MAUSAM, 48, 2 (April 1997), 225-238

551.515.2 : 551.509.313

Prediction of tropical cyclones by numerical models — A review

K. PRASAD

Meteorological Office, New Delhi 110 003, India

सार — गतिकीय निदर्शों द्वारा चक्रवात के मार्ग के पूर्वानुमान में आने वाली कठिनाईयों के समाधान में कुछ पहले तथा हाल में हुई प्रगति की समीक्षा इस शोध-पत्र में की गई है । आरम्भ में किए गए प्रयासों का उद्देश्य ऊर्ध्वाधर एकीकृत भ्रमिलता वाले समीकरण पर आधारित साधारण दाबानुवर्ती निदर्शों के प्रयोग द्वारा उष्णकटिबंधीय चक्रवात की चाल का पूर्वानुमान लगाना था। प्रयोग में सरलता के कारण कुछ केन्द्रों में दाबानुवर्ती निदर्श का प्रयोग इस समय भी हो रहा है। तथापि, इस समय आधुनिक आद्य समीकरण निदर्शों पर बल दिया जा रहा है, जिसमें कपासी संवहन जैसी भौतिक प्रणालियाँ शामिल हैं, जो चक्रवात की गति से संबंधित मुख्य घटकों का पता लगाने के लिए आवश्यक हैं। पूर्वानुमान निदर्शों को चलाने के लिए गतिकीय निदर्शों द्वारा चक्रवात के पूर्वानुमान का एक महत्वपूर्ण पहलू आरम्भिक क्षेत्रों में सही ढंग से विश्लेषित कृत्रिम भ्रमिल का निर्धारण है। कृत्रिम भ्रमिल तैयार करने के लिए विभिन्न समूहों द्वारा तैयार किए गए कई प्रस्तावों पर चर्चा की गई है। भारत मौसम विज्ञान विभाग में सीमित क्षेत्र निदर्श और भूमंडलीय निदर्शों द्वारा चक्रवात के मार्ग के पूर्वानुमान से संबंधित कुछ मामलों की उदाहरण सहित व्याख्या की गई है।

ABSTRACT. This paper contains a review of some past and recent developments in cyclone track prediction problem by dynamical models. The early attempts aimed at predicting tropical cyclone motion by using simple barotropic models based on vertically integrated vorticity tendency equation. Barotropic models are still used operationally in some centres due to their simplicity. However, current emphasis is on advanced primitive equation models incorporating physical processes, like cumulus convection, which are necessary to account for a major component of the cyclone movement. An important aspect of cyclone prediction by dynamical models is prescription of a correctly analysed synthetic vortex in the initial fields for running a forecast model. Several approaches developed by various groups for generating synthetic vortex are discussed. Examples of some cases of track prediction by limited area model in IMD and by global models are illustrated.

Key words — Models, Track prediction, Tropical cyclone, Vortex, Initialisation, Forecast.

1. Introduction

Prediction of tropical cyclone by numerical models is, in principle, attempted by formulating a suitable numerical model, initialize it with observed data and integrate the time-dependent hydrodynamic equations numerically for a suitable time period to obtain the desired forecast. However, when a model is applied to the tropics, especially to tropical cyclone forecast problems, certain difficulties arise. Firstly, tropical cyclones occur most frequently over data sparse regions of the tropical oceans where an accurate specification of the initial state of the atmosphere is difficult. Secondly, the high-wind region of a tropical cyclone is small when compared to synoptic-scale systems. This makes it impractical to resolve the details of the vortex using a single mesh or grid length. Thirdly, the dynamics of the tropical atmosphere and the interaction of a tropical cyclone with its surrounding environment are not as well understood as the circulation regimes found in middle latitudes.

Recent technological advances and the use of ingenious numerical methods or schemes have partly solved some of these problems. The problem of grid scale size has been solved to some extent by development of high speed supercomputers, capable of handling the vast amount of data required by a multi-level large-area, fine- mesh numerical model. The so-called nested grids have been employed to resolve the structure of tropical cyclones with a fine-mesh grid, centred on the storm and "nested" within a large grid which is used to define the storm's environment adequately. The smaller (fine) grid is moved, or relocated, as the storm traverses the large stationary grid. Programmes, such as the Global Atlantic Tropical Experiment (GATE), which focussed on the problems of understanding the dynamics of the tropical atmosphere and the interaction of tropical weather systems/disturbances with their environments, have served to improve our diagnostic and predictive skills in relation to these phenomena.

The capability of primitive equation models in tropical cyclone prediction problems has been effectively demonstrated by several groups in recent times. Specially designed numerical models, coupled with some special techniques of initialization of tropical cyclones, have been successfully applied in track predictions. We provide a historical perspective of the numerical models applied in tropical cyclone prediction studies in section 2. Section 3 contains a brief overview of the operational numerical weather prediction system operative in India Meteorological Department (IMD) for producing cyclone forecasts and a few case studies of track prediction with IMD model. Performance of a few global models in cyclone forecasting with particular reference to Indian seas is illustrated in section 4. Information about skill of current NWP models in cyclone track prediction in different ocean basins is given in section 5. Section 6 contains concluding remarks.

2. Tropical cyclone prediction by numerical models — a historical perspective

2.1. *Early studies using barotropic models*

The early attempts at prediction of tropical cyclones were essentially based on single level barotropic models. The so called SANBAR barotropic model, after Sanders and Burpee (1968), was the first such model used for cyclone track prediction studies. SANBAR is a filtered barotropic model which uses winds averaged with respect to mass through the troposphere. The model, originally developed by Sanders and Burpee and later modified by Pike (1972), predicts tropical cyclone motion by the tracking of minimum stream function and maximum vorticity centres. The pressure-depth over which the initial wind observations are averaged is the 1000 to 100 hPa layer. These winds are objectively estimated from the automated 200 hPa and low level analyses. Both observed and estimated winds form the basis of an objective analysis, which produces a wind field specified at the grid points. Once the initial winds are specified, their non-divergent components are obtained by relaxation for the stream function in the interior of the grid. With suitable boundary conditions specified, a simple barotropic vorticity equation is used to predict the movement or track of the stream function minima and the vorticity maxima. The basic dynamical framework of this model is a simplified form of the vorticity equation averaged over the depth of the troposphere.

$$\partial \bar{\zeta}/\partial t = -\overline{\mathbf{V}} \cdot \nabla\eta - \mathbf{V}' \cdot \nabla\eta' + \phi(\omega_{1000} - \omega_{100}) \quad (1)$$

where, η is the absolute vorticity. $\mathbf{V}'$ and η' denote the deviations of winds and vorticities from the vertical averages.

Since details of the wind structure of a storm's vortex are not available and unresolved by the model grid, the storm is replaced by an idealized, symmetrically circular vortex. Pike (1972) also suggested inclusion of the current storm motion at forecast time, which resulted in much improved forecasts of the storm's direction of movement, especially during the first 24 hours. However, there still remained too slow a speed bias. Sanders *et al.* (1975) found that this bias was largely the result of:

(a) Truncation error in the finite difference analogue of stream function ψ, and the prediction equation calculations resulted in underestimated phase speeds, especially for short wavelengths and

(b) Relaxation of ψ produced a steering flow which was too weak. These problems were later corrected.

De las Alas and Guzman (1976) used a similar, but simpler model to predict typhoon tracks in the vicinity of Philippines. Their model employs a relaxation of the non-divergent barotropic vorticity to compute the stream function. The track of the typhoon is computed by following the trajectory of a point representing the initial surface position of the vortex centre as it is advected by the large-scale wind field.

Initial experiments with this model on a small number of cases produced encouraging results.

