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Tropical cyclones prediction by numerical models in India Meteorological Department

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सार – इस शोध–पत्र में भारत मौसम विज्ञान विभाग (भा. मौ. वि. वि.) में अपनाई गई चक्रवात प्रतिरूपित करने की कल्पित तकनीकों पर चर्चा की गई है। अक्तूबर 1999 में उड़ीसा में आए महाचक्रवात के प्रारम्भिक क्षेत्रों में काल्पनिक भ्रमिलता का उपयोग करके, चक्रवात के विशिष्ट मॉडल, क्वासी लैंगरगियन मॉडल (क्यू. एल. एम.) से 72 घंटे के पूर्वानुमान और भारत मौसम विज्ञान विभाग के सीमित क्षेत्र निदर्श (एल. ए. एम.) से 36 घंटे के पूर्वानुमान प्रतिरूपित किए गए। इस शोध में, 26 से 28 अक्तूबर तक की प्रारंभिक स्थितियों के आधार पर क्यू. एल. एम. से चक्रवात के मार्ग के पूर्वानुमान की औसत त्रुटियाँ 24 घंटे के लिए 21 कि.मी., 48 घंटे के लिए 91 कि.मी. और 72 घंटे के लिए 179 कि.मी. रही। 1998–2004 तक के पिछले सात वर्षों के दौरान क्यू. एल. एम. से चक्रवात के मार्ग के पूर्वानुमान की त्रुटियों के आँकड़ों पर भी इसमें चर्चा की गई है। इसके अलावा, एल. ए. एम. से किए गए पूर्वानुमान पर प्रारंभिक स्थितियों के प्रभाव की भी जाँच की गई। विभिन्न प्रारंभिक स्थितियों से तैयार किए गए औसत (समेकित) पूर्वानुमान से 24 घंटे के पूर्वानुमान में 123 कि.मी. और 36 घंटे के पूर्वानुमान में 81 कि. मी. की त्रुटियाँ पाई गई, जो एकमात्र पूर्वानुमान की तुलना में कम रही। इन प्रयोगों से यह पता चला कि काल्पनिक भ्रमिलता वाले क्यू. एल. एम. मॉडल से चक्रवात के मार्ग का सटीक पूर्वानुमान प्राप्त किया जा सकता है जो अभी तक संख्यात्मक मॉडलों से उपलब्ध हो पाता था।

ABSTRACT. In the present paper, the cyclone bogusing techniques followed in India Meteorological Department (IMD) were discussed. Using the idealized vortex in the initial fields for Orissa super cyclone October 1999, the specialized cyclone model, Quasi-Lagrangian Model (QLM) 72 hours track forecast and also 36 hours forecast with IMD limited area model (LAM) were simulated. In this case, the QLM average track forecast errors based on 26-28 October initial conditions were 21 km for 24 hours, 91 km for 48 hours and 179 km for 72 hours. Also the QLM track forecast error statistics during the last 7 years 1998-2004 are discussed. In addition, the impact of initial conditions on the LAM forecast was examined. It was observed that the mean (ensemble) forecast generated from different initial conditions was shown track error of 123 km in 24 hours and 81 km in 36 hours forecast which is less than individual forecast. These experiments have established that the QLM model, with idealized vortex, provides track forecast within an accuracy level that was currently available from numerical models.

Key words – Super cyclone, Model simulation, Track errors.

1. Introduction

Prediction of track and intensity of a tropical cyclone (TC) is one of the many challenging problems in meteorology, but very important for issuing timely warning for many agencies engaged in disaster preparedness and mitigation. Since a TC has genesis invariably over warm tropical oceans, a major difficulty arises in defining it accurately in the initial analysis fields. With the advancement in observational technology, especially weather satellites, buoys and Doppler Radar there is considerable improvement in the quantum of observational data around a TC and many forecast centres utilise the prediction generated by high resolution numerical models for cyclone track forecast. Even then, representing a TC in the initial analysis adequately for use in numerical weather prediction (NWP) models is a major problem. At most NWP centers a 'bogusing' scheme is thus employed to force a tropical cyclone vortex into the numerical analysis. This is typically done by using a vortex with suitable horizontal and vertical structure to derive a set of bogus observations for inclusion in analysis/assimilation cycle. Bogusing methods vary between the centers but most involve a symmetric vortex with some added asymmetry to take into account current movement of cyclone and environmental flow.

There are primarily three bogusing methods that are widely used in operational models, as summarized by Peng *et al*. (1993). The first is to bogus observational data before the objective analysis is carried out. Examples of this type of bogusing are those used in the US National Centers for Environmental Prediction (NCEP) global forecast model (Lord, 1991), in the US Navy Operational Global Atmospheric Prediction System (NOGAPS), UK Meteorological Office global model (Heming *et al*. 1995) and India Meteorological Department (IMD) limited area model (Prasad *et al*. 1997). The second approach is to add

a more complex vortex circulation defined by an analytical expression after the objective analysis but before the model initialization. Examples of this type of bogusing are those used in the Quasi-Lagrangian Model (QLM) (Prasad & Rama Rao, 2003 and Mathur, 1991) and Typhoon Model of the Japan Meteorological Agency (JMA) (Ueno, 1995). The third approach is to bogus a 'spinup' vortex generated by the same forecast model, instead of using an analytical one. Examples of this are the multiple nested tropical cyclone model of the GFDL (Kurihara, 1998) and the typhoon-Track Forecast System (TFS) of the Central Weather Bureau (CWB) in Taiwan (Peng *et al*., 1993). In addition to the different methods, both the horizontal and vertical structures of the axisymmetric vortex vary considerably between the centers even for the same method.

IMD is running a limited area analysis and forecasting system (LAFS) to provide numerical guidance for operational short range forecasts. The present operational system uses the 1° × 1° Lat./Long. analysis and forecast model at 0.75° horizontal resolution In addition to the LAFS, a specialized cyclone model, the Quasi-Lagrangian Model (QLM) is also run for cyclone track forecast up to 3 days during the cyclone situation over the Arabian Sea and Bay of Bengal. In the present study, using LAM and QLM models, the track and intensity forecast in case of 25-31 October 1999 Orissa Super Cyclone was discussed. In the present study, a new version of LAFS analysis and forecast model at 0.5° horizontal resolution was created to simulate the cyclone with high horizontal resolution. Using the initial conditions from European Centre for Medium-Range Weather Forecasts (ECMWF), NCEP, USA reanalysis and National Centre for Medium Range Weather Forecasting (NCMRWF) global T-80 initial and forecast fields, forecasts up to 36 hours were produced. In case of QLM, using NCMRWF initial and boundary conditions 3 day forecast based on 26, 27 and 28 were produced and results of both the models were discussed. Also the QLM track forecast error statistics during the last 8 years 1997-2004 were discussed.

A brief description of the cyclone bogus methods and forecast models used in IMD are given in the Section 2. Section 3 describes the experimental design and the model simulation results. The track forecast errors and conclusions given in Section 4 and 5 respectively.

