elements on model simulated environment.

Currently many parameterization schemes are used in numerical models. They are based on different closer assumptions for triggering convection and further feedback to the environment. Kain-Fritsch scheme (Kain and Fritsch, 1993) rearranges the mass vertically that eliminates the convective available potential energy (CAPE) within a specified time scale (approximately 30 minutes). Betts-Miller scheme (Betts and Miller, 1986) is a moist adjustment scheme that adjusts the environment towards a reference profile which is based on numerous observations. Grell (1993) scheme is based on the single cloud with parameterized updrafts and downdrafts and Anthes-Kuo scheme (Anthes, 1977; Kuo, 1974) triggers the deep convection based on the integrated moisture convergence in the column. Many studies have been carried out to study the sensitivity of cumulus parameterizations schemes in different type of environments. Wang and Seaman (1997) using MM5 compared the Betts-Miller, Anthes-Kuo, Grell and Kain-Fritsch cumulus parameterization schemes for some cases of summer and winter rainfall events. Their findings did not show any single scheme to be outperforming the others for all the cases. In general the skill for winter precipitation was better than for summer precipitation. Prater and Evans (2002), while simulating hurricane Irene (1999) with Betts-Miller and Kain-Fritsch schemes, have noted that choice of parameterization schemes has significantly impacted the modelled track and structure of the hurricane. Puri and Miller (1990) studied the sensitivity of the ECMWF analysis-forecast system for four tropical cyclones during the Australian Monsoon Experiment period to cumulus parameterizations. Two parameterization schemes were compared namely, the Kuo scheme and the Betts-Miller scheme. Both analyses and forecasts show considerable sensitivity with the Betts-Miller scheme generating more intense cyclonic systems. Braun and Tao (2000) carried out several experiments to see the impact of planetary boundary layer schemes on the simulation of hurricane Bob (1991). Numerical studies on ensemble forecasts have shown that there can be significant dependency of the forecasts on the initial conditions and model physics (Leith, 1974).

Mohanty *et al.* (2004) has shown the skill of MM5 in simulating the super cyclone of Orissa (1999). The current paper discusses the sensitivity of different cumulus and planetary boundary layer parameterization schemes on the simulation of Orissa super cyclone using MM5. This was one of the deadliest cyclones of the century and caused considerable loss of life and damage to property. In the following sections we will describe briefly the mesoscale model, data, experiments carried out and results.

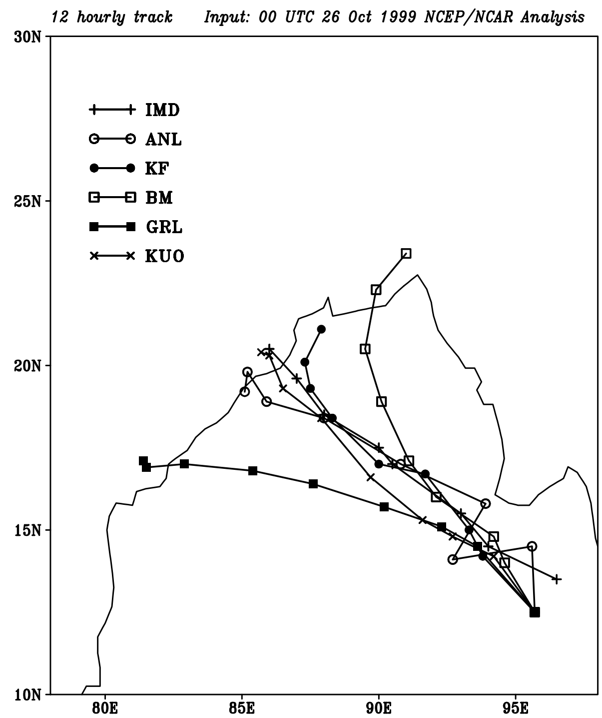
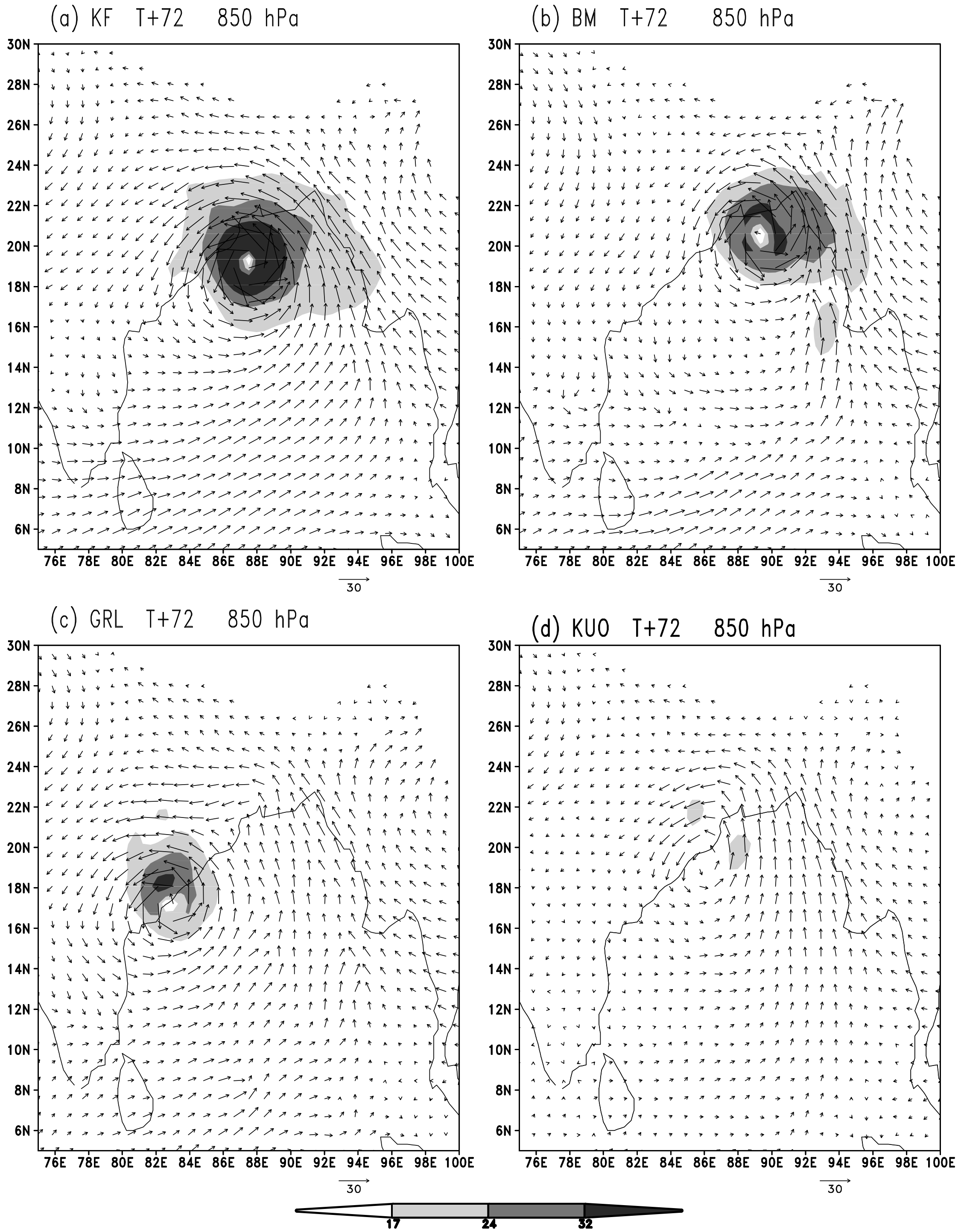