Though barotropic models have their own limitations, the interest in using them continues even in the present times. A justification for choosing a barotropic (*versus* a baroclinic) model for tropical cyclone prediction is to achieve higher horizontal resolution for a better representation of the storm structure and the interaction between the vortex and its environment, which is possible due to its simplicity and modest requirements of computing resources. Amongst the current operational barotropic models for cyclone track prediction are the Hurricane Research Division model called VICBAR and Bureau of Meteorology Research Centre (BMRC) model. VICBAR utilizes a nested grid with high resolution near the centre and coarser grids at greater distances (De Maria *et al.* 1992). In the operational version the inner grid resolution is 50 km. The initial analysis contains a symmetric vortex profile fit to the maximas of wind, eye size and storm size values estimated by the National Hurricane Centre (NHC). The VICBAR model is initiated whenever a named tropical storm (maximum winds > 34 kt) exists in the Atlantic region. VICBAR's performance has been found to be comparable or even better than some of the best known models like NHC-90 or a limited area quasi-Lagrangian baroclinic model.

Holland *et al.* (1991) have installed a barotropic model for tropical cyclone track prediction on a workstation at BMRC Australia. This model is run interactively to test various scenarios that might apply in a particular situation, *e.g.*, with different displacements and structures.

Disadvantages of the barotropic models are that the model performance diminishes after about 36 h when baroclinic effects become more prominent, particularly during recurvature stages after interaction with a westerly wave. Secondly, vertical shear effects in tropical cyclone structure and environment cannot be represented by barotropic dynamics. For this reason baroclinic models based on primitive equations have been developed and are the primary dynamic track prediction tools in major forecasting centres.

2.2. *Experiments with baroclinic primitive equation models*

In a first such study, Bengtsson *et al.* (1982) described "intense hurricane-type vortices" which developed in many ECMWF operational grid-point model forecasts of 1980 around the fourth day of their forecasts. Although in some cases the model storms appeared similar to actual storms, there were several cases where spurious cyclogenesis occurred. The model exhibited a definite bias in development of storms in the north west Pacific region. The authors felt that this was attributable to relatively high sea-surface temperatures used in the model. That was required to enhance the transport of moisture upward from the boundary layer.

Dell'Osso and Bengtsson (1985), in a latter study made forecast experiments on typhoon Tip of 1979. Tip was a major super typhoon of that year. The two models were the ECMWF operational global grid-point model and a limited-area version (ELAM) of the same model. The global model output was used to provide boundary conditions for ELAM. ELAM's grid resolution was around 57 km, as compared to roughly 208 km for the global model. The most striking aspect of the ELAM was its ability to provide a reasonable track forecast. The track of the typhoon in the global model run was somewhat poorer. It appeared from this study that model resolution had a significant impact on the accuracy of track forecasts. Such an increase in skill may in part be due to the simulation of the mesoscale typhoon structure on the finer grid. The typhoons' cross sectional structure was much more realistic in the ELAM forecasts. The ELAM storm exhibited realistic tangential velocity, a smaller radius of maximum wind, a stronger warm core, and a steeper surface pressure gradient compared to the global model. Another remarkably realistic aspect of the ELAM forecast was the prediction of very realistic-looking spiral precipitation bands, the location of these bands corresponded closely with those seen on satellite photographs. In this study, the authors demonstrate that, beginning with large scale data, sufficiently high resolution model can, with reasonable accuracy, simulate the development, structure, and motion of a tropical cyclone; although the model's need for time to develop the mesoscale structure from the large-scale data contributes substantially to errors in the track forecast.

Heckley *et al.* (1987) described two forecasts of Hurricane Elena starting from 31 August 1985. These were made with a global spectral model at a resolution of T 106 waves (Triangular Truncation). The passage of this storm along the northern Gulf of Mexico was of interest here. One of these was an operational forecast while the other used an experimental version of the operational global spectral model. The only difference in these two experiments was in the parametrization of cumulus convection. The operational model utilized a version of Kuo's parametrization scheme (Kuo 1974) for deep convection. The experimental model used a lagged adjustment scheme (Betts 1986, Betts and Miller 1986) for its parametrization of deep and shallow convection. The operational forecast was somewhat poor, it carried the storm roughly 200 km to the south of the Louisiana coast, whereas the experimental forecast, showed a landfall very close to the reported location on the Louisiana coast.

Krishnamurti *et al.* (1988) reported results of prediction experiments of several major hurricanes/typhoons in the Atlantic/Pacific region with a high resolution global spectral model. The cases examined were those of Hurricane Frederics (1979), Hurricane David (1979), Typhoon Hope (1979) and Typhoon Abby (1983). The spectral model utilizes the transform method for the calculations of nonlinear and physical processes. The physical processes include the parameterization of the planetary boundary layer, deep and shallow cumulus convection, radiative processes (including cloud feedback processes, diurnal change and surface energy balance) and large scale condensation. 'Envelope orography' is used to represent steep mountains globally. Ocean temperatures are prescribed from a preceding 10-day averaged data set for the storm periods.

Sensitivity of the storm forecasts to horizontal and vertical resolutions, data sets and representation of physical processes were examined. The experiments showed useful skill of the high resolution global model in track prediction. The position errors at the end of three days in these experiments were of the order of 200 to 300 km which compared very well with the best estimates of operational forecasts provided by statistical or movable nested grid models. The high resolution model produced a reasonable steering flow which is important for cyclone motion. The sensitivity experiments carried out on data density, model resolution and physical parameterization processes brought out the following important results:

(*i*) A major difference in the quality of forecasts appeared when the model was run with high density FGGE IIIb data sets as against operational FGGE IIIa data with short cut off time sets of NMC Washington which highlighted the importance of data coverage in the tropics.

(*ii*) A modified Kuo's scheme for cumulus parametrization yielded successful results in the prediction of formation and motion of a monsoon onset vortex (a typical storm) in Arabian Sea off the southwest coast in India in June 1979.

(*iii*) The role of radiative processes was important in a reasonable prediction of sub-tropical highs. This had an impact on the successful forecast of the recurvature of Typhoon Abby of August 1983. The prediction motion of 'Abby' in 24 and 48 hours had a good closeness of fit with the best track positions, the errors being around 1° latitude. The prediction of sub-tropical highs, which is very sensitive to the radiative forcing, contributed to an improved prediction of the high and the attendant steering flow.

(*iv*) Marked improvements were seen in the track forecasts by increasing the resolution from T 21 to T 106.

(*v*) A major factor turned out to be the improved resolution in the planetary boundary layer. It was found that the surface fluxes in the constant flux layer are markedly enhanced by an improved vertical resolution near the earth's surface. The hurricane maintenance is particularly sensitive to the latent heat flux.

(*vi*) The global models with the highest resolution of T 106 used in their study was able to resolve maximum winds of only 35-40 ms^{-1} which were underestimated by a factor of 2. The central pressure was overestimated.

The model could not resolve the inner rain area of the storm which is located within 100 km from the storm centre. Resolution of the model needed to be further refined in order to resolve the inner rain area.

In another experiment with a mesoscale multilevel regional primitive equation model of the landfall of an intense tropical cyclone in Bay of Bengal during May 1979, Krishnamurti *et al.* (1990) showed the efficacy of the model in accurate prediction of the landfall. The predicted motion field showed very little error in the first 72 hours. The predicted track was remarkably close to the observed track.