2. Cyclone bogusing methods followed at IMD

2.1. *Limited Area Analysis Forecast System (LAFS)*

(*i*) *Data assimilation*

The grid point data for running the forecast model are prepared from the conventional and non-conventional data received through the GTS in real-time. All the data are quality controlled and packed into a special format for objective analysis. Provision exists for inclusion of cyclone bogus data in the input data file whenever required.

The objective analysis is carried out by a three dimensional multivariate optimum interpolation procedure. The variables analyzed are the geopotential, *u* and *v* components of wind and specific humidity. The temperature field is derived hydrostatically from the geopotential field. Analysis is carried out on 12 sigma surfaces in the vertical and on a 1° × 1° Latitude-Longitude grid for a 'regional' or 'limited area' horizontal domain (0° - 150° E; 30° S - 50° N). The sigma fields are post-processed to pressure surfaces for display and archival. The background fields (first guess) required for objective analysis are obtained from the global model forecasts of the NCMRWF, New Delhi.

(*ii*) *Initialization of TC's (The first approach)*

The scheme used for initialization of tropical cyclones generates synthetic observations based on an empirical structure of cyclone. First, the surface pressure field is constructed on a dense grid. Surface winds are obtained from the surface pressure by use of the gradient wind relationship. Upper winds are obtained from the surface winds with the aid of composite vertical wind shear factors. Inflow and outflow angles are added to the computed winds to ensure proper convergence in the lower levels and divergence in the upper levels. The humidity field is prescribed as near saturation value within the field of the vortex. These steps have been introduced to ensure a proper spin up of the vortex during the course of integration of the forecast model. Details of the scheme are provided in the following paragraphs.

(*iii*) *Construction of surface pressure field*

We make use of the empirical model developed by Holland to prescribe the surface pressure field. The relationship is given by :

$$P_r = P_c + (P_e - P_c) \exp (-a/r^b)$$

Where P_r : is the pressure at radius r, P_e : is the environmental pressure, P_c : central pressure, and a and b are empirical constants.

The constants 'a' and 'b' are related to the radius of maximum wind (RMW) in a cyclone by the following equation.

$$RMW = (a)^{1/b}$$

The constants 'a' and 'b' have to be determined empirically and may differ from region to region and even

from cyclone to cyclone. It has been found by Mandal and Gupta (1992) that the value of 'b' is a function of cyclone intensity has impact on the profile shape varies from 1.0 to 2.5 for cyclones for the Indian seas and that each has a unique value.

Application of the above method for deriving the surface pressure distribution is dependant upon the availability of central pressure, radius of maximum wind and value of constant 'b'. The central pressure is estimated with the help of the pressure drop corresponding to the satellite T - Number classification of the storm and the pressure of the outermost closed isobar. The radius of maximum wind may be estimated from the radius of the eye as available either from the radar report, if already in the range of a coastal cyclone detection radar station, or the satellite imagery if the storm is out at sea. The value of RMW is taken as 30 km based on the average observed value of cyclones over the Indian seas. As mentioned earlier, the value of constant 'b' needs to be determined for the region and the particular cyclone empirically. In the present case, however it is taken as 1.5, which is tentatively found to be appropriate for the Indian region. Pressure data are generated up to 400 km radius, on a grid of 50 km spacing.

(*iv*) *Surface winds*

After the surface pressure distribution is defined, the surface winds are derived using the gradient wind relation. A correction for storm motion is applied. In the absence of friction, an expression for wind speed, *V*, inside the cyclone field is obtained in the form :

$$V = -\alpha + (\alpha^2 + r/\rho.\partial p/\partial r)^{1/2}$$

where $2\alpha = fr - V_c \sin\theta$, f = Coriolis parameter, r = radial distance, V_c = storm speed, θ = Azimuthal angle measured clockwise from direction of motion (taken as 0°)

The above expression is obtained from the gradient wind equation expressing balance of forces in the absence of friction :

$$1/r.\partial p/\partial r - fV - V^2/r + VV_c \sin\theta / r = 0$$

(*v*) *Upper winds*

The upper winds are derived from the surface winds by assuming an vertical wind shear, which decreases the strength of the vortex with increasing height. Values of composite vertical wind shear factors are taken as proposed by Andersson and Hollingsworth (1988), given below :

Surface	*850 hPa*	*700 hPa*	*500 hPa*	*400 hPa*	*300 hPa*
1.0	0.9	0.8	0.7	0.65	0.35

The above factors are based on the rawinsonde composites constructed by McBride (1981). The composites indicate a wind speed varying very slowly with height up to 400 hPa with rapid decrease above. The factors would vary from case to case and depend upon thermal stability and stage of development of the system (Andersson and Hollingsworth, 1988).

In order to ensure a proper low level convergence and an upper level divergence in the vortex field, an inflow angle is added in the lower levels varying from 30° at the surface becoming zero at 500 hPa. The circulation at the upper levels 250 and 200 hPa is made anticyclone and an outflow angle of 20° is added.

(*vi*) *IMD Limited Area Forecast Model (LAM)*

The forecast model is a semi-implicit semi-Lagrangian multilayer primitive equation model. It uses the sigma vertical co-ordinate system and has staggered Arakawa C-grid in the horizontal. The present version of the model has a horizontal resolution of 0.75° × 0.75° Lat./Long. and 16 sigma levels (1.0 to 0.05) in the vertical. The lateral boundary conditions for running the forecast model are obtained from the global model forecasts of the NCMRWF. The model is run on operational mode twice a day using 0000 UTC and 1200 UTC observations. The detailed description of model formulation, horizontal and vertical descretization and time integration scheme of the model has been described in detail by Krishnamurti *et al*. (1990) and Prasad *et al.* (1997). In the present study the LAFS analysis and forecast model at 0.5° Lat./Long. resolution was used to minimize the track forecast error in the initial and subsequent model forecast.

2.2. *Quasi-Lagrangian Limited Area Model (QLM)*

IMD's operational cyclone track prediction model is known as the Limited Area Quasi-Lagrangian Model, specially designed for cyclone track prediction. The model is an adapted version of the hurricane prediction model of the National Centers for Environmental Prediction (NCEP - erstwhile National Meteorological Center), Washington (Mathur, 1991). The model has been implemented at IMD, New Delhi in year 2000 after validating the model for the cyclones formed during 1997-2000 over the Arabian Sea and Bay of Bengal. A special feature of the QLM is prescription of an idealized vortex and a steering current.

The idealized vortex is created from the three dimensional structure of a cyclone *via* empirical functions. The construction of idealized vortex is done from the current observed structure of the storm and needs information like the present location of the storm, the central pressure, the value of the outermost closed isobar, size of the storm etc., which are gathered from the preliminary synoptic analysis and satellite imagery. The vortex so generated is nearly symmetric with size and intensity close to that of the observed storm. The procedure in brief for generating the initial vortex and merged analysis are given below.

(*i*) *Data assimilation*

A new version of the IMD's operational optimum interpolation scheme for objective analysis (used for generating initial fields for IMD LAM) has been developed to suit the QLM grid structure, which is quite different from the grid structure of LAM in horizontal and vertical. The symmetric vortex (as described in the next subsection) and the analysis are then merged using appropriate weighing functions. The symmetric vortex fields are first projected on the QLM grid and then merged with the analysed fields. The background fields for initial analysis and lateral boundary conditions are generated from operational analysis and forecasts produced by the global spectral model of NCMRWF.