Fig. 1. 12 hourly observed best track (IMD), analysis and simulated tracks for the experiments

2. Methodology

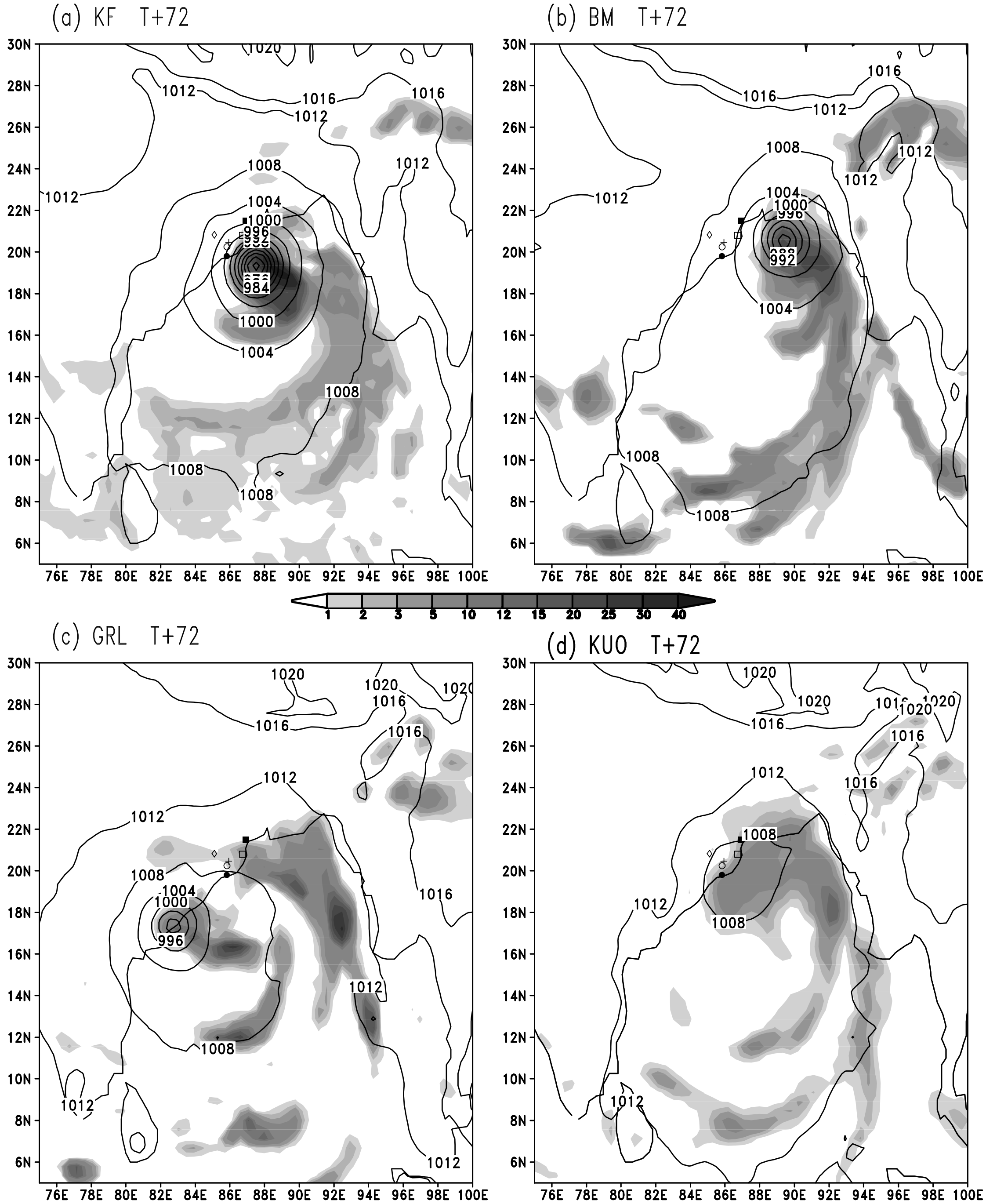
2.1. *The mesoscale model*

The Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model Generation 5 (MM5) described in detail by Dudhia (1993) is utilized for the present study. The model is integrated with 50 km horizontal resolution and 23 unevenly spaced half sigma levels. More vertical levels are placed within the lower troposphere (with decreasing resolution above) to better resolve the planetary boundary layer and the moist processes. The domain extends from 7° S to 38° N in the north-south direction and 65° E to 115° E in the east-west direction with 111 grid points. There are several physics options incorporated in MM5. The physics selected for this study include an explicit moisture scheme which predicts rain and cloud water with microphysical processes including simple ice-physics, multi layer soil diffusion model, the long and short wave radiation schemes are those described by Dudhia (1989), the radiation effects due to clouds are considered and these effects are updated every 30 minutes. Klemp and