In yet another sensitivity experiment Krishnamurti *et al.* (1990) used the Australian Monsoon Experiment (AMEX) data sets to initialize tropical storms IRMA and CONNIE which formed in the Australian region during the AMEX special observing period. Incorporation of the additional AMEX data had a very substantial impact on the initial conditions. Additional data improved the location of the middle-level cyclone, strengthened the horizontal wind shear across the low-level monsoon trough, enhanced the curvature and outflow jet of the tropical upper tropospheric trough, made the vorticity at all levels over the genesis area cyclonic, strengthened the low-level convergence over the genesis area, and enhanced the mid to low-level moisture. All these features led the regional forecast model to generate a tropical cyclone with attendant mesoscale structure in the correct location and with correct temporal evolution in both the cases - IRMA and CONNIE. However, the movement of these systems was not well forecast. The reason attributed was a gradual contamination of the large-scale steering influenced by the inadequacies in the physical processes. The authors observed that accurate representation of the 4-dimensional structure of convective heating is important for track prediction.

In the control experiments without inclusion of AMEX data, the forecasts of motion and strength of the storms were reported to be extremely poor and the model failed to predict cyclogenesis. Without proper data the weak vertical motions, relatively weak low level cyclonic vorticity and a small Coriolis parameter in the initial fields resulted in inefficient convective heating and slow adjustment between the mass field, the divergent wind component, and the rotational wind component. This not only adversely influences the motion directly (via the divergence term in the vorticity equation) but also indirectly by degrading the large-scale (rotational) steering flow. The importance of adequate data coverage was thus again brought out.

2.3. *Recent advances and operational cyclone prediction models*

In the recent years, several studies with much advanced multilevel primitive equation (PE) models (regional and global) have been carried out in tropical cyclone intensity and track prediction and simulation, specially at the European Centre for Medium Range Weather Forecasts (ECMWF), the U.K. Meteorological Office; the Bureau of Meteorological Research Centre, Australia; the Geophysical Fluid Dynamics Laboratory, Princeton; the National Meteorological Centre Washington and the Japan Meteorological Agency, Tokyo. These studies have amply demonstrated the capability of current numerical models in handling the tropical cyclones. The models, while providing reasonable forecasts of the genesis, intensification and movement of cyclones, do not, however, have the capability to resolve their core structure and the inner rain area. This is due to the fact that the finest resolution operational models currently available have a horizontal grid resolution of the order of 50-100 km which could at best resolve the outer structure of the systems. Further, the vertical motions in the cumulus bands in tropical cyclones are essentially nonhydrostatic, whereas the models are usually constructed on hydrostatic assumption. In order to resolve the core structure adequately one needs to design models of 5-10 km horizontal resolution and which are based on nonhydrostatic formulations. At the same time the model should have a domain which extends over several thousand kilometres. Currently, it is feasible computationally only to use a small limited area with a grid spacing of tens of kilometres.

Many centres currently include special cyclone forecasting models in their operational NWP systems. As is well known and as mentioned in the beginning, application of numerical models in cyclone forecasting is fraught with special kind of problems primarily because of the fact that the initial structure of a storm cannot be resolved due to lack of observations in the storm field. The storms form in data sparse oceanic regions where observations are not adequate to resolve even the large-scale environmental flow. In some cases, even if observations in the vicinity of a storm are available, quality control checks on the (observation-first guess) residuals may prevent these data from entering the analysis system. Because of these deficiencies in the initial analysis, the forecasts produced by the models are generally in large error. This problem has in recent times attracted the attention of NWP community engaged in cyclone forecasting, and a correct representation of the storm vortex in the initial gridded fields through artificial means has been a subject of deeper study. Procedures have been developed to construct an idealized vortex in the storm location based on current information about the size and intensity of the observed storm that are usually inferred from satellite data and synoptic analysis. Several schemes have been suggested to produce the idealized vortex and merge it with initial analysis. Broadly speaking, there are two approaches followed in generating an idealized vortex for assimilating into the analysis system. In one approach, a spin-up vortex, whose structure depends on the observed size and intensity of the storm is generated and merged into the objectively analysed fields. For example, such an approach is followed in the quasi-Lagrangian Model (QLM) of the National Centre for Environmental Prediction (NCEP; formerly National Meteorological Centre), Washington (Mathur 1988, 1991). The prescription of a symmetric bogus vortex is based on the storm's central pressure, the pressure of the outermost closed isobar and size of the storm. The symmetric fields so obtained are projected on the grid of the forecast model which is a fine resolution (40 km) limited area model. In addition to introducing a bogus vortex in the initial analysis, a steering current is also introduced through a dipole secondary circulation.

A similar merging procedure is used at the Japan Meteorological Agency (Iwasaki *et al.* 1987), but the specification of the idealized vortex is different from the NCEP Washington QLM. JMA runs a typhoon forecast model (TYM) alongwith a Global Spectral Model (GSM) and a limited area Asia Spectral Model (ASM) for typhoon predictions. The initialization of typhoon is accomplished by generating bogus data from standard axi-symmetric vortices for well-developed tropical cyclones based on a few manually analysed parameters such as storm position, central pressure and radius of gale force winds (WMO 1994). Relative humidity is prescribed as 90% in the troposphere around the cyclone centre, so as to enhance the spin-up of the vortex through convection scheme. The bogus typhoon is superposed onto the objectively analysed fields through a weighted mean formula. After the bogus typhoon is embedded into the analysis fields, a non-linear normal mode initialization is applied to the fields to reduce excitation of gravity-inertia oscillations. Finally asymmetric flow field of wave number 1 with respect to typhoon centre is superposed onto the entire wind field including the bogus typhoon to get a reasonable initial movement of the model typhoon.

Kurihara *et al.* (1993) have propsoed a scheme in which a crudely resolved tropical cyclone is first removed from the large scale analysis with the help of suitably designed filters and a new specified vortex is then merged with the analysis. The specified vortex consists of both axisymmetric and asymmetric components. The symmetric component is generated by the time integration of an axisymmetric version of a hurricane prediction model. The symmetric flow thus produced is used to generate an asymmetric wind field by the time integration of a simplified barotropic vorticity equation. The asymmteric wind field, which can make a significant contribution to the vortex motion, is then added to the symmetric flow. Bender *et al.* (1993) in a companion paper have demonstrated good improvements in the performance of the Geophysical Fluid Dynamics Laboratory high resolution nested movable mesh hurricane model in predicting track and intensity of cyclones by using the above procedure of generating vortices in the initial analysis. Peng *et al.* (1993) use the spin up vortex approach to generate three categories of vortices (strong, weak and large, weak and small). The catalogued vortex is selected that most closely matches the present storm.

The second approach is to generate synthetic observations from an idealized storm structure, and these observations enter the analysis system as if they are real observations. Several different schemes have been suggested under this category. The procedure used at the United States Naval Environment Prediction Research Facility (NEPRF) consists of first simulating a nearly steady state storm starting from a symmetric vortex, and then the data generated from this simulated storm inserted as bogus observations in the analysis (Hodur 1989). At the European Centre for Medium Range Weather Forecasts (ECMWF), Andersson and Hollingsworth (1988) performed some experiments to study the impact of bogussing in the prediction of tropical cyclone movement by the ECMWF global spectral model. The bogus observations were generated with a simple idealized tropical cyclone model which consists of two parts; (i) an idealized symmetric vortex and (ii) a background field. The two parts are merged. The symmetric wind field at all levels is modelled by a 'Rankine Vortex'. Gradient wind relation is used to compute winds from geopotential field. Upper winds are obtained by applying a composite and constant vertical wind shear factor, which is a function of height. The observations enter the analysis system as if they are conventional radiosonde observations. The authors reported improvements in cyclone prediction by using the above methodology. In the United Kingdom Meteorological Office (UKMO) system (Morris and Hall 1987, Hall 1988, Morris 1989), the analysis of tropical cyclones was done earlier by inserting bogus winds at four positions around the centre at each level between 850 and 500 hPa. UKMO was applying the above method of bogussing of tropical cyclones in its global model since 1986. By this method while the 24 h forecast position errors were observed to be rather large as compared to manual forecasts, at 48 hours and beyond, the model showed considerable skill in predicting the positions of cyclones. A new scheme for the initialisation of tropical cyclones for use in the UKMO global model has recently been developed by Heming *et al.* (1995). In this scheme a profile of wind speed at the surface is constructed by using information from TC advisories (*e.g.*, radius of 35, 50, 100 knot winds) and combining these with any real observations of surface or low level winds in the area if the maximum sustained wind of the storm is greater than 30 knots. A simple exponential curve-fitting routine is used to produce a best-fit curve through the observations and advisory information. The introduction of new bogussing scheme produced substantial reductions in forecast errors of tropical cyclone tracks.