The NCMRWF forecast fields are a set of spectral coefficients being the outputs of a T 80 GCM on 18 sigma levels. The spectral coefficients are transformed to QLM grid and vertical interpolation carried out to get QLM sigma fields from GCM sigma levels. OI analysis is carried out directly on the QLM sigma levels. First, the analysis valid at the map time is carried out by updating the NCMRWF GCM forecast, 12H (for 1200 UTC run) or 24H (for 0000 UTC run) with current observations by optimum interpolation (OI) scheme. However in the present case, NCMRWF model initial analysis and forecast fields at 6 hourly for boundary condition are used.

(*ii*) *Initialization of TC (The second approach)*

The prescription of idealised vortex is based on the storm's central pressure p_c, the pressure of the outer most closed isobar p_b and its distance R (size) from the centre. These parameters (p_c, p_b and R) together with the location of the storm centre are derived from synoptic analysis and satellite imagery information like T - Number estimate.

The surface pressure $p_{sfc}(r)$ at a radius r in the idealised symmetric vortex is obtained from:

$$p_{sfc}(r) = p_{max} - [\Delta p \exp(-x^2)] / (1+ax^2)^{1/2} \quad r < R \qquad (1)$$

$$p_{sfc}(r) = p_b \quad r \geq R$$

where $x = r/R$, a is a specified constant and the other two constants, p_{max} and Δp are evaluated from the conditions $p_{sfc}(0) = p_c$, and $p_{sfc}(R) = p_b$.

The large pressure gradients observed in intense cyclones cannot be prescribed well with the use of a coarse grid (40 km in the QLM). Therefore a lower limit has to be set to the central pressure, which is 970 hPa whenever a lower value occurs. This has been arrived at based on past cases of model runs. In the rare cases when the reported storm size R is less than 170 km, R is reset to 170 km, because at least four grid points in the radial direction are required to capture a storm's basic structure.

The winds at pressure levels are specified as follows:

First, the wind $v_g(r)$ at 1000 hPa is obtained from the gradient law:

$$v_g^2 / r + f_c v_g - \partial\phi / \partial r = 0 \qquad (2)$$

where f_c is the Coriolis parameter at the latitude of the storm centre, g is the acceleration due to gravity and geopotential ϕ at 1000 hPa is obtained from the approximate relation $\phi = 8[p_{sfc}(r) - 1000]$ (with p_{sfc} in hPa).

A set of horizontal and vertical functions are used to derive the winds at higher levels.

$$v(r, p) = [F(p) - G(p)H(r)] v_g(r) \qquad (3)$$

Where $F(p) = 0.5 [1 + \tan h (\pi (p-P_a)/\Delta P_a)]$

$$G(p) = \sec h [(p - P_a)/\Delta P_a]$$

$$H(r) = \sec h [(r - R_a)/\Delta R_a]$$

The location of maximum cyclonic winds is controlled by the parameter 'a' in Eqn. (1); the rate of decrease of cyclonic winds in the vertical by P_a and ΔP_a; and the strength and location of anticyclonic winds in the higher atmosphere by R_a and ΔR_a.

Fixed values of a = 100 was chosen to conform with the typical capacity for current numerical system to resolve the core region at distance of 2 to 3 grid points away from the center. The other parameters P_a = 150 hPa, ΔP_a = 200 hPa, R_a = 280 km and ΔR_a = 200 km are used in the QLM, although it might be more realistic to specify some of these parameters as functions of storm size and intensity. With the above specifications and the values of

p_c, p_b and R corresponding to a mature cyclonic storm, the structure of the winds obtained from Eqn. (3) consists of cyclonic winds everywhere in the lower levels with the maximum winds located at 2 to 3 grid intervals from the centre, cyclonic winds extending into the middle troposphere with a slight decrease in their strength, the cyclonic winds decreasing rapidly above the middle troposphere, and anticyclonic winds appearing in the upper troposphere.

The mean geo-potentials on the circle with radius R at any standard pressure level is evaluated from the initialized analysis. The geo-potentials at the interior grid points are obtained from the wind field with the use of gradient wind relation using the geo-potential at radius R as the boundary condition. The hydrostatic assumption is used to derive the virtual temperature from the geo-potential.

The vertical column at the vortex centre is specified to be nearly saturated. Somewhat lower values of RH are specified at R. The RH at intermediate grid points is interpolated linearly from the values at the centre and R. The rate of convective precipitation depends on RH distribution. Since this rate is expected to be smaller in weaker storms, the RH values are reduced by a factor $B = 0.85 + 0.015 (p_b - p_c)$ for an initial disturbance with $p_b - p_c < 10$ hPa. Prescription of near saturation values of RH is necessary to induce proper convection in the storm field, which has a significant contribution in its development and movement process.

The following relation is used for the merging process :

$$X = w X_v + (1-w) X_a$$

where X is one of the variables u, v, θ, q and p_{sfc} and the subscripts 'v' and 'a' denote a field in the vortex and analysis respectively.

The weight w is given by :

$w = \cos (\pi/2 . r/R)$ $r < R$;

$w = 0$ otherwise.

(*iii*) *Prescription of a steering current*

A steering current, which is specified, based on the current storm speed and direction is superimposed on the analyzed fields. The steering current is computed by constructing a dipole circulation. The dipole winds and geopotential height fields (incremental heights calculated from dipole winds geostrophically) are added to the vortex fields at all levels.

Thus the two special attributes of the QLM are : (*i*) merging of an idealized vortex into the initial analysis to represent a storm in the QLM initial state; and (*ii*) imposition of a steering current over the vortex area with the use of a dipole.