Figs. 2(a-d). 72 hour predicted wind vector and wind magnitude at 850 hPa for experiments (a) KF; (b) BM; (c) GRL and (d) KUO. The shadings are for winds greater than 17 ms^{-1} representing the winds of cyclonic storm strength

Durrans (1983) upper radiative boundary condition is applied in order to prevent gravity waves from being reflected off the upper boundary of the model. In order to see the sensitivity to cumulus and PBL schemes,



+ Cuttack (1.5), ○ Bhubaneshwar (2.6), ● Puri (4.8), □ Chandbali (4.4), ■ Balasore (4.1), ◊ Angul (8.6)

Figs. 3(a-d). 72 hour predicted mean sea level pressure and 24 hour accumulated rainfall in cm valid for 0000 UTC 29 October, 1999 for experiments (a) KF; (b) BM; (c) GRL and (d) Kuo. Rainfalls greater than 1 cm are shaded. The figures depict the location of the stations and amount of rainfall in cm

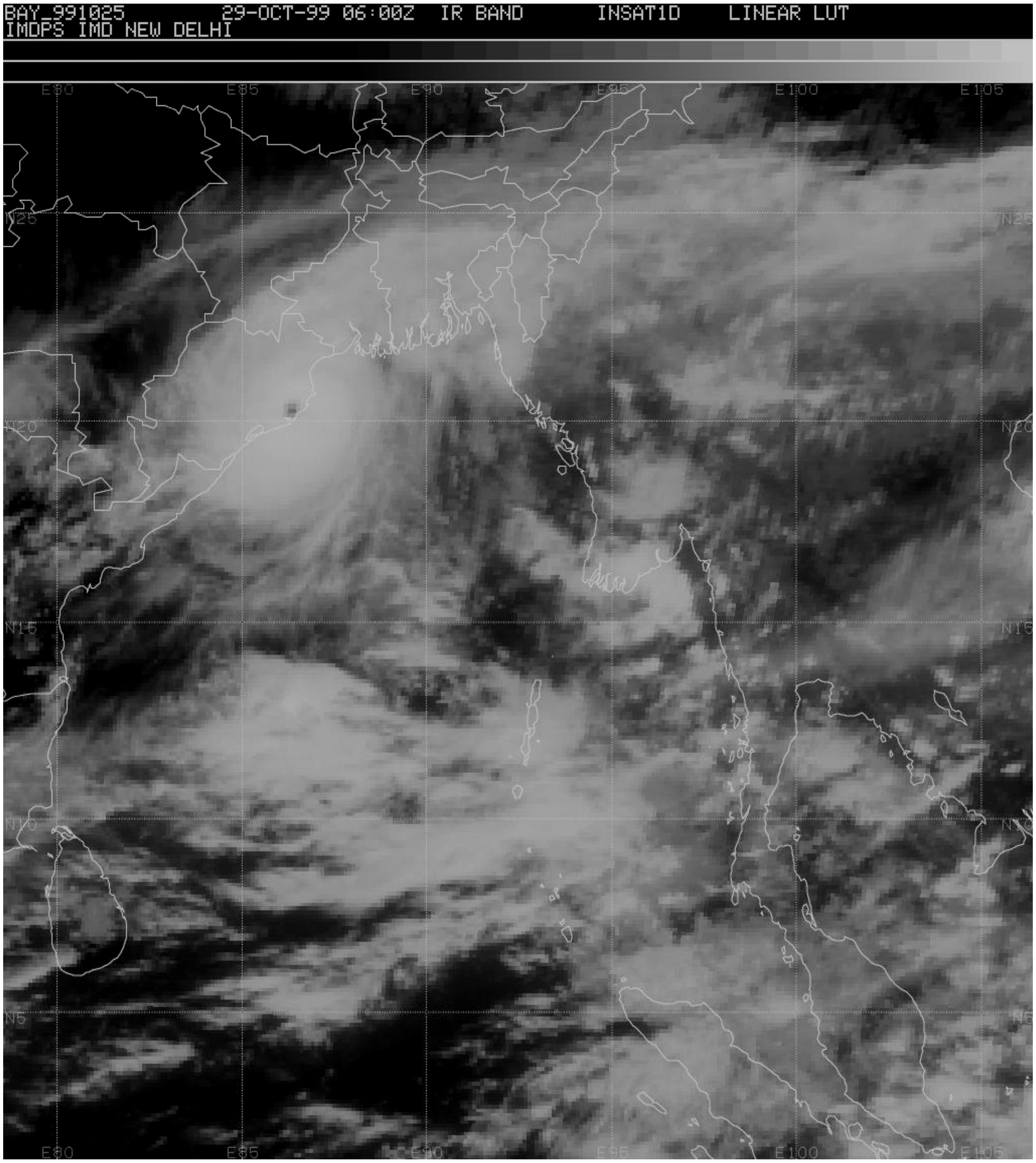
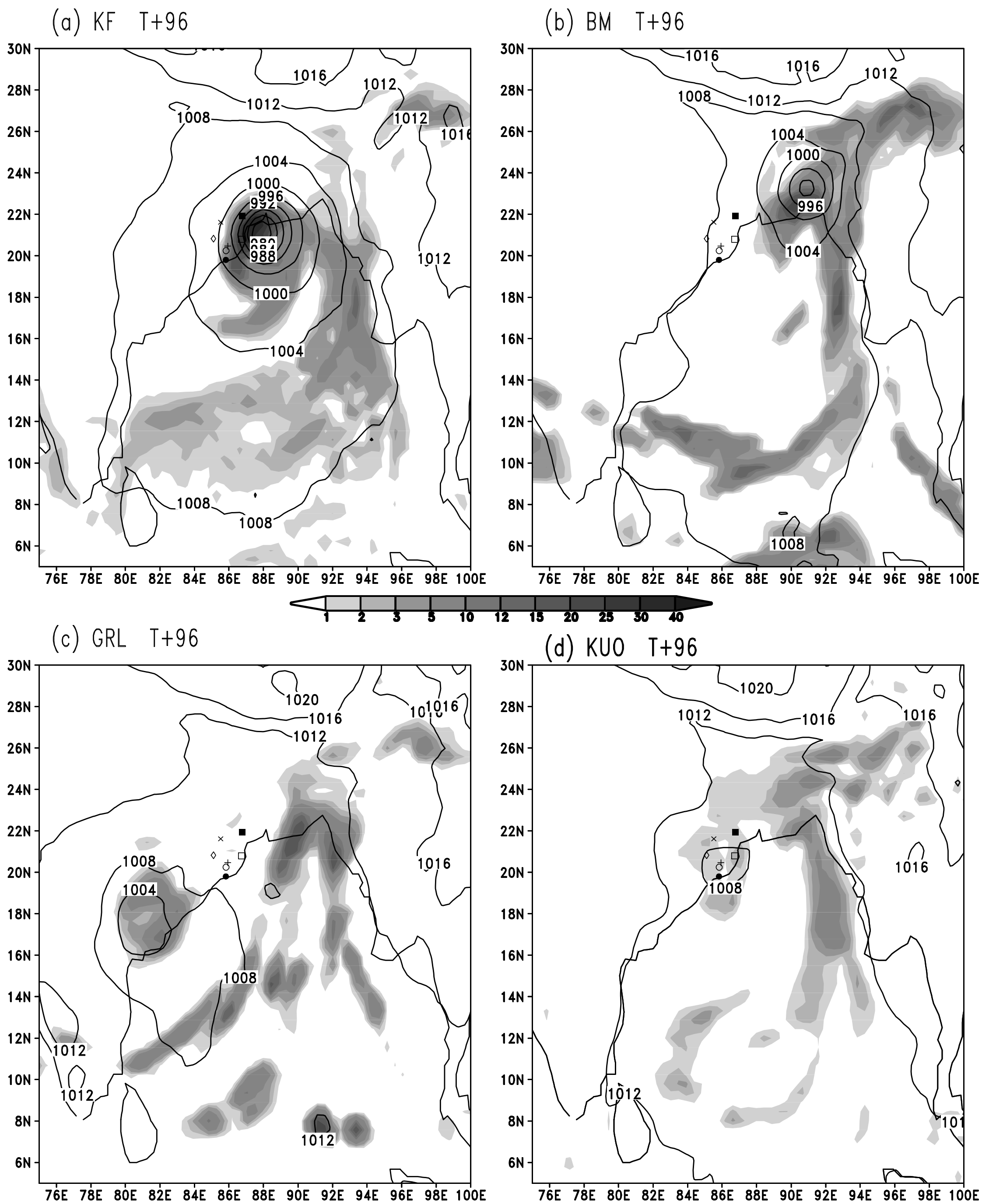