Both the above approaches have their own advantages and disadvantages. The advantage of the first approach is that the spin-up vortex is consistent with the model dynamics and physics which ensures a smooth start of integration with minimum noise (Elsberry 1987). However, this procedure has the obvious limitation that it is not possible to always ensure that the prescribed vortex has the intensity, three dimensional structure and the size characteristics similar to the actual storm. The second method overcomes the disadvantage of the first in that it is possible to generate observations at any fine resolution conforming to the three dimensional structure of a cyclone, and reproduce the analysed structure as close as possible to the actual storm. However, a drawback here is that proper assimilation schemes as yet do not exist to handle observational data at a very high density. Nevertheless the second aproach is more close to the natural process where actual observations are used for analysis, being simpler at the same time, and hence more desirable.

A large number of studies with operational numerical models on cyclone track and intensity prediction with bogus vortex introduced in the initialized fields have shown that these predictions improve very substantially. The success of these experiments has prompted some of the major NWP centres running global models to introduce bogus vortices on a worldwide basis in their operational data assimilation systems. A similar study in India Meteorological Department based on the second approach above was initiated by Prasad (1990) and applied for cyclone track prediction by Prasad *et al.* (1992). A procedure for generating synthetic observations in the cyclone field was developed and combined with a multivariate optimum interpolation analysis scheme of objective analysis. Several experiments on cyclone track prediction in Bay of Bengal and Arabian Sea have been carried out with a multi-level limited area primitive equation model. The remainder of this paper described the NWP system used for cyclone forecasting in IMD and results of some case studies.

3. Cyclone forecasting with NWP model in India Meteorological Department (IMD)

3.1. *The Limited Area Analysis Forecast System (LAFS)*

A Limited Area Analysis Forecast System (LAFS) consisting of automated data decoding procedures, multivariate optimum interpolation scheme of objective analysis and a high resolution ($1^\circ \times 1^\circ$ lat./long. grid) multi-layer (12 sigma levels) primitive equation model runs in operational mode on Cyber 2000U computer system in IMD, twice a day based on 00 00 UTC and 12 00 UTC inputs. The initial grid point fields for running the forecast model are prepared from the conventional and non-conventional data received through GTS. The analysis system uses observational data from surface (SYNOP/SHIP), upper air (TEMP/PILOT), satellite (SATEM, SATOB) and aircraft (AIREP) which are extracted and decoded from the raw GTS data sets. All the data are quality controlled and packed into a special format for objective analysis. First guess and lateral boundary data files are constructed from the global model forecasts run by the National Centre for Medium Range Weather Forecasting (NCMRWF). The LAFS gives several products of basic flow variables and derived fields, as also forecasts of accumulated precipitaton. The forecast model is a semi-implicit semi-Lagrangian multilayer primitive equation model cast in sigma coordinate system and staggered Arakawa C-grid in the horizontal (Krishnamurti *et al.* 1990). The present version of the model has a resolution of $1^\circ \times 1^\circ$ lat./long. (91×51 grid; covering a domain 10°S - 40°N and 40°-130°E), in the horizontal and 12 sigma levels (1.0 to 0.05) in the vertical. The model incorporates physical processes such as planetary bounday layer parameterization, shallow and deep cumulus convection, and radiation etc. Envelope orography is used in the current version. Model is run up to 48 h forecasts.

3.2. *Cyclone track prediction*

The same model has also been implemented for tropical cyclone track prediction in conjunction with a bogussing scheme for initializing the cyclone vortex

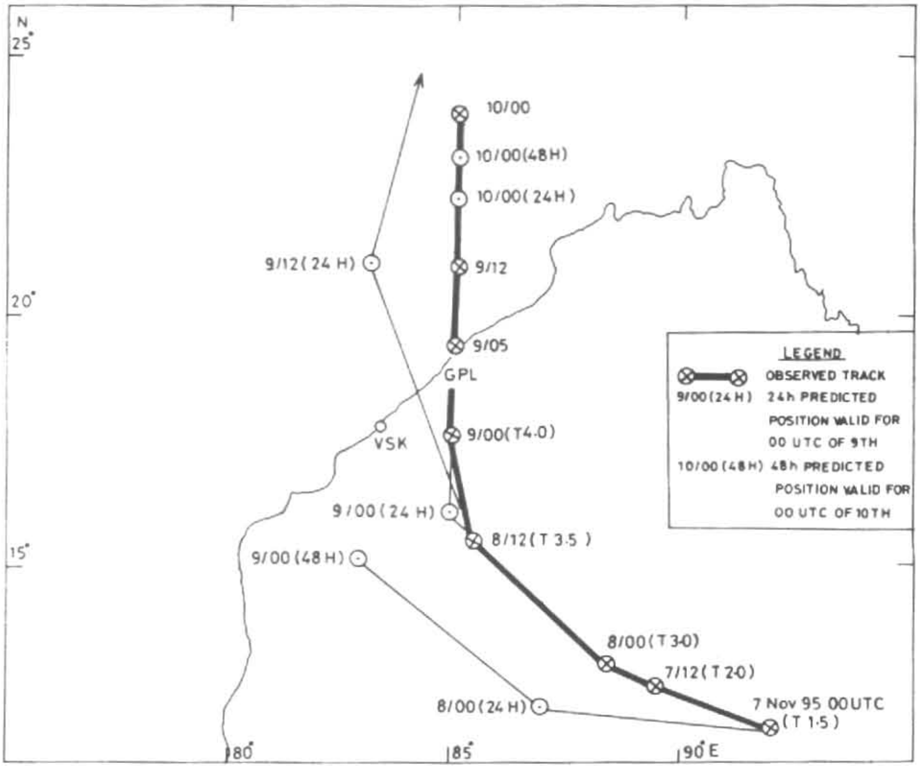


Fig. 1. Observed and predicted (24 H, 48 H) tracks of the severe cyclonic storm, 7-10 November 1995; (adapted from Prasad *et al.* 1994)