(*iv*) *Forecast model*

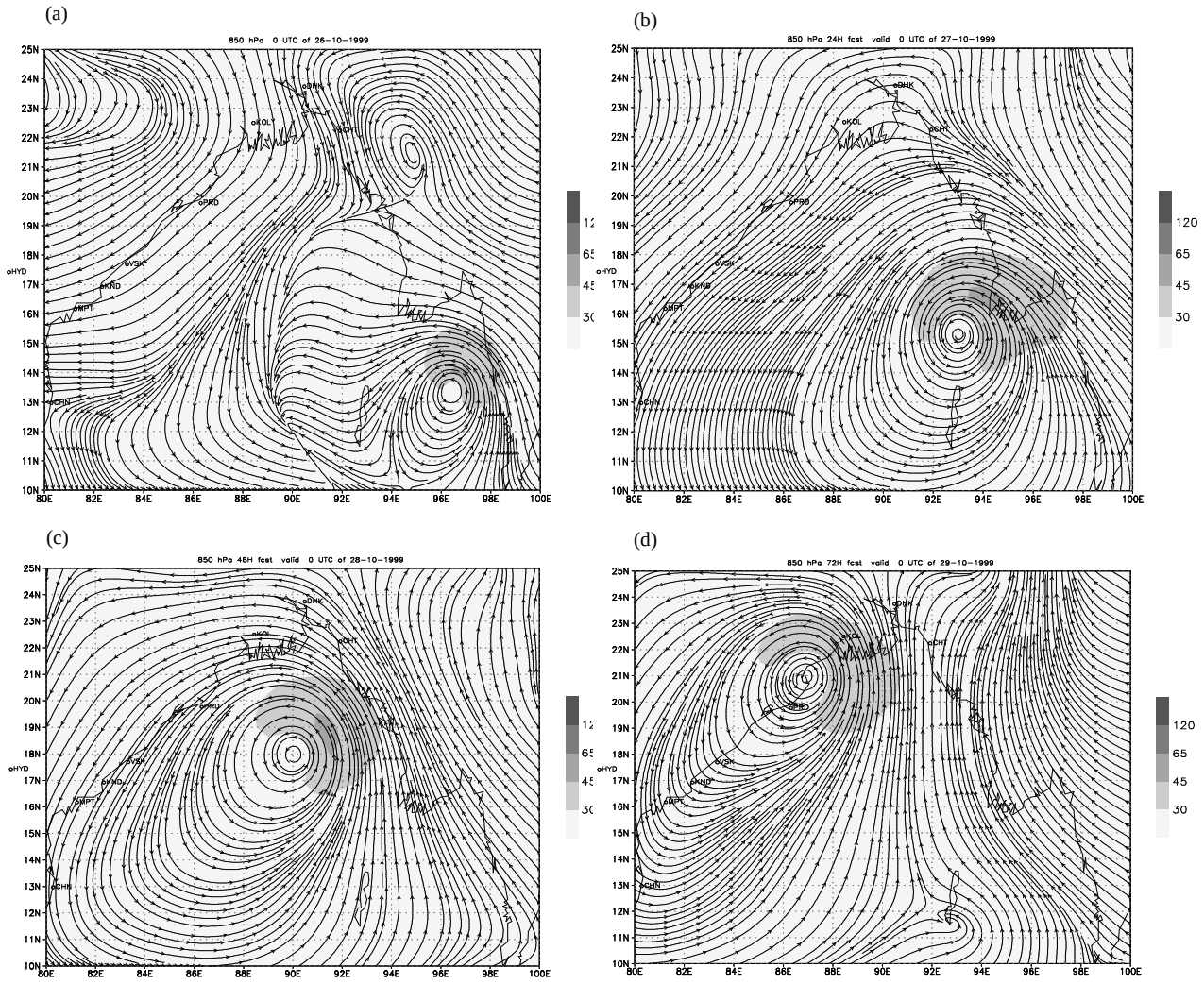
QLM is a multilevel primitive equation fine-mesh model cast in the σ ($= p/p_s$) coordinate system (Mathur, 1991). The numerical integration of the model is carried out by using the so-called quasi-Lagrangian method. The model has a limited domain in a Cartesian grid system. The horizontal grid spacing is 40 km and the integration domain consists of 111 × 111 grid points in a 4400 × 4400 km^2 area that is centred on the initial position of the cyclone. The QLM uses 16 σ layers (17 σ interfaces) in the vertical. Resolution in the lower portion of the atmospheric column is finer where the vertical gradients are usually large. The full details of the model dynamics and initialization procedure can be found in Mathur (1991).

(*v*) *Physical parameterisation*

The model incorporates physical processes which include surface frictional effects, sea-air exchange of sensible and latent heat, convective release of latent heat, divergence damping, horizontal diffusion, and isobaric condensation of water vapour. Radiation and turbulent processes, which have only marginal impact in the development, are currently excluded to minimize computational time. The numerical integration of the model is carried out by using the so called quasi-Lagrangian method. The details of the physical parameterization schemes used in the model are given in Mathur, 1991. Some of the details of the model are given in Appendix I.

3. Forecast experiments

This section describes results of track forecast experiment, which were carried out in respect of the super cyclonic storm of October 1999 over Bay of Bengal that hit Orissa coast near Paradip. The parameters required for cyclone vortex generation used for constructing the vortex and steering current, *viz*., the location of the storm, the central pressure, the outermost isobar, size of the storm, current storm speed and direction of movement etc. are derived from the synoptic and satellite imagery information. These parameters are of crucial importance in the model forecasts and care has to be exercised while



Figs. 1(a-d). Stream flow and isotach (speed in knots) pattern at 850 hPa QLM initial analysis and 24, 48 and 72 hours forecast based on 0000 UTC of 26 October 1999 initial conditions

finalizing their values. In the following subsections we provide very brief characteristics of the storms for which track forecast experiment was run.

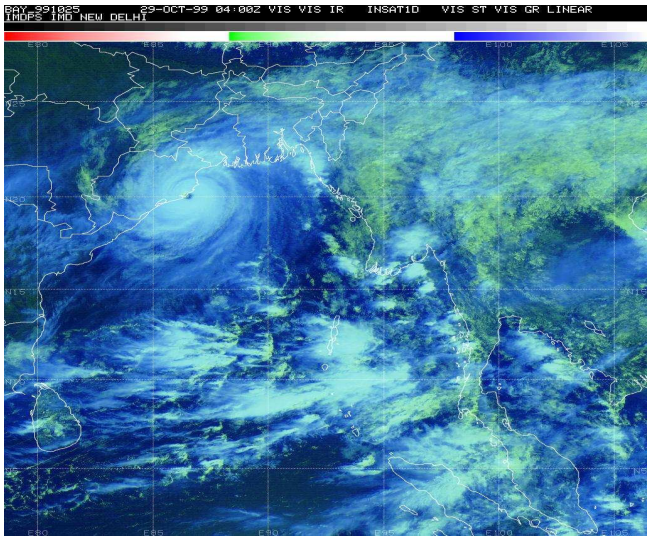
3.1. *Super cyclonic storm over Bay of Bengal, 25-31 October 1999*

The initial development of the storm was seen in the Gulf of Thailand on 24 October. It emerged into the Andaman Sea on 25 October. It moved in a northwesterly direction throughout its history. It intensified through several stages during its long journey over the Bay of Bengal and reached a super cyclonic storm stage with a peak intensity of T-7.0 (maximum wind speed 140 knots) on the morning of 29 October before its land fall close to Paradip on Orissa coast. After crossing the coast, the storm tracked very slowly further northwest and then remained practically stationary for 36 hours from 0600 UTC of 29th to 0000 UTC of 31. Afterwards, the vortex moved slightly eastwards and eventually drifted southward. It finally dissipated off north coastal Andhra Pradesh and adjoining sea areas of northwest Bay of Bengal by the morning of 1 November (India Met. Dept., 2000).