Fig. 4. Satellite cloud imagery (IR) for 0600 UTC, 29 October 1999

experiments are performed with four cumulus and two PBL schemes, the details of which are discussed in the next section.

2.2. *Data and experimental design*

Terrain and land use data (United States Geological Survey, USGS) at 10 minutes resolution are interpolated to model grids to obtain the topography and other surface parameters over the model domain. The model is initialized with geophysical parameters derived by interpolating National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) global reanalyses data at 2.5° Lat.-Long. resolution of 0000 UTC of 26 October, 1999 to the model grids. The same global NCEP/NCAR reanalyses at 6 hour

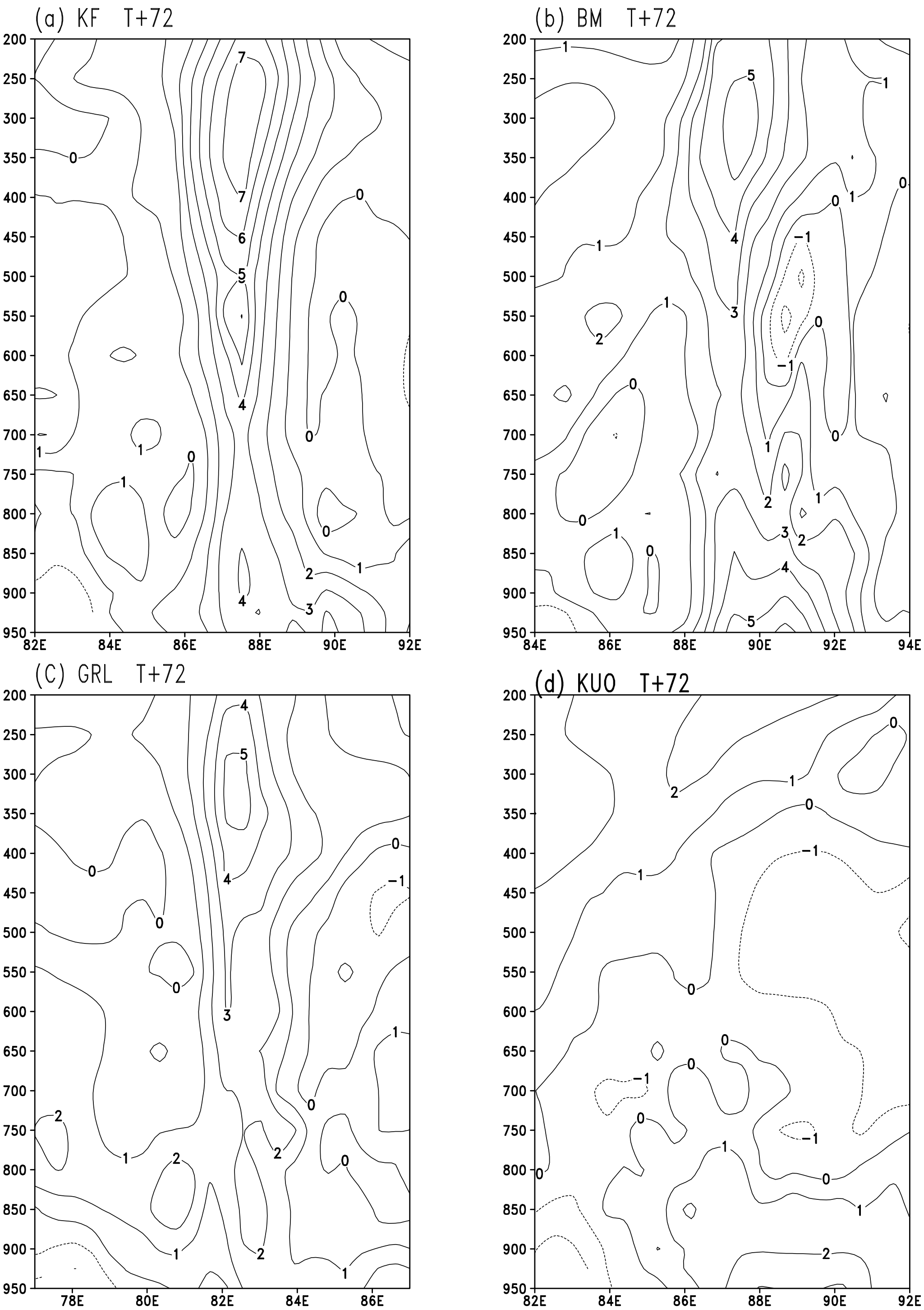


+ Cuttack (25.5), ○ Bhubaneshwar (42.6), ● Puri (18.1), □ Chandbali (24.8), ■ Baripada (6.7), × Keonjhar (7.7), ◊ Angul (5.7)

