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Tropical cyclone track prediction by a high resolution limited area model using synthetic observations

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सार — भारतीय समुद्रों में उष्णकटिबंधीय चक्रवातों के मार्ग पूर्वानुमान से संबंधित प्रयोग के परिणाम एक उच्च विभेदन सीमित क्षेत्र संख्यात्मक मौसम प्रागुक्ति मॉडल (1° x 1° अक्षांश / देशान्तर ग्रिड) के द्वारा यहाँ प्रस्तुत किए गए है। चूँकि उष्णकटिबंधीय चक्रवात उष्णकटिबंधीय महासागरों के ऐसे क्षेत्रों में बनते है, जहाँ आँकड़े बहुत कम उपलब्ध होते है, जिसके कारण इनके विश्लेषण का भली-भाँति सूत्रपात नहीं किया जा सकता है। अतः पूर्वानुमान मॉडल के परिचालन हेतु आरम्भिक स्थिति तैयार करने के लिए उष्णकटिबंधीय चक्रवातों की आनुभविक संरचना और उनके वस्तुपरक विश्लेषण में स्वांगीकरण पर आधारित संश्लिष्ट प्रेक्षण लेने की एक स्कीम तैयार की गई है। 1990-95 की अवधि के दौरान बंगाल की खाड़ी और अरब सागर में बने चक्रवातों के मार्ग के पूर्वानुमान के संबंध में प्रयोग किए गए हैं। मॉडल की 24 घंटे और 48 घंटे के पूर्वानुमानों की त्रुटियों का परिकलन किया गया है। पूर्वानुमान मॉडल के कार्य निष्पादन में आरम्भिक आर्द्रता फील्ड की महत्ता को प्रदर्शित कने के लिए एक सूक्ष्मग्राहिता प्रयोग किया गया है। पूर्वानुमान मॉडल द्वारा चक्रवात के मार्ग के संबंध मे सही पूर्वानुमान देने में आरम्भिक आर्द्रता फील्ड निर्धारण की निर्णायक महत्ता का पता चला है।

ABSTRACT. Results of tropical cyclone track prediction experiments in the Indian seas by a high resolution limited area numerical weather prediction model ($1^\circ \times 1^\circ$ lat./long. grid) are presented. As the tropical cyclones form in data sparse regions of tropical oceans, and are, therefore, not well analysed in the initial fields, a scheme has been developed for generation of synthetic observations based on the empirical structure of tropical cyclones, and their assimilation into the objective analysis for preparing initial fields for running a forecast model. Experiments on track prediction have been conducted for the cyclones forming in the Bay of Bengal and Arabian Sea during the period 1990-95. Forecast errors of the model for 24 hr and 48 hr forecasts have been computed. A sensitivity experiment has been carried out to demonstrate the importance of initial humidity field on forecast model performance. The experiment brings out crucial importance of the initial humidity field prescription in accurate track prediction by the forecast model.

Key words — Synthetic vortex, Limited area model, Cyclone track prediction, Impact of initial humidity specification, Forecast errors.

1. Introduction

Despite the inherent limitations in the understanding of tropical dynamics and inadequacies of tropical data base for numerical weather prediction, notable success has been achieved in tropical cyclone predictions by regional and global models in recent years. A major problem in the use of numerical models in operational cyclone forecasting is the near absence of conventional and inadequacy of nonconventional data out in the sea areas where cyclones develop. Due to these deficiencies in the oceanic observing systems, the cyclones are generally not well represented in the initial analysis for running a forecast model. The vortex at cyclone's location may either be completely missing or badly represented in terms of intensity, size and location. They may be too large or too weak. Not even the large scale flow in the vicinity of the storm, which acts as a steering current, is properly analyzed. Due to poor initial analysis, performance of a forecast model would naturally be in large error. The models have 'spin up' problems in such events, affecting the storm motion and intensity forecast.

To overcome the problems of misrepresentation of cyclone's structure in the initial analysis, methods have been devised where a cyclonic ('bogus' or 'synthetic') vortex of appropriate intensity and size is forced into the objectively analyzed fields before running a forecast model. Several studies have demonstrated that such a process can lead to successful forecasts of cyclone tracks. Even recurvature of cyclones, which is normally difficult to predict, has been shown to be captured by the model in some cases. Early attempts at cyclone track predictions following the above approach include studies by Andersson and Hollingsworth (1988) who suggested a scheme for typhoon bogus observations in the European Centre for Medium Range Weather Forecasts (ECMWF) data assimilation system. Morris and Hall (1987), Hall (1988) and Morris (1989) demonstrated the ability of the United Kingdom Meteorological Office (UKMO) global model in handling tropical cyclones by including bogus observations. Prasad (1990) developed a scheme for generating synthetic observations in tropical cyclone field for initializing a limited area primitive equation model in India Meteorological Department (IMD) Mathur (1988, 1991) has reported improvements in the forecast of the storm track and intensity by prescribing an idealized vortex in the initial fields in the National Centre for Environmental Prediction (NCEP), Washi- ngton quasi-Lagrangian model for hurricane prediction. Similar procedures have been developed in Japan Meteorological Agency (JMA) for typhoon forecasts (Kanamitsu 1985, Iwasaki et al. 1987). Kurihara et al. (1993) and Bender et al. (1993) formulated a procedure for initializing a 'spin up' vortex in the GFDL nested grid hurricane model.