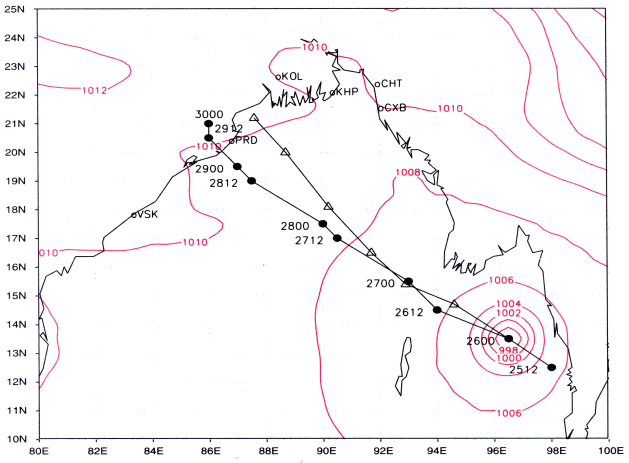
3.2. *QLM forecasts*

The sigma level data sets required for initial and boundary conditions for running the model were obtained from the NCMRWF. Sigma data files at 06 hourly

(a)

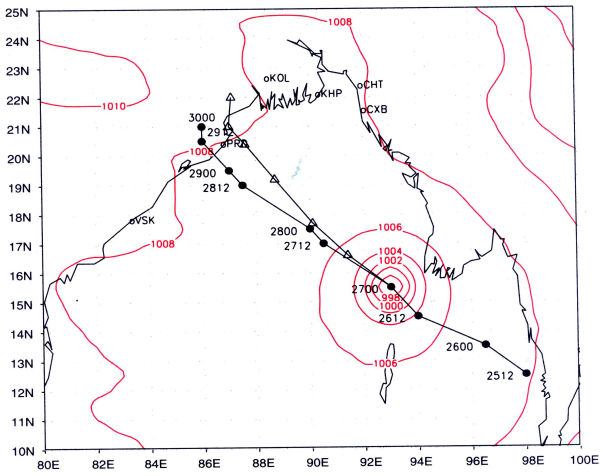


(b)



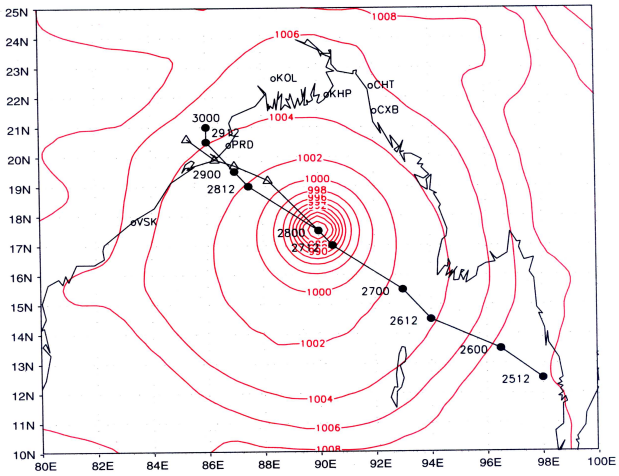
Mean sea level pressure (hPa) analysis valid 00 UTC of 26 October 1999 and track forecast based on 26 October/00 UTC initial conditions with idealized vortex; (● : observed; ∆: predicted)

(c)



Mean sea level pressure (hPa) analysis valid 00 UTC of 27 October 1999 and track forecast based on 27 October/00 UTC initial conditions with idealized vortex; (● : observed; ∆: predicted)

(d)



Mean sea level pressure (hPa) analysis valid 00 UTC of 28 October 1999 and track forecast based on 28 October/00 UTC initial conditions with idealized vortex; (● : observed; ∆: predicted)

Figs. 2(a-d). (a) INSAT picture at 0400 UTC of 29 October 1999; (b, c, d) Mean sea level pressure (hPa) QLM analysis and track forecast & observed track based on initial conditions of 26, 27 and 28 October 1999 (circle : observed; triangle : predicted)

intervals were used for calculating the boundary conditions. In Figs. 1(a-d) the stream flow and isotach pattern at 850 hPa initial analysis based on 0000 UTC of 26 October 1999 when the system was in a cyclonic storm stage and corresponding 24, 48 and 72 hours forecast fields are given. The analysis shows 30-45 kts to the northeast of the circulation center. In the 24 hours forecast, the wind speed increased to 45-65 kts and maintained up to 48 hours. However, in 72 hours forecast valid for 29th October, the strength reduced to 30-45 kts, where as the observed system attained strength of 140 kts. In Figs. 2 (a-d) the satellite picture of 0400 UTC for 29 October 1999, observed track of the storm and the track forecasts obtained from initial conditions of 0000 UTC for 26, 27 and 28 October with the corresponding 12 hourly predicted positions up to 72 hours superimposed on the MSLP analysis are given. It shows, the model was able to capture the north-west movement very well in this case.

TABLE 1

QLM forecast verification for Super Cyclone October 1999

	Date	12H	24H	36H	48H	60H	72H
Vector errors (km)	26 Oct '99	68	15	139	70	168	199
	27 Oct '99	106	25	128	118	118	159
	28 Oct '99	77	22	74	85	-	-
Mean		84	21	114	91	143	179
Angular deviation between observed and predicted track vectors[@] (deg.)	26 Oct '99	10.7	-2.0	1.7	4.6	8.6	8.8
	27 Oct '99	3.6	3.6	8.4	8.7	7.1	9.7
	28 Oct '99	12.6	2.6	-4.0	-7.9	-	-
*Errors (km) in distance travelled	26 Oct '99	-47	4	-138	20	-38	62
(Distance travelled in observed – Distance travelled in forecast)	27 Oct '99	-105	5	-88	13	-45	-7
	28 Oct '99	-44	13	-64	30	-	-
Landfall point errors DPE (km)	29 Oct '99	-	22	-	118	199	-