Figs. 5(a-d). Same as Figs. 3(a-d) but for the 96 hour prediction valid for 0000 UTC 30 October, 1999

intervals are used to update the lateral boundary conditions.

Four experiments are carried out with different cumulus schemes namely Kain-Fritsch, Betts-Miller, Grell



Figs. 6(a-d). Vertical cross section of temperature anomalies through the centre of the respective storm centre predicted at 72 hour for experiments (a) KF; (b) BM; (c) GRL and (d) KUO

and Anthes-Kuo. Hereafter, the experiment with Kain-Fritsch is referred as KF, with Betts-Miller as BM, with Grell as GRL and Anthes-Kuo as KUO. In these experiments the Hong and Pan (1996) planetary boundary layer parameterization scheme based on Troen-Mahrt representation of counter gradient transports and eddy diffusivity profiles in the well mixed boundary layer, incorporated in the NCEP Medium Range Forecast (MRF) model is used along with the other physics mentioned in the above section. Since KF produced the better results, one more experiment is carried out using planetary boundary layer scheme of Burk and Thompson (1989) with Kain-Fritsch cumulus scheme in order to compare the performance of two PBL schemes. The latter scheme is based on turbulent kinetic energy (TKE) formulation. Hereafter, the experiment with Hong and Pan scheme will be referred as MRF and with Burk-Thomson scheme as BT. The model is integrated for 4 days for all the experiments. The model results will be verified against the available observations for tracks and minimum pressure reported by India Meteorological Department (IMD). Since no observations are available for horizontal and vertical structure for the cyclone, these features will be discussed qualitatively in the light of known features through the earlier works.

3. Results

3.1. *Sensitivity to cumulus schemes*

3.1.1. *Cyclone movement*

Fig. 1 shows the 12 hourly tracks from the simulations along with the observed track (as reported by IMD) and as in the analysis. The centre positions for analysis and other experiments are based on winds at 850 hPa. The observed movement is north-westwards throughout the integration period. The track in the analysis shows very erratic movement till 36 hours when the cyclone is away from the coast and thereafter shows smooth west-northwesterly movement. The erratic movement in the analysis in the initial hours may be attributed to the non-availability of data in the open ocean. Although the initial position of the cyclone in the analysis is to the south of the observed position, the simulated position almost caught up the observed one after 12 hours. Beyond this the predicted movement in KF shows very good agreement with the observation up to 72 hours, however, it recurved northward parallel to the coast in the subsequent 24 hours. The experiment KUO produces the movement parallel to the observation but slightly south till third day but has closely followed the observation thereafter. The predicted centre in BM took the north-northwesterly course from the beginning till 72 hour and subsequently recurved north to north-eastward making landfall into West Bengal much to the north of the observed position. GRL produces the west-northwesterly movement making landfall much south with respect to the observed position. Table 1 compares the track errors with respect to observation for the simulations with different cumulus parameterization schemes at 12 hour interval. Initially the cyclone position in the analysis is 141 km south of the observed location by the IMD. As it is already mentioned above, Table 1 shows that KF has produced significantly less track error up to 72 hour in comparison to other schemes except KUO at 60th hour. However, KUO scheme, following the observed track at the time of landfall, produces the least track errors during the last day of integration.

TABLE 1

12 hourly track errors (km) for different simulation experiments with respect to the best track after IMD

Forecast hour	KF	BM	GRL	KUO
0	141	141	141	141
12	40	86	44	40
24	64	153	89	84
36	136	208	147	223
48	55	129	290	104
60	35	235	342	16
72	64	292	534	64
84	150	472	634	22
96	219	636	629	35

Note : 24 hour track error varies from 64 to 153 km, 48 hour varies from 55 to 290 km and 72 hour (near landfall) varies between 16 to 534 km. Ensemble average forecast for 24, 48 and 72 hour would be 97 km, 145 km and 239 km respectively.

3.1.2. *Wind*

The lower tropospheric winds in the cyclones are characterized by relatively calm winds at the centre, surrounded by very strong winds close to the centre at the radius of maximum winds and thereafter decreasing slowly outwards. During the first 24 hour GRL developed stronger winds at and around the cyclone centre compared to other schemes (fig. not shown). But in the 48 hour forecast the cyclone development is better predicted with KF in respect of areal coverage of strong winds, stronger gradients and wind maxima to the right of the direction of movement (figs. not shown). Figs. 2(a-d) shows the 72 hour forecast wind vector and magnitude at 850 hPa valid for 0000 UTC of 29 October, 1999. On this day the observed cyclone attains its highest intensity with estimated maximum wind of approximately 70 ms^{-1}.