The objective of this paper is to present the results of cyclone track forecast experiments by a high resolution limited area model using synthetic observations in the Indian seas. The model is run from initial conditions where a properly analysed vortex at the cyclone location is ensured by performing objective analysis after incorporating the synthetic observations in the input data. The synthetic observations are generated from an empirical structure of the cyclone. Brief details of the data input, analysis and forecast models are described in section 2. Section 3 contains the methodology of generating synthetic observations. Results of track prediction experiments in respect of tropical cyclones formed in the Bay of Bengal and Arabian Sea during the six year period 1990-95 are given in section 4; both westward moving and northward moving storms have been included. An important aspect of the study is to carry out a sensitivity experiment by varying the initial humidity bogus in the field of cyclone vortex and see its impact on forecasts of track and intensity. Evolution of vorticity, vertical motion, and integrated moisture flux divergence under two different conditions of initial humidity are examined. Results are discussed in section 4. In section 5 forecast errors are computed and discussed. Finally, concluding remarks are given in section 6.

2. The analysis-forecast system

(a) *Input data*

The grid point fields for running the forecast model are prepared from the conventional and non-conventional data received through GTS. The input data used for analysis consist of the surface SYNOP/SHIP, upper air TEMP/PILOT, SATEM, SATOB and AIREP which are extracted and decoded from the raw GTS data set. All the data are quality controlled and packed into a special format for objective analysis. The synthetic observations in the cyclone field, generated by a scheme, which is the subject matter of the present paper, are added to the input data file.

(b) *Analysis procedure*

The objective analysis is carried out by three dimensional multivariate optimum interpolation procedure. The variables analysed are the geopotential, u and v components of wind and specific humidity. Temperature field is derived from the geopotential field hydrostatically. Analysis is carried out on 12 sigma surfaces 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0.07, 0.05 in the vertical and on 1° × 1° horizontal lat/long. grid, for a 'regional' or 'limited area' horizontal domain (91 × 51). The sigma fields are post-processed to the pressure surfaces for display and archival.

(c) *Forecast model*

The forecast model is a semi-implicit semi-Lagrangian multilayer primitive equation model cast on sigma coordinate system and staggered Arakawa C-grid in the horizontal (Krishnamurti *et al.* 1990). The present version of the model has a horizontal resolution of 1° × 1° lat/long. (domain 91 × 51) in the horizontal and 12 equispaced sigma levels (1.0 to 0.05) in the vertical. The model consists of the usual equations of motion, thermodynamic energy equation, mass continuity equation, moisture continuity equation, hydrostatic equation and equation of state.

The following physical processes are included :

- Large scale condensation
- Shallow moist convection
- Deep cumulus convection
- Surface fluxes
- Vertical diffusion
- Short-wave radiation
- Long-wave radiation
- Surface energy balance
- Orography

Further details of the model formulation can be found in Krishnamurti *et al.* (1990).

(d) *Background field and boundary conditions*

The background field required for objective analysis and lateral boundary data for running the forecast model are obtained from the global model forecasts of the National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi.

The complete system as described above will be referred to as the Limited Area Analysis Forecast System (LAFS) in subsequent discussion.

3. Procedures for generating synthetic vortices

Broadly speaking, there are two approaches followed in generating a synthetic vortex for assimilating into the analysis system. In one approach, an idealized '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 was followed in the operational quasi- Lagrangian Model (QLM) of NCEP Washington (Mathur 1991). The prescription of bogus vortex is based on the storm's central pressure, the pressure of the outermost closed isobar and size of the storm. 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. Roy Abraham *et al.* (1995) have conducted sensitivity experiments to investigate the influence of synthetic vortices on cyclone forecasts by a global spectral model using FGGE III-b data sets, making a comparative study of Rankine vortex and Holland vortex. The synthetic vortices are incorporated in the initial analysis by a merging process.