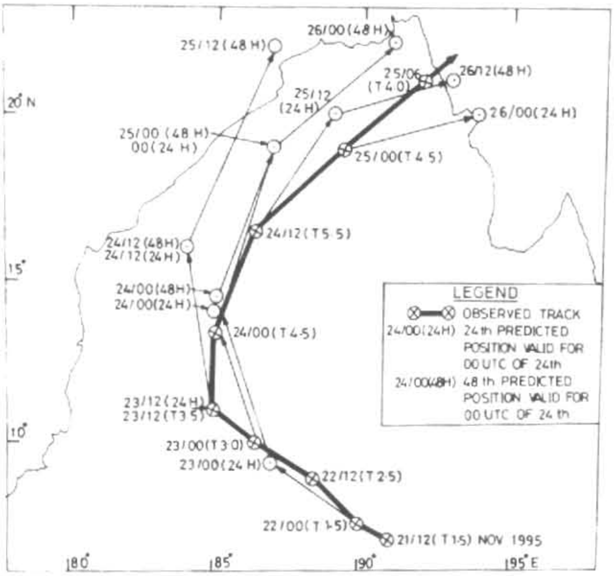


Fig. 2. Observed and predicted (24 H, 48 H) tracks of the severe cyclonic storm, 21-25 November 1995; (adapted from Prasad *et al.* 1994)

through synthetic data. The scheme basically generates radial distribution of surface pressure within the vortex from an empirical formula proposed by Holland (1980). Basic inputs for generating the surface pressure are the parameters like central pressure of the storm, its environmental pressure, radius of maximum wind, current position, movement and intensity of the storm, which are inferred from the surface synoptic charts and satellite imagery. Central pressure is estimated from the environmental pressure (outermost closed isobar) and pressure defect at the centre corresponding to the satellite T-Number estimate of the respective satellite imagery. Once the surface pressure field has been constructed, surface winds are obtained from the gradient wind relationship. Upper winds are computed from surface winds by using composite vertical wind shear factors proposed by Andersson and Hollingsworth (1988). Inflow and outflow angles are added to the computed winds to ensure proper convergence in the lower levels and divergence in the upper levels. Humidity is prescribed as near saturation value within the field of the vortex. The latter step is necessary to ensure a proper spin up of the vortex during the course of integration of the forecast model. The bogus observations are included in the data assimilation system as if they are conventional observations. Details of the scheme are discussed in Prasad *et al.* (1994).

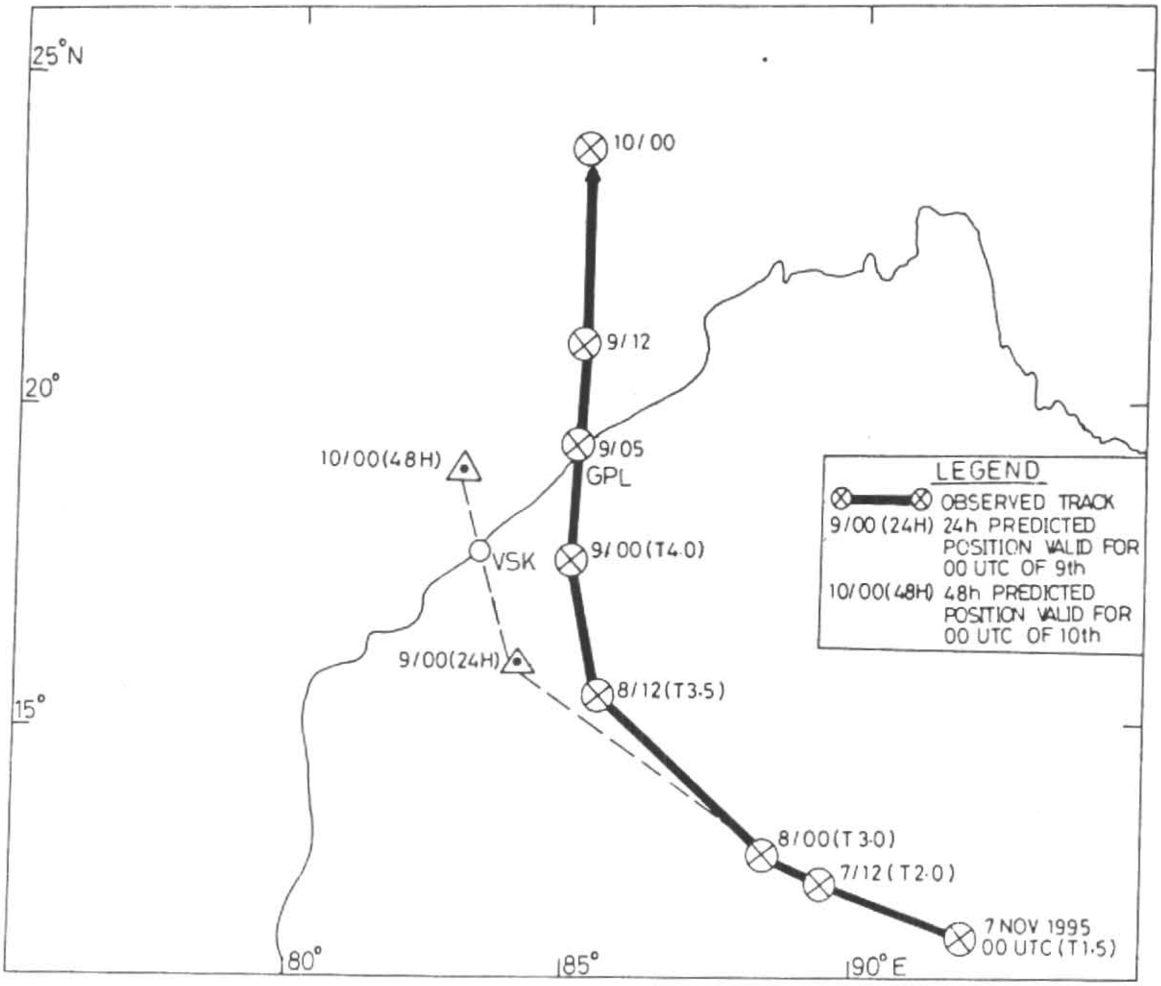


Fig. 3. Observed and predicted (24 H, 48 H) tracks of the severe cyclonic storm, 7-10 November, 1995 with 60% RH as initial bogus; (adapted from Prasad *et al.* 1994)

In a recent study using the above scheme with the limited area model, Prasad *et al.* (1994) have reported results of several track prediction experiments in Bay of Bengal and Arabian Sea for storms occurring during the period 1990-95. Initial analysis was corrected in all cases by supplementing GTS data with synthetic observations generated by the above scheme. The cases included both westward moving and northward moving (recurving) storms. Figs. 1 & 2 show two typical cases of track prediction by the IMD model in respect of severe cyclonic storms of 7-10 November 1995 and 21-25 November 1995 in Bay of Bengal. The skill of the limited area model is demonstrated in forecasting the movement of the cyclones in both the cases. A noteworthy feature of the model's performance is that recurvature of the system is well predicted in the case of Bangladesh cyclone of 21-25 November 1995. Capability of the model to predict intensity changes of the disturbance was also demonstrated.

Cumulus convection plays a dominant role in storm movement. In a sensitivity experiment JMA (WMO 1994) found that replacement of the Kuo convective scheme by Arakawa-Schubert scheme helped in reducing the northward bias in storm movement existing with the former scheme. Krishnamurti and Oosterhof (1989) have also demonstrated that improvements in Kuo type cumulus parametrization resulted in good track forecasts of a super typhoon. These studies thereby established the dominant role of convection in storm movement. The initial humidity analysis greatly influences the convection process in turn during course of integration of the model. In order to examine the impact of initial humidity field on track forecasts, the authors carried out a sensitivity experiment on the initial conditions of 8 Novemebr 1996/0000 UTC, in which the bogus relative humidity observations within the cyclone field were prescribed at near-saturation value of 95% in one case and at a medium level of 60% in another case, all other conditions remaining