TABLE 2

Minimum sea level pressure (hPa) as observed and for different simulation experiments. Figures in bracket show the fall from environmental sea level pressure

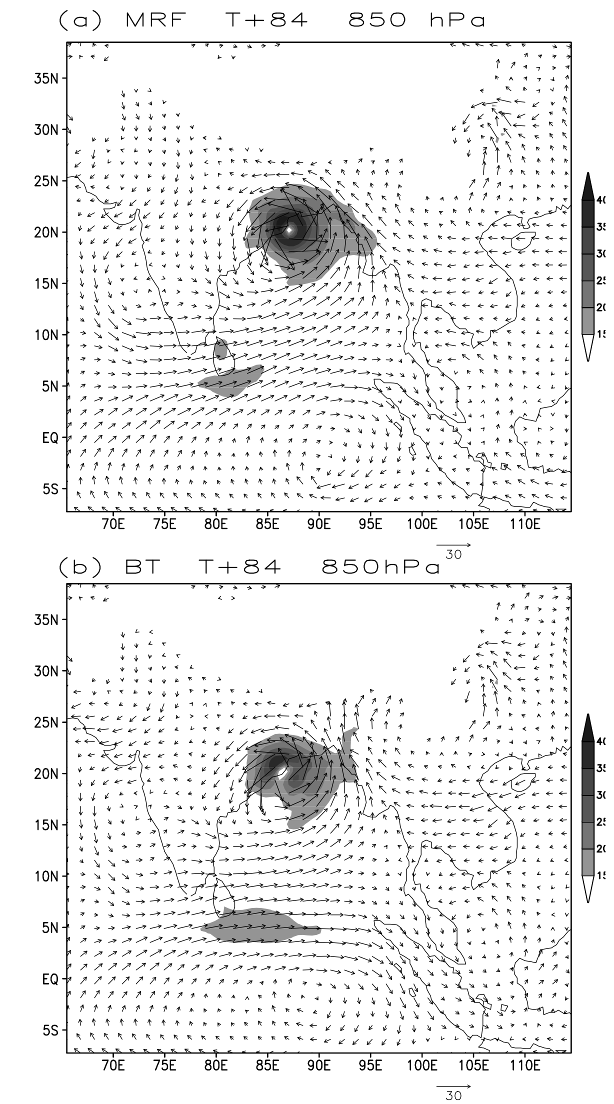
Forecast hour	Observed	KF	BM	GRL	KUO
0	1002 (6)	1005 (5)	1005 (5)	1005 (5)	1005 (5)
12	998 (10)	1001 (9)	1000 (10)	999 (11)	1005 (5)
24	998 (10)	999 (11)	1000 (10)	994 (16)	1005 (5)
36	992 (16)	992 (18)	997 (13)	988 (22)	1004 (6)
48	986 (22)	983 (27)	995 (15)	990 (20)	1005 (5)
60	940 (68)	968 (42)	988 (22)	990 (20)	1004 (6)
72	912 (96)	966 (44)	983 (27)	991 (19)	1005 (5)
84	-	972 (38)	987 (23)	998 (12)	1006 (4)
96	-	972 (38)	987 (23)	998 (12)	1006 (4)

Note : Observed environmental sea level pressure was 1008 hPa. Environmental sea level pressure is assumed 1010 hPa for the experiments.

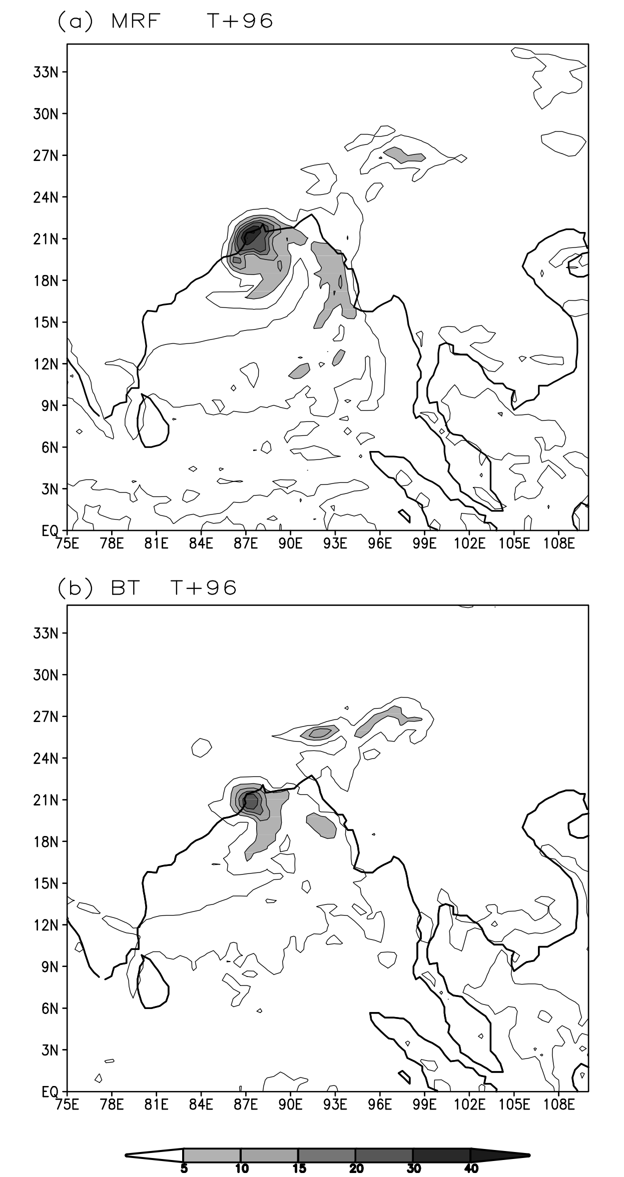
The simulated wind by KF and BM on 29 October 1999 also shows the cyclones at their maximum intensity. It is to be noted that KF produced better structure with winds greater than 32 ms^{-1} (~64 knots) corresponding to the magnitude of very severe cyclonic storm encircling the centre [Fig. 2(a)] which is a well known feature of a very severe cyclone. In BM winds more than 32 ms^{-1} are confined to the right [Fig. 2(b)] of the cyclone centre while in GRL [Fig. 2(c)] winds of this much strength are confined to a very small region over the land to the front sector of the cyclone. The high winds completely encircling the centre in KF scheme are more plausible. However the observed strength of this cyclone has been almost twice the simulated strength with different parameterization schemes. The Anthes-Kuo has produced the weakest storm throughout the integration period.