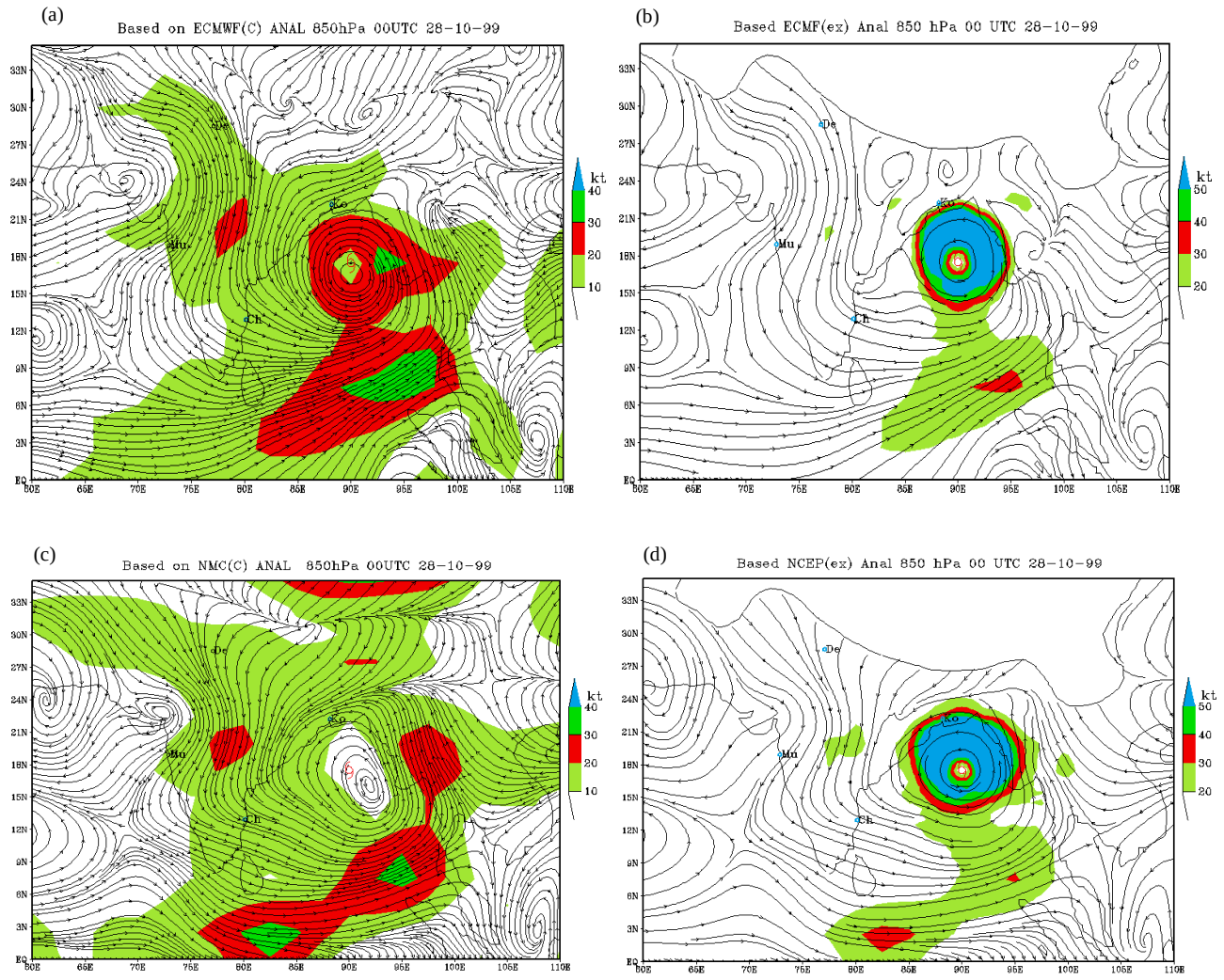
@ Observed track vector : Initial (at T_0) to observed (at T_0 + 12H … T_0 + 72H) positions
Predicted track vector : Initial (at T_0) to predicted (at T_0 + 12H … T_0 + 72H) positions

The track forecast errors of the case were given in Table 1. The day-3 forecast based on 26 October initial conditions, the model predicted landfall about 179 km northeast of the observed location where the observed storm made its landfall south of Paradip and the model track forecast errors in 24 and 48 hours are 15 and 70 km. The predicted track based on 27 October input of day-2 forecast of landfall point was 118 km to the right of actual position. The track and landfall point based on 28 October initial conditions almost coincided with the observed track with error of 22 km south of the observed position. Also the track forecast errors of 24, 48 and 72 hours (0000 UTC positions) are less compared to the 12, 36 and 60 hour forecasts (1200 UTC positions). This is due to the fact that the observed movement of the system from 0000 UTC to 1200 UTC is large compared to 1200 UTC to 0000 UTC from 27th onwards. However the model predicted uniform speed up to 72 hours forecast. Overall the mean forecast error in the present case was loss than 100 km up to 48 hours.

3.3. *LAM forecast*

In this experiment the model forecast for the case of Orissa super cyclone October 1999 are generated based on the initial conditions of 0000 UTC for 27 and 28 October. The basic data to run the cases were taken ECMWF, NCEP re-analysis global data at 2.5° Lat./Long. resolution and NCMRWF global model T-80 fields at 1.5° Lat./Long. resolution.

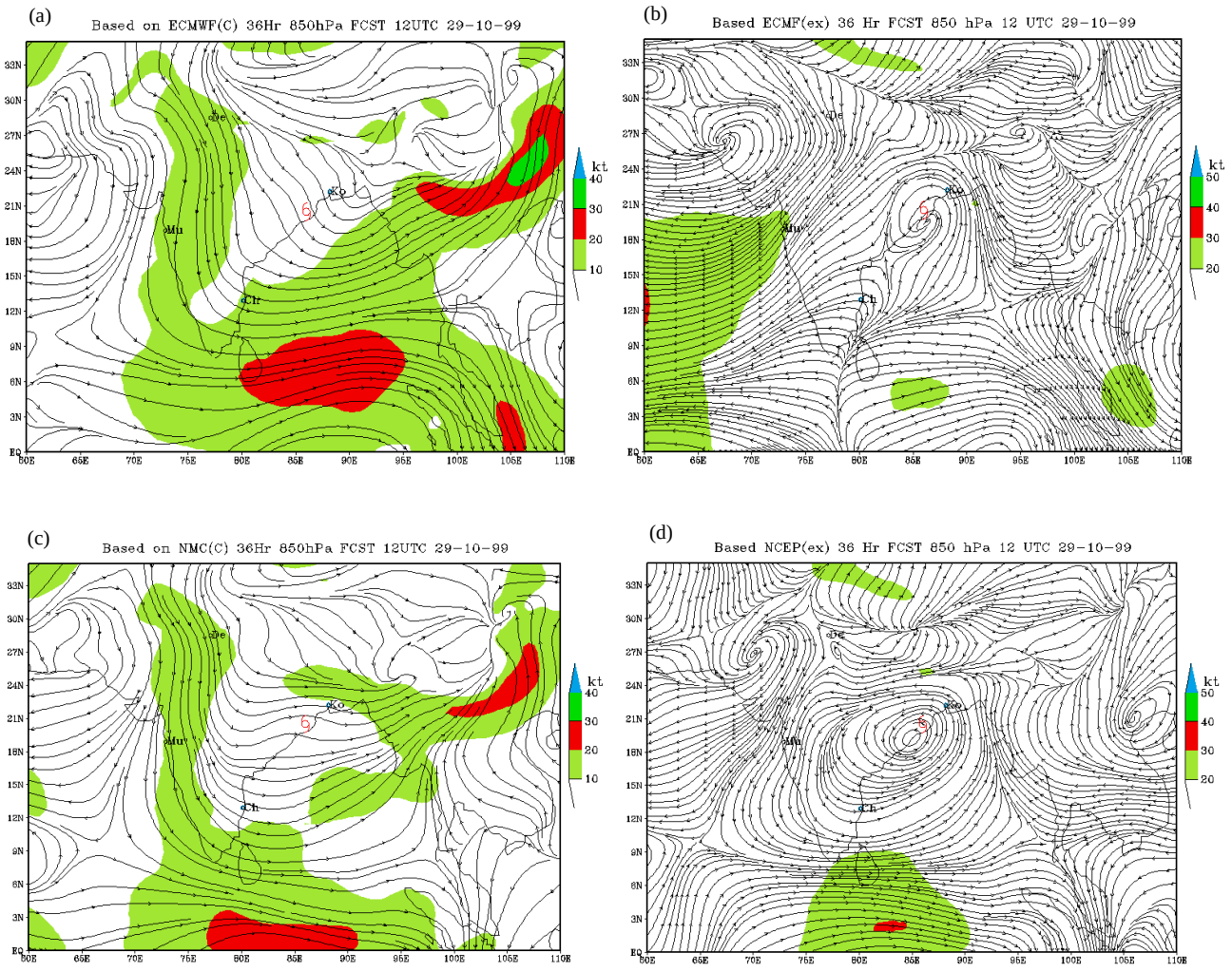
In Figs. 3(a-d) the 850 hPa initial analysed wind fields based on ECMWF and NCEP reanalysis data for 0000 UTC of 28 October with (experiment) and without (control) synthetic vortex were given. The ECMWF (control) wind field shows wind speed of 20-30 knots with the center coinciding the observed center. However, in the NCEP initial fields, the center is located 100 km southeast of the observed position with wind speed of 20-30 located 2° to 3° away south & southeast of the center. After the synthetic vortex inserted in the initial fields, both ECMWF and NCEP fields show symmetric vortex with sustained wind speed of more than 50 knots decreasing to minimum at the center of the storm. However, the NCEP analysis shows large size of vortex approx. 800 kms compared to ECMWF analysis of 400-600 kms and strength of the basic fields outside the vortex remained same in both the analysis. The large vortex in NCEP fields may be due to the asymmetric circulation in the initial analysis (control). The 36 hours LAM forecast based on 0000 UTC of 28 October with the above initial conditions valid for 1200 UTC of 29 October were given in Figs. 4 (a-d). In this case, with the ECMWF initial conditions, the control forecast 850 hPa wind fields shows weakening of the system into a trough of low with north-south orientation along east coast of India and with the