Kurihara *et al.* (1993) have proposed 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 asymmetric 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 (GFDL) 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 is inserted as bogus observations in the analysis (Hodur 1989). At the European Centre for Medium Range Weather Forecasts (Andersson and Hollingsworth 1988), the bogus observations are generated from an idealized Rankine vortex. At the United Kingdom Meteorological Office (Morris and Hall 1987) tropical cyclone vortices are ensured in the analysis fields by inserting bogus winds at four positions around the centre at each level between 850 and 500 hPa. In the BMRC model both the symmetric and asymmetric circulations are represented by synthetic observation, which are combined with the surrounding observations in the objective analysis step. A nudging assimilation technique is used to make the observations consistent with the model equations (Davidson 1992).

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 approach is more close to the natural process where actual observations are used for analysis, being simpler at the same time and hence more desirable.

The approach followed in our scheme is to generate synthetic observations from the known empirical structure of tropical cyclones. Such a scheme was first proposed by Prasad (1990) and tested on a coarse resolution ($2^\circ \times 2^\circ$) forecast model (Prasad *et al.* 1992) which has Arakawa-A discretization. In this scheme, first, surface pressure field is constructed at dense enough 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. A significant improvement over the scheme originally developed (Prasad 1990) has been affected in that appropriate 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 field is prescribed as near saturation value within the field of the vortex. These steps would ensure a proper spin up of the vortex during the course of integration of the forecast model. The model used in the present study is cast on $1^\circ \times 1^\circ$ lat./long. grid and has Arakawa-C discretization. Very substantial improvements have resulted by using the new procedure in terms of improved track forecasts, and rainfall rates being much higher and realistic.

In the current version of the scheme we provide only the bogus wind observations and leave it to the initialization process to generate its own mass field. Though mass observations (surface pressure and upper level geopotential profile) are generated in the scheme, these are not included in the observational data based for objective analysis; only wind observations are taken into consideration. Such a decision was taken after it was discovered following a number of experiments that inclusion of only the wind observations and allowing the model to generate its own mass field yields the best results. The new scheme handles not only the tropical cyclones but also the weaker disturbances - low pressure areas and depressions - so that the forecast model can be run from the incipient stage itself. The scheme is discussed in the following paragraphs.

3.1. *Tropical cyclone*

(a) *Surface pressure field*

We make use of the empirical model developed by Holland (1980) to prescribe the surface pressure field. The relationship is given by:

$$P_r = P_c + (P_e - P_c)\ \mathrm{EXP}\ (-\ a/r^b) \tag{1}$$

where P_r is the surface pressure at radius r, P_e is the environmental pressure, P_c is the 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 :

$$\mathrm{RMW} = (a)^{1/b} \tag{2}$$

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, 1993) that the value of constant 'b' varies from 1.0 to 2.5 for cyclones in the Indian seas and that each cyclone has a unique value. Application of the above model for deriving the surface pressure distribution is dependent upon the availability of the following parameters:

(*i*) central pressure

(*ii*) radius of maximum wind

(*iii*) value of constant 'b'

The central pressure is estimated with the help of 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 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 in the sea. For the purpose of the present study we have assumed the value of RMW as 30 km in all cases 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 was taken as 1.5 which is tentatively found to be appropriate for the Indian region. Pressure data are generated upto 400 km radius, on a grid of 50 km spacing.

(b) *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 speeds V inside the cyclone field can be obtained in the form:

$$V = -\alpha + (\alpha^2 + r/\rho\ \partial p/\partial r)^{1/2} \tag{3}$$

where,

$2\alpha = f_r - V_c \sin\theta$

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 (Basu and Ghosh 1986)

$$1/r \cdot \partial p/\partial r - fV - V^2/r + VV_c\, Sin\theta/r = 0 \tag{4}$$

(c) *Upper winds*

TABLE 1

Composite vertical wind shear factors

	Level (hPa)				
Surface	850	700	500	400	300
1.0	0.9	0.8	0.7	0.65	0.35

The upper winds are derived from the surface winds by assuming an ad-hoc vertical wind shear which decreases the strength of the vortex with increasing height. Values of vertical wind shear factors are taken as proposed by Andersson and Hollingsworth (1988), given in Table 1. The above factors are based on the rawinsonde composites constructed by McBride (1986). The composites indicate a wind speed varying very slowly with height upto 400 hPa with a rapid decrease above. The factors would vary from the case to case and depend upon thermal stability and stage of development of the system (Andersson and Hollings worth 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 level varying from 30o. at the surface becoming zero at 500 hPa. The circulation in the upper levels 250 and 200 hPa is made anticyclonic and an outflow angle of 20o added.

3.2. *Low pressure area/depression*

In the case of low pressure area/depression the methodology is to compute gradient winds from only the central pressure and the outer pressure assuming a linear pressure profile. Remaining procedure is the same as in the case of tropical cyclone. Data are generated only upto 500 hPa in these stages.