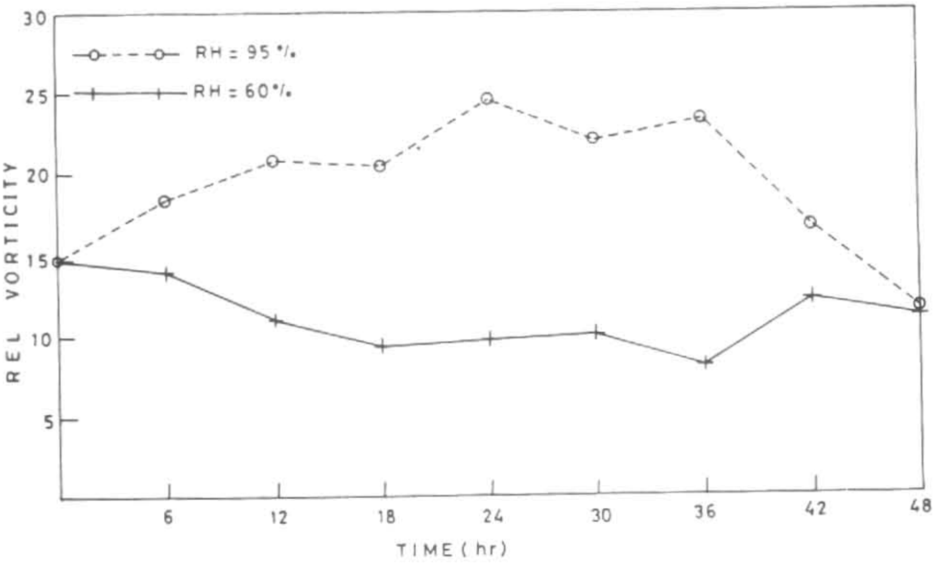


Fig. 4. Evolution of 6-hourly forecast relative vorticity with RH bogus prescription at near-saturation level of 95% (upper curve) and 60% (lower curve); (adapted from Prasad *et al.* 1994)

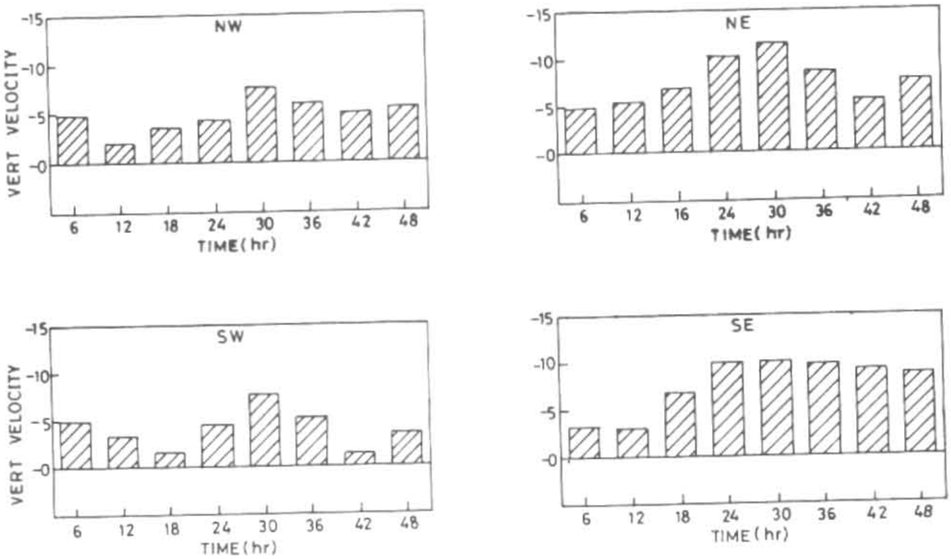


Fig. 5. Evolution of vertical velocity with time in model integration in four quadrants around the moving storm with RH bogus prescription at 95% level; (adapted from Prasad *et al.* 1994)

identical. The focus of the impact study was on the predicted tracks under the two conditions of initial humidity *vis-a-vis* evolution of the crucial dynamical parameters, like vorticity, vertical motion and integrated moisture flux divergence. A large deviation in the predicted track *vs* actual in the case of 60% RH was noticed. The cyclone moved northwestward in forecast with a speed much slower than actual, resulting in a very large position error at 48 h (nearly 500 km), in sharp contrast to the 95% RH case, where the predicted track was very close to the actual track with the position error just around 100 km at 48 h. The predicted track in 60% RH case is shown in Fig. 3.

Time evolution of some crucial dynamical parameters, which could account for such wide deviations in storm tracks in the two cases, *viz.*, the distribution of the vorticity maxima at the centre, vertical motion field and integrated moisture flux divergence in four quadrants around the moving vortex within a radius of 2° lat./long. were looked into. The evolution of vorticity field showed that

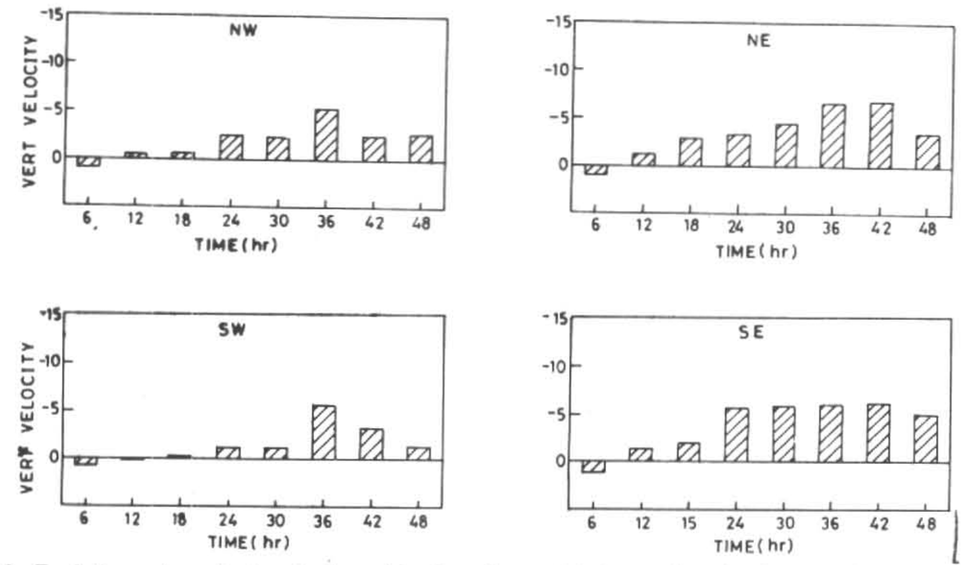


Fig. 6. Evolution of vertical velocity with time in model integration in four quadrants around the moving storm with RH bogus prescription at 60% level; (adapted from Prasad *et al.* 1994)