3.1.3. *Mean sea level pressure (MSLP) and rainfall*

A tropical cyclone is characterized by very low pressure values at the centre with steep gradients within about a hundred kilometres radius of the inner core of the storm. Pressure gradient reduces away from the inner core region. Table 2 shows the minimum central pressure as reported by IMD and for different simulation experiments. The numbers in the brackets are the pressure drop as reported by IMD and for simulation experiments taking 1010 hPa as environmental pressure. During first 24 hours of integration KF with central pressure of 999 hPa closely resembles with the observation (998 hPa) while GRL produces more intense system (994 hPa) and remaining two schemes produce weaker systems. On 2nd day KF has produced the intensity (983 hPa) comparable to observation (986 hPa). Other schemes produced the shallower systems. Figs. 3(a-d) shows the forecast MSLP at 72 hour and accumulated rainfall during 48-72 hours. These results are valid for 0000 UTC of 29 October, 1999 when the cyclone was about to make landfall with central pressure of 912 hPa and had attained its peak intensity. The high intensity of the cyclone is well reflected in the infrared (IR) satellite imagery (Fig. 4) of 0600 UTC of 29 October 1999 which shows the eye surrounded by deep clouds and rainbands extending northwards. KF and BM schemes also produce their peak intensity at this time with minimum pressure reaching 966 and 983 hPa respectively (Table 2). However, GRL produces its maximum intensity at 36 hours (valid for 1200 UTC of 27 October, 1999) which is much earlier and KUO fail to produce any intensification. Although no schemes could produce the observed pressure drop of 98 hPa from the initial pressure of 1010 hPa but KF with drop of 44 hPa (Table 2) has followed the trend of the evolution of the system. The pressure distribution with many closed isobars and steep gradients very close to the cyclone's



Figs. 7(a&b). 84 hour predicted wind vector and wind magnitude at 850 hPa for experiments (a) MRF and (b) BT. The shadings are for winds greater than 17 ms^{-1} representing the winds of cyclonic storm strength



Figs. 8(a&b). Predicted 24 hour accumulated rainfall in cm valid for 0000 UTC 30 October, 1999 for experiments (a) MRF and (b) BT. Rainfall greater than 5 cm are shaded

centre, depicted in KF [Fig. 3(a)], is much better than the other schemes. KF [Fig. 3(a)] shows a typical hook like structure protruding to north and south and with rainfall maxima of more than 40 cm to the right of the cyclone which matches with the feature of cyclones over Indian region (Raghavan, 1990). The BM [Fig. 3(b)] with rainfall amount of 18-25 cm near the centre and with rainband extending to the south is consistent with the development during this period. The rainfall in GRL [Fig. 3(c)] shows the fragmented rainy area as the simulated cyclone weakens between 2nd and 3rd day. KUO [Fig. 3(d)] produces small amount of rainfall (less than 10 cm) in the vicinity of the centre. The observed rainfall over the coastal stations of Orissa under the influence of this cyclone on 0300 UTC of 29 October, 1999 varied from 1 to 8 cm. The cyclone centre in KF, BM and GRL being away from the observed position could hardly produce the rainfall over the observed locations [Figs. 3(a-c)]. However, KUO being nearer to the observed location has produced the rainfall amount of 5-10 cm over coastal Orissa. Figs. 5(a-d) depicts the 4th day predicted MSLP and rainfall fields. At this time the super cyclonic storm

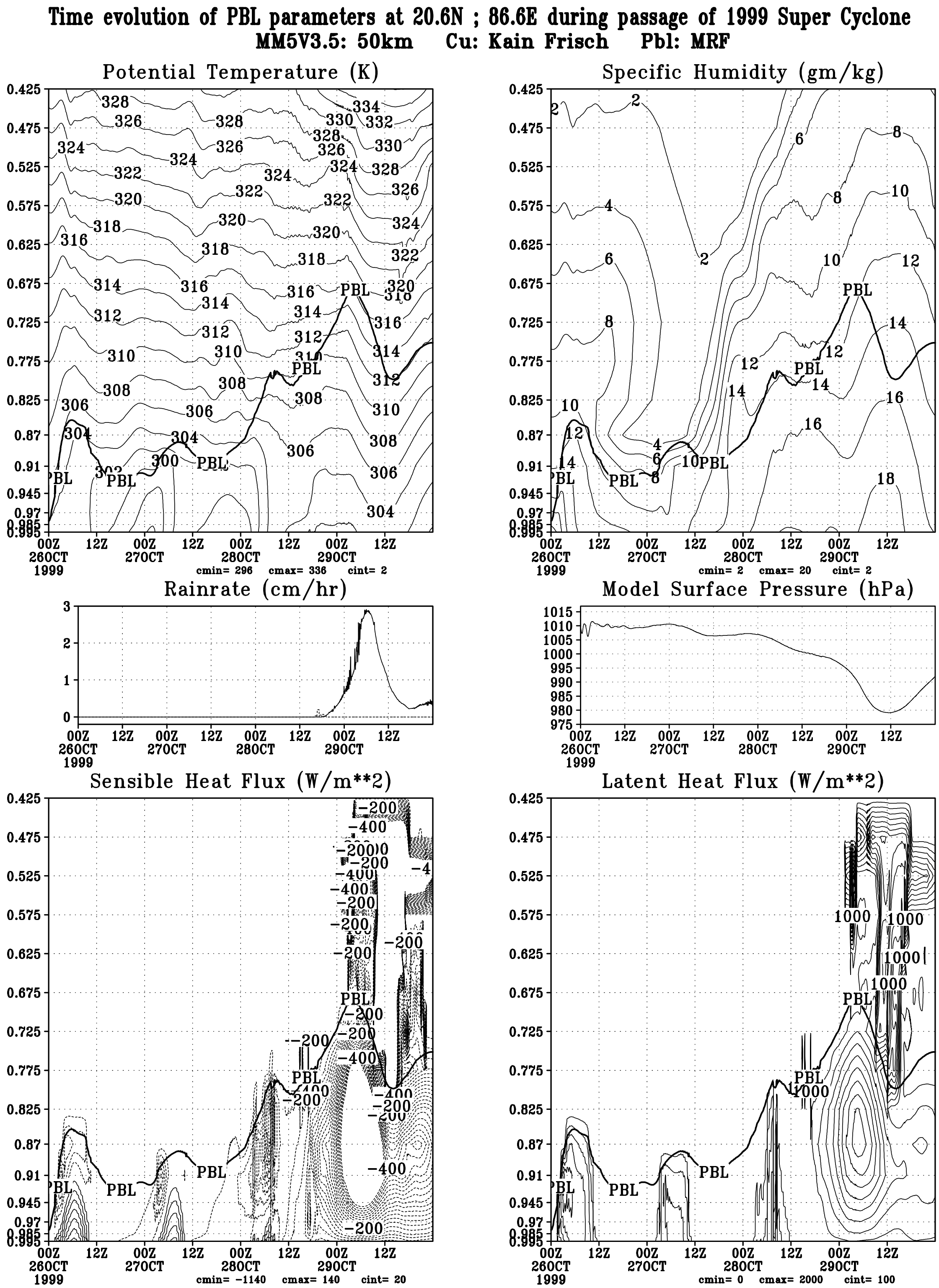


Fig. 9. The vertical-time sections of potential temperature, specific humidity, convective and non-convective rain rates, model surface pressure, sensible heat and latent heat fluxes at a model grid point located at 86.6° E; 20.6° E. This grid point is closer to Bhubaneswar