4. Track prediction experiments

Several experiments for track prediction have been run with the limited area forecast model. Eleven tropical cyclone cases in the Bay of Bengal and Arabian Sea during the six year period 1990-95 have been studied: 5-11 May 1990, 24-30 April 1991, 11-15 November 1991, 3-6 November 1992, 11-17 November 1992, 15-21 November 1992, 12-15 November 1993, 1-4 December 1993, 29 April-2 May 1994, 7-10 November 1995 and 21-25 November 1995. The storm of 12-15 November 1993 occurred in the Arabian Sea and all others in Bay of Bengal. Initial analysis was corrected in all cases by supplementing GTS data with synthetic observations generated according to the above scheme. The input parameters required for creating the synthetic observations are picked up from the synoptic analysis and satellite imagery information. Forecasts were run out to 24 hours for storms prior to 1994, and 48 hours for the cases of 1995. The cases included both westward moving and northward moving (recurving) systems.

For the purpose of illustration, we have chosen the case of two recent severe cyclonic storms of 7-10 November 1995 and 21-25 November 1995 which formed in the Bay of Bengal, and the one of 12-15 November 1993 in Arabian Sea. The former crossed the east coast of India in Orissa, travelled initially northwestward for sometime and later recurved northward. The second one, moving north and northeastward hit Bangladesh. The one in Arabian Sea had a distinguishing feature in that it weakened over the sea before landfall. We present the results of forecast experiments to demonstrate the accuracy of track predictions by the limited area model and evolution of the field of basic flow variables and some crucial derived parameters. The main focus here would be on the sensitivity experiment which was carried out to study the impact of contrasting initial humidity fields on the evolution of cyclone's intensity *vis-a-vis* the associated fields of dynamical parameters like vorticity, vertical motion and integrated moisture flux divergence and to demonstrate the capability of the model in predicting the changes in intensity and direction of movement of the storms. The sensitivity experiment is carried out on the initial conditions of 8 November 1995 00UTC.

4.1. *Severe cyclonic storm, 7-10 November 1995*

4.1.1. *Brief synoptic history*

The storm's incipient stage was observed in the southeast Bay of Bengal as a T 1.5 vortex near 11°N 92°E on 7 November 1995 morning. Subsequent intensification led to its development into a severe cyclonic storm with a T 3.0 classification on 8 November. The vortex initially moved northwest from 7 to 8 November, and took a northerly course from 8th onward. It crossed Orissa coast near Gopalpur in the forenoon of 9 November. It weakened as usual after landfall and continued its northward propagation during the subsequent 24 hours.

4.1.2. *Track and intensity prediction*

The observed track of the cyclone and model predicted positions at 24h and 48h starting from the initial conditions on each date of the duration of the storm are shown in Fig. 1. The tracked positions are the grid point coordinates corresponding to the maxima of relative vorticity at 850 hPa. It is interesting to see that the predicted direction of movement closely follows the observed track on all days of the forecast. In fact the predicted track starting from 8 November/00 UTC overlies the observed track, predicted positions at 24h and 48h being reasonably close to the actual positions.

Another noteworthy feature of the experiment is the capability of the model to predict the intensity changes of the disturbance. This is brought out by mapping the wind, vorticity and mean sea level pressure (MSLP) fields of initial analysis and forecasts. The maps of analyzed wind and vorticity fields at 850 hPa with synthetic data are shown in Fig. 2. The predicted (24h) vorticity and MSLP fields based on 8 November/00 UTC initial conditions are presented in Fig. 3. It would be seen that the relative vorticity which has a maxima of around 12 units ($\times 10^{-5}$ S^{-1}) in the analysis has enhanced to a level of around 20

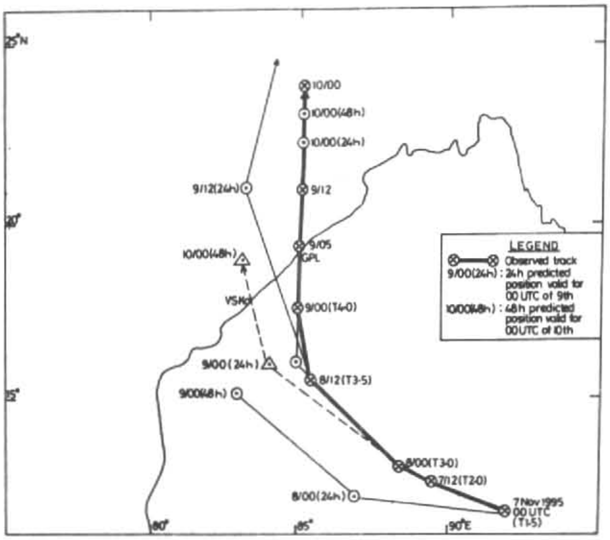