Figs. 3(a-d). (a&b) Wind flow (speed in knots) 850 hPa ECMWF initial analysis, without and with synthetic vortex.; (c&d) same with NCEP analysis for 0000 UTC of 28 October 1999 (cyclone symbol: observed position)

NCEP initial conditions, the trough were seen over Bihar to Telengana region. In the experiment, the forecast with ECMWF initial conditions shows the center of the system is close to the observed center, whereas with NCEP initial conditions the center is nearly 60 km southwest of the observed center.

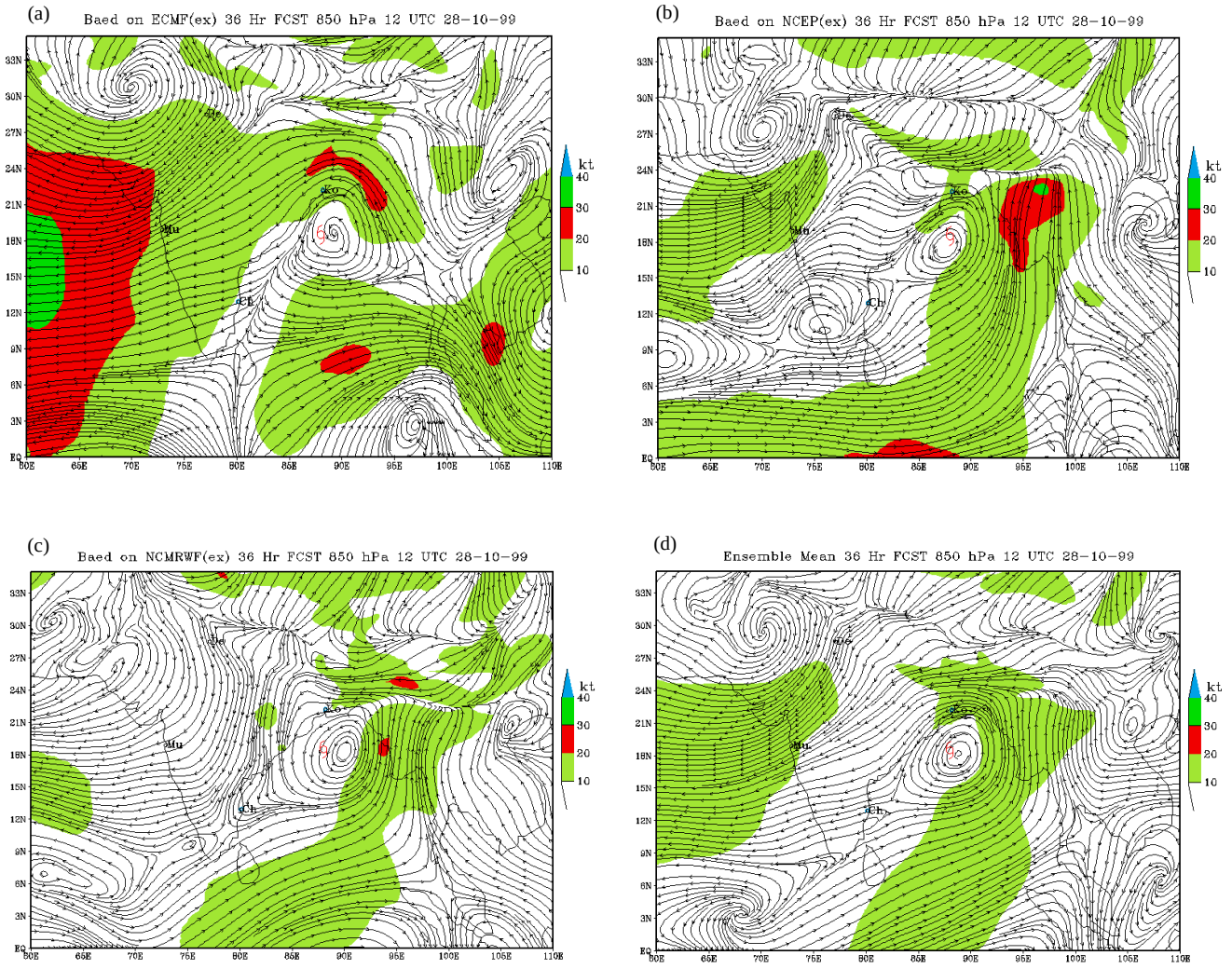
In Figs. 5(a-c) the 36 hours LAM forecast 850 hPa wind fields based on 0000 UTC of 27 October initial conditions of ECMWF, NCEP and NCMRWF valid for 1200 UTC of 28 October along with the mean (ensemble) of all the three forecasts [Fig. 5(d)] are given. These forecasts were produced after adding the synthetic vortex in the initial fields. This experiment was carried out to examine the impact of initial conditions on the forecast produced by the model. In this case, the 36 hours forecast center of the storm with ECMWF analysis shows 127 km to the east, forecast with NCEP analysis 113 km southwest, forecast with NCMRWF analysis 212 km east and finally the mean forecast shows 81 km southeast of the observed position. In respect of intensity of the system, based on ECMWF initial conditions, the 36 hours forecast shows 20-30 knots winds to the north of the system, forecast using NCEP initial conditions shows 20-30 knots winds to the northeast of the system and forecast with NCMRWF initial conditions shows 10-20 knots winds to the north and east of the system. However, the mean forecast shows 10-20 knots wind speed to the north and east of the system with symmetric vortex close to the observed position of the system.