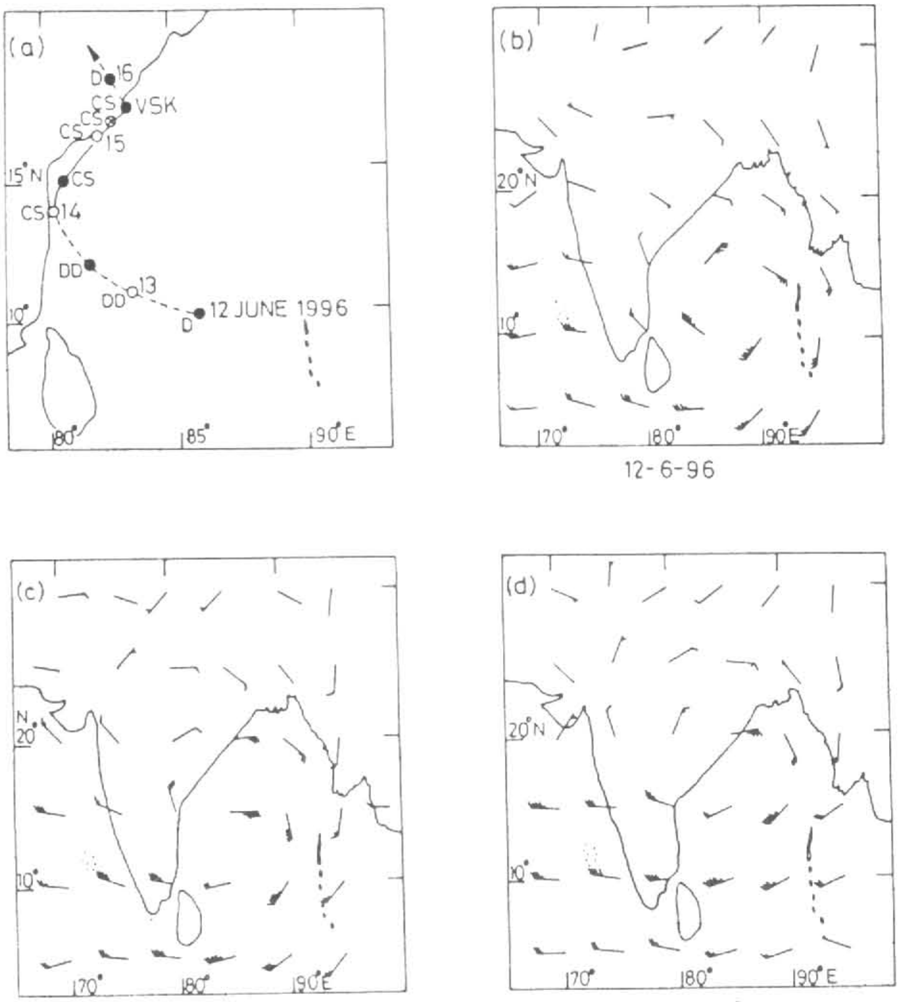
while in the saturation RH case the model showed intensification of the vortex with time, in the other case weakening of the system was evident (Fig. 4). In the vertical motion field, as the model integration proceeds, there is a sustained increase in upward vertical motion with time in the saturation case. With the initial humidity field prescribed at 60% level, the model brought out a clear spin up problem as the vertical motion failed to take off even after many hours of integration; the direction of vertical motion was in fact found to be downward in the first 6-12 hours. The time evolution of vertical motion is shown in Fig. 5. (95% RH case) and Fig. 6 (60% RH case). Likewise the distribution of integrated moisture flux divergence from 1000 to 300 hPa, which is a good parameter to monitor the net moisture convergence occurring in the total vertical column and a good indicator of the precipitation process, showed similar outcome. The sensitivity experiment clearly established the dominant role of initial humidity field and the attendant convection in influencing the vortex motion due to positive vorticity tendencies.

4. Cyclone predictions by global models

Many centres now run global NWP models with fine resolution comparable to limited area models of earlier years. Due to increase in model resolution and better data coverage these models have shown an improved skill in tropical cyclone predictions. A few examples of the performance of global models in cyclone track predictions in the Indian seas would be of interest here.

Krishnamurti (1996) gives an example of successful track forecast by a T 213 (transform grid separation 60 km) global spectral model with physical initialization, developed in Florida State University, in the case of a major cyclone in Bay of Bengal which hit Bangladesh in April 1991 and caused extensive loss of human life. Though the initial analysis had some deficiency in representing exact location and intensity of the storm, the model was able to produce a reasonably accurate track forecast and landfall.

Another example is that of the ECMWF model forecast in respect of an unusual case of a cyclonic storm in the Bay of Bengal in June 1996 which developed at the time of advance of southwest monsoon. A depression appeared in a southerly latitude around 10° N in the south and adjoining central Bay on 12 June. It initially moved northwestward upto 14th morning. It intensified into a cyclonic storm on 14th evening, recurved northeastward and kept moving in that direction very close to Andhra coast upto 15th evening. It made the landfall on 16th morning. Track of the cyclonic storm is shown in Fig. 7(a). We examined the performance of the ECMWF operational model in capturing the storm. ECMWF operational model is again a T 213 model and its grid point forecast data are received in IMD through GTS and processed on the Cyber computer. Figs. 7(b-d) show low level (850 hPa) 72 h tropical area forecast wind charts in the Bay region valid for 1200 UTC of 12, 13 and 15 June respectively, based on the



12-6-96

13-6-96

15-6-96

Figs. 7(a-d). Track of cyclonic storm of (a) 12-16 June 1996; (b) 12 June 1996; (c) 13 June 1996 and (d) 15 June 1996

corresponding day-3 initial conditions. Though ECMWF operational system does not provide for any bogussing procedure for correcting the initial storm position, as far as author is aware, the vortex was captured in their assimilation system on all the days from whatever observational data might have been available in that region. It is encouraging to see that the model was able to predict the movement correctly, particularly its recurvature, and even its initial formation on 12 June, with a lead time of three days, as can be easily inferred from the wind flow patterns shown in Fig. 7. This would go to demonstrate that the present day global models with very high resolution are able to provide useful advance guidance of tropical cyclone movement.

5. Forecast errors

The skill of a numerical model in storm track forecasting is best seen in terms of forecast errors. These are usually calculated in two ways : (*i*) absolute displacements between the actual and the model realized positions, and (*ii*) along-track and cross-track displacements. More usually the absolute displacements (position errors) are measured. It would be interesting to know the magnitude of forecast errors reported by various groups working on the problem. Mathur (1991) reported errors of the order of 180 km for the 1988 and 1989 hurricane seasons in respect of Atlantic hurricanes by the NCEP QLM. Likewise, 24 h forecast errors reported by Japan Meteorological Agency in respect of their Typhoon Model and Asia spectral model during 1988 and 1989 vary between 180 and 190 km (Kitade 1990). The statistics reported by UKMO in respect of their global model during the year 1994 vary from 176 to 278 km for 24 h forecasts and 312 to 370 km for 48 h forecasts for different ocean basins (UKMO 1995). The mean 24 h position errors in respect of the IMD model for all the cases studied from 1990 to 1995 work out to about 170 km and the mean 48 h position error or 1995 cases (5 in number) is around 210 km.

Many groups have reported a slow and poleward bias in their model predictions, for example UKMO (UKMO 1993) and JMA (WMO 1993). In fact all the JMA models have a noticeable start bias error and also northward drifting bias error in tropical cyclone movement (WMO 1994). Similar biases have also been noted by Prasad *et al.* (1994) in respect of IMD model. These biases are attributed possibly to cumulus parameterization scheme and the method of generating bogus data. In a sensitivity experiment carried out at JMA it was found that both the slow-start bias error and northward bias error can be reduced by introducing asymmetric components into the bogus data.

6. Concluding remarks

The review has brought out the capability of limited area and global models in producing successful cyclone track forecasts. An encouraging feature of these models is their ability to capture recurving motions much in advance; prediction of recurvature by dynamical models has been recognized as a difficult problem. Resolution of the model, initial moisture analysis and initial correct representation of the tropical cyclone vortex through an appropriate bogussing procedure seem to be the key factors in successful forecasts of cyclone movement by the models. An accurate moisture analysis in the tropical oceanic regions has to place a heavy reliance on the satellite retrievals. Additional data sources, such as rainfall rates and satellite OLR estimates need to be tapped which can provide proxy data for the data assimilation system through suitable inverse algorithms (physical initialization).

An emerging area for the future analysis systems is the three-dimensional and four-dimensional variational analysis (3DVAR and 4DVAR) which has the capability of assimilating those data coming from satellites which do not constitute direct model variables. Better results are expected from a combination of all the above factors as far as track predictions are concerned. Prediction of intensity variations in the core region of a cyclone needs further attention.

References

Andersson, E. and Hollingsworth, A., 1988, "Typhoon bogus observations in the ECMWF data assimilation system", Technical Memorandum No. 148, ECMWF, September, 1988.