has already made the landfall and very heavy rainfall over 24 hours was reported over the coastal Orissa with Bhubaneswar receiving 42 cm. Only KF is able to produce the 24 hour rainfall amount of 30-40 cm over the coastal Orissa which matches well with the areal coverage of the clouds seen in the IR imagery (Fig. 4). All the heavy rainfall reporting stations of Orissa coast are covered under the simulated heavy rainfall region in KF [Fig. 5(a)]. BM and GRL could not produce the heavy rainfall over the observed locations as their simulated centres are far away [Figs. 5(b&c)]. The areal coverage of forecast rainfall in KUO is reasonably good but it is underestimated [Fig. 5(d)].

3.1.4. *Vertical temperature profile*

The intensity of a cyclone is directly related with the temperature anomaly in its central region with more temperature anomaly producing lower surface pressure. Here, temperature anomaly values are the difference between temperature and its latitudinal mean. Figs. 6(a-d) shows the east-west cross section of the temperature anomaly for all the four experiments passing through the respective simulated cyclone's central latitude at 72 hour. The KF produced the warmest core with temperature anomaly of more than 7° C [Fig. 6(a)] in the upper middle troposphere of the model atmosphere. No intensification in experiment KUO may be attributed to the absence of warm core region [Fig. 6(d)]. The temperature anomalies are in good agreement with the simulated intensity of the cyclone for different cumulus schemes except those after KUO.

3.2. *Sensitivity to PBL schemes*

3.2.1. *Wind*

The super cyclone has made landfall near Paradip between 0430 and 0630 UTC of 29 October, 1999. Figs. 7(a&b) shows the horizontal wind vector and magnitude (shaded) at 850 hPa for 84 hour forecast valid at 1200 UTC of 29 October 1999 for experiments MRF and BT. The wind magnitude with sharp increase from centre towards the maximum wind region and then slow decrease towards the outer side of it shows typical structure of a cyclone of high intensity in simulation with MRF scheme [Fig. 7(a)]. Although the BT [Fig. 7(b)] scheme also produced the high wind speed of more than 35 ms^{-1} but confined to very narrow region over the land.

3.2.2. *Rainfall*

Some of the stations that reported very heavy rainfall on 0300 UTC of 30 October, 1999 under the influence of this storm over coastal Orissa are: Bhubaneswar AP 42.6 cm, Chandbali 24.8 cm, Balasore 19.5 cm, Puri 18.1 cm etc. The forecast field with MRF scheme valid for 0000 UTC of 30 October 1999 shows very heavy rainfall of 30-40 cm covering most of the cyclone affected Orissa coast. Apart from this it shows rain-band structure protruding south and east from the central region [Fig. 8(a)]. The rainfall in BT scheme is much less in magnitude and in spatial coverage [Fig. 8(b)]. The heavy rainfall surrounding the centre of the simulated cyclone in MRF matches well with the dense clouds as seen in the satellite imagery (Fig. 4).

3.2.3. *Temporal evolution of different PBL parameters at a point near Bhubaneswar with MRF scheme*

In order to make an attempt to understand the role of modelled PBL parameters in the occurrence of heavy precipitation associated with this super cyclone, a model grid point located at 86.6° E; 20.6° N is selected. This grid point, which is closer to Bhubaneswar, shows heavy rainfall of about 28 cm with MRF scheme. Fig. 9 shows at this grid point the vertical-time sections of potential temperature, specific humidity, convective and non-convective rain rates, model surface pressure, sensible heat and latent heat fluxes. Also shown in all the vertical time sections are the PBL depth (indicated by PBL) diagnosed within the MRF scheme. The diurnal variation of PBL depth is found to be typical of tropical coastal stations till this grid point comes in the direct influence of the cyclonic storm on 29 October. As the system approaches, the PBL depth increases significantly indicating the presence of enhanced turbulence. The temperature and moisture profiles are found to have lesser gradients within the PBL suggesting well-mixed PBL. As the storm approaches, a significant moisture build-up is found in the lower troposphere extending beyond the top of PBL. This has resulted in super saturation leading to non convective precipitation, with maximum rain rate of 3 cm hr^{-1} during the last day of integration. Enhanced sensible heat and latent heat fluxes are also found in the lower troposphere extending beyond PBL in association with this heavy precipitation.

4. **Conclusions**

The Penn State University-National Center for Atmospheric Research mesoscale model MM5 has been used to simulate the super cyclonic storm of Orissa (1999). The MM5 model successfully developed the tropical cyclone from the very weak circulation in the initial condition with all the cumulus schemes except after Anthes-Kuo. The simulated track shows much sensitivity to cumulus parameterizations with Betts-Miller and Grell producing more while Kain-Fritsch and Anthes-Kuo producing less errors. The Kain-Fritsch scheme with most intense simulated cyclone brought out many well known embedded mesoscale (meso-β) features in a tropical cyclone such as maximum wind region of 1° - 2° extent encircling the cyclone centre, spiralling rainband and warm core structure.

In the experiments with PBL parameterization, it is found that wind field at 850 hPa level and the amount and location of precipitation associated with the cyclone are very well predicted by Hong and Pan scheme compared to Burk-Thompson scheme. The rainfall and the characteristic feature of hook type structure with spiralling rainy area around tropical cyclone is also very well predicted by this scheme.

These set of numerical experiments clearly demonstrate that Kain-Fritsch cumulus scheme with Hong and Pan scheme of planetary boundary layer parameterization has better simulated the super cyclonic storm. It is not possible to categorically conclude from one experiment whether the schemes found to produce better results in this experiment would do likewise in a statistical sample.

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