Figs. 4(a-d). (a&b) LAM 36h forecast wind flow (speed in knots) 850 hPa valid for 1200 UTC of 29 October 1999 based on ECMWF initial analysis, without and with synthetic vortex.; (c&d): same with NCEP initial analysis (cyclone symbol: observed position)

4. Track and intensity prediction

A quantitative assessment of the performance of forecast model was made by computation of track prediction errors. Direct position errors (DPE) have been calculated by taking the geographical distance between the predicted position in each case of forecast and the corresponding observed position, which gives a measure of the absolute error of prediction. The vector errors (VE) are the differences of the vectors joining the initial position and the forecast position coupled with angular deviations of the two lines. They give an indication of the bias. Negative values mean a slow bias. The angular deviation between the observed and predicted track vectors (deg.) are positive if the forecast position lies right of the observed track in the northern Hemisphere. IMD regularly evaluates the performance of LAM and QLM forecasts at the end of each year. However, it was observed that the QLM forecast track errors are less than LAM and from 2002 onwards the operational cyclone track prediction model QLM track errors are only reported. The QLM real-time run for the super cyclone 25-31 October 1999, the mean position errors for 24 hr forecast was 108 km and for 36 hours 186 km (Prasad and Rama Rao, 2003). In the present case of rerun with additional late observations, the track forecast has shown significant improvement with mean forecast errors (Table 1) based on 26-28 October 1999 were 21 km for



Figs. 5(a-d). (a) LAM 36h forecast, wind flow (speed in knots) 850 hPa valid for 1200 UTC of 28 October 1999 based on ECMWF initial analysis with synthetic vortex, (b) with NCEP initial analysis, (c) with NCMRWF initial conditions of 0000 UTC 28 October and (d) the mean forecast of all the three (cyclone symbol: observed position)

24 hours, 91 km for 48 hours and 179 km for 72 hours. The angular deviation was shown with 10 deg. position (right of the observed track) bias. However, the vector errors shown large negative values for 12, 36 and 60 hours positions which show the slow bias compared to 24, 48 and 72 hours positions. The LAM forecast error shows (Table 2), 24 hours position error varies from 116 to 254 km and 36 hours forecast shown 113 to 212 km depending upon the initial fields. However the mean (ensemble of 3 members) forecast shown the track error of 123 km in 24 hours and 81 km in 36 hours forecast. While the track forecasts are reasonable, the model has a general tendency to weaken the intensity of the system. The intensity forecasting with operational numerical models still remains a major problem which needs to be addressed. In case of QLM, the model has shown the intensification up to 48 hours and then gradually the reduced intensity. In case of LAM, it has shown gradually reducing the intensity and at the end of 36 hours forecast, the sustained wind speed in 850 hPa reduced to 10-20 kts from the initial fields of 50-60 kts.

QLM model is running up to 36 hours operationally till 2004. Recently, the model code modified to run up to 72 hours and for validation of the model hind cast experiments were conducted for the cyclonic storms

TABLE 2

LAM forecast verification (Direct position errors in km)

	Initial conditions	12 h	24 h	36 h
Super cyclone October 1999	ECMWF	104	139	127
based on 0000 UTC of 27 Oct. 1999	NCEP	265	254	113
	NCMRWF	154	116	212
	Ensemble	116	123	81
Mean errors of (1997-2004) -16 cyclones	IMD	86(37)	145(37)	312(29)

TABLE 3

QLM & LAM forecast verification (Direct position errors in km)

Year	24 Hour forecast				48 Hour forecast				72 Hour forecast
	QLM	LAM	PERS.	CLIM	QLM (36 hrs)	LAM	PERS.	CLIM	QLM
1998	143 (2)	169 (4)	206	216	224	254	234	299	--
1999	119 (3)	136 (3)	341	205	248	287	497	250	--
2000	100 (3)	140 (3)	208	264	173	193	333	383	--
2001	106 (3)	137 (3)	269	204	183	204	373	402	--
2002	150 (2)	---	191	131	115	---	247	278	425 (2)
2003	187 (3)	---	267	231	251	---	382	358	280 (2)
2004	176 (4)	---	141	221	223	---	242	215	240 (2)
Mean error	140	145	232	210	202	234	330	312	315

Figures in brackets: Number of cases.

occurred from 1997 to 2004 (Prasad, 2004; Rama Rao and Prasad, 2005). Table 3 shows the operational track forecast errors of QLM & LAM from 1998 onwards. The QLM mean forecast errors during 1998-2004 were 140 km in respect of 24 hours and 202 km in 36 hours forecast and 315 km in 72 hours. Similarly the mean position errors of LAM based on 1998-2001, 145 km for 24 hrs forecast and 234 km for 48 hrs. The model forecast errors of both the models shows less than persistence errors and climatology. However, the model has not shown any trends in improvement forecast prediction skills from 2002 onwards. The increase in track forecast errors during the recent years may be due to the erratic nature of the movement of the cyclonic storms. Similar trends also observed in UKMO cyclone track forecast (UKMO web site) errors over North Indian Ocean.

5. Concluding remarks

The experiments on cyclone track forecast prediction with QLM and LAM carried out for Orissa super cyclone October 1999 has established that the model, with

idealized vortex, provides track forecast within an accuracy level that are currently available from numerical models. The QLM track forecast error for super cyclone is minimum compared to other cases. This may be due to the system nearly followed the climatological track of the storms in this month. The large scale/steering flow was better predicted in this case. Also the model predicted error was minimum all 24 hours forecasts. In the case of LAM forecasts, the forecast generated with bogus vortex using different initial fields have shown large variation in track forecast of the storm in 24 and 36 hours forecasts. However, the mean (ensemble) was able to evolve with minimum of track error. As a future work programme, the authors propose to continue further development work with the QLM for improvement in the track and intensity forecasts. The improvements are expected to be brought about by (*i*) improved initial analysis with incorporation of enhanced observational data base and better first guess from the outputs of higher resolution global model; (*ii*) increasing the horizontal and vertical resolution of the model and increased domain; and (*iii*) better treatment of lateral boundary conditions by updating at more frequent intervals. The intensity change issues are one of the most crucial aspects of the cyclone prediction problem, for which models of very fine resolution are needed. We intend to adopt the nested grid approach, which can better handle the intensity change problems.

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Appendix I

An outline of the QLM

Independent variables: (x,y,t)

Dependent variables: surface pressure, u, v, 0, q

Horizontal resolution: 40 km

Time step: 50 sec

Vertical resolution: 16 σ layers (17 σ interfaces). The 17 σ interfaces carry the following values: 1.0, 0.965, 0.922, 0.872, 0.816, 0.754, 0.688, 0.618, 0.546, 0.472, 0.397, 0.328, 0.250, 0.181, 0.114, 0.054, 0.0.

Domain size : 4400 × 4400 km^2

Storm's center: Storm's center is initially located at the center of the domain. The domain fixed during the forecast.

Convection: Kuo (1965) with large scale condensation surface fluxes

Surface fluxes : Bulk over Ocean, none over land

Quasi-Lagrangian time-differencing scheme