Bender, M.A., Ross, R.J., Tuleya, R.E. and Kurihara, Y., 1993, "Improvements in tropical cyclone track and intensity forecasts using the GFDL initilization system", *Mon. Wea. Rev.*, **121**, 2046-2061.

Bengtsson, L., Bottger, H. and Kanamitsu, M., 1982, "Simulation of hurricane-type vortices in a general circulation model", *Tellus*, **34**, 440-457.

Betts, A.K., 1986, "A new convective adjustment scheme, Part I: Observational and theoretical basis", *Quart. J. R. Met. Soc.*, **112**, 677-691.

Betts, A.K. and Miller, M. J., 1986, "A new convective adjustment scheme, Part II : Single column tests using GATE - Wave, BOMEX, ATEX and Artic airmass data sets", *Quart. J. R. Met. Soc.*, **112**, 693-709.

Dell'Osso, L. and Bengtsson, L., 1985, "Prediction of a typhoon using a fine-mesh NWP model", *Tellus*, 37A, 97-105.

De Maria, M., Aberson, S.D., Ooyama, K. V. and Lord, S. J., 1992, "A nested spectral model for hurricane track forecasting", *Mon. Wea. Rev.*, **120**, 1628-1643.

Elsberry, R.L., 1987, "Tropical cyclone motion; A Global view of Tropical Cyclones" (based on Proceedings of the International Workshop on Tropical Cyclones, Bangkok, Thailand, November 25- 5 December 1985), chapter 4.

Hall, C.D., 1988, "Forecasts of tropical cyclones from the UK operational, global model", WMO PSMP Report Series No. 27, WMO/TD No. 213, 1988.

Heckley, W.A., Miller, M. J. and Betts, A. K., 1987, "An example of hurricane tracking and forecasting with a global analysis forecasting system", *Bull. Amer. Meteor. Soc.*, **68**, 226-229.

Heming, J. T., Chan, J.C.L. and Radford, A. M., 1995, "A new scheme for the initialisation of tropical cyclones in the UK Meteorological Office global model", *Meteorol. Appl.*, **2**, 171-184.

Hodur, R.M., 1989, "Tropical cyclone track prediction in a regional model", Extended Abstracts, 18th Conference on Hurricanes and Tropical Meteorology, San Diego, Amer. Meteor. Soc., 174-175.

Holland, G. J., 1980, "An analytical model of the wind and pressure profiles in hurricanes", *Mon. Wea. Rev.*, **108**, 1212-1218.

Holland, G. J., Leslie, L. M., Ritchie, E. A., Dietachmayer, G. S., Powers, P. E. and Klink, M., 1991, "An interactive analysis and forecast system for tropical cyclone motion", *Wea. Forecasting*, **6**, 415-424.

Iwasaki, T., Nakano, H. and Sugi, M., 1987, "The performance of a typhoon track prediction model with cumulus parameterization", *J. Meteor. Soc. Jpn.*, **65**, 555-557.

Kitade, Takeo, 1990, "Advances in Numerical Modeling since IWTC- 1", Proceedings of the Second WMO International Workshop on Tropical Cyclones (IWTC-II), Manila, November 27-8 December, 1989, WMO TD- No. 361, 21p.

Krishnamurti, T.N., Oosterhof, D. and Nancy, Dignon, 1988, "Hurricane prediction with a high resolution global model", FSU Report No. 88-8, Dept. of Meteorology, Florida State University, Tallahassee, Florida.

Krishnamurti, T. N. and Oosterhof, D. 1989, "Prediction of the life cycle of a super typhoon with a high resolution global model", *Bull. Amer. Meteoro. Soc.*, **70**, 1218-1230.

Krishnamurti, T.N., Arun Kumar, Yap, K. S., Ashu, P., Dastoor, Noels Davidson and Jian Sheng, 1990, "Performance of a high-resolution mesoscale tropical prediction model", *Advances in Geophysics*, **32**, Academic Press INC., 133-286.

Krishnamurti, T. N., 1996, "Advances in Numerical Weather Prediction in the Tropics with Particular Emphasis on Tropical Cyclones," FSU Report No. 96-7, June 1996.

Kuo, H.L., 1974, "Further studies of the parameterization of the influence of cumulus convection on large scale flow", *J. Atmos. Sci.*, **31**, 1232-1240.

Kurihara, Y., Bender, M. A. and Ross, R. J., 1993, "An initialization scheme of hurricane models by vortex specification", *Mon. Wea. Rev.*, **121**, 2030-2045.

Mathur, M. B., 1988, "Numerical prediction of tropical cyclones", International Symposium on Monsoon - Understanding & Prediction, 23-28 November 1988, Pune, India, 55-57.

Mathur, M. B., 1991, "The National Meteorological Centre's quasi-Lagrangian model for hurricane prediction", *Mon. Wea. Rev.*, **119**, 1419-1447.

Morris, R.M. and Hall, C. D., 1987, "Forecasting of the tracks of tropical cyclones with the UK operational global model", ESCAP/WMO Typhoon Committee Annual Review, 1987, Typhoon Committee, Secretariat, UNDP, Manila, Philippines, 102-105.

Morris, M., 1989, "Forecasting the evolution of tropical storms", Workshop on Numerical Products from Bracknell", UKMO, Meteorological Office College, Reading 26-28 June, 1989.

Peng, M. S., Chen, D.S., Chang, S. W., Chang, C. P. and Jeng, B. F., 1993, "Forecast of typhoon tracks near Taiwan by a numerical model incorporating past typhoon motion and different spin up vortices", Preprints 20th Conf. Trop. Meteor. Amer. Meteor. Soc., Boston, MA 02108, 367-369.

Pike, A.C., 1972, "Improved barotropic hurricane track prediction by adjustment of the initial wind field", National Oceanic and Atmospheric Administration Tech. Memo. NWS SR-66, National Weather Service, Southern Region Headquarters, Fort Worth, TX. U.S.A., 16 p.

Prasad, K., 1990, "Synthetic observations for representation of tropical cyclones in NWP data assimilation systems", Proceedings of the International symposium on assimilation of observations in Meteorology and Oceanography, Clermont-Ferrand, France, July 9- 13, 1990.

Prasad, K., Singh, B. V. and Hatwar, H. R., 1992, "Objective analysis and track prediction of tropical cyclones with synthetic data", Physical Processes in Atmospheric Models, edited by D. R. Sikka, and S. S. Singh, Wiley Eastern LTD., 349-363.

Prasad, K., Rama Rao, Y. V. and Sen, Sanjib, 1994, "Tropical cyclone track prediction by a high resolution limited area model using synthetic observations", submitted for publication in Mausam.

Sanders, F. and Burpee, R.W., 1968, "Experiments in barotropic hurricane forecasting", *J. Appl. Meteor.*, **7**, 313-323.

Sanders, F., Pike, A.C. and Gaertner, J.P., 1975, "A barotropic model for operational prediction of tracks of tropical storms", *J. Appl. Meteor.*, **14**, 265-280.

UKMO, 1993, "Monthly Summary of Tropical Cyclone Activity and Forecasts, December, 1993", Central Forecasting Division, UK Met. Office, Bracknell.

UKMO, 1995, "Monthly Summary of Tropical Cyclone Activity and Forecasts, November 1995", U.K. Met. Office, Bracknell.

WMO, 1993, "Numerical Weather Prediction Progress Report for 1992", NWPP Report Series No. 19, WMO/TD NO. 548, 109-110.

WMO, 1994, "Numerical Weather Prediction Progress Report for 1993", NWPP Report Series No. 20, WMO/TD NO. 618, 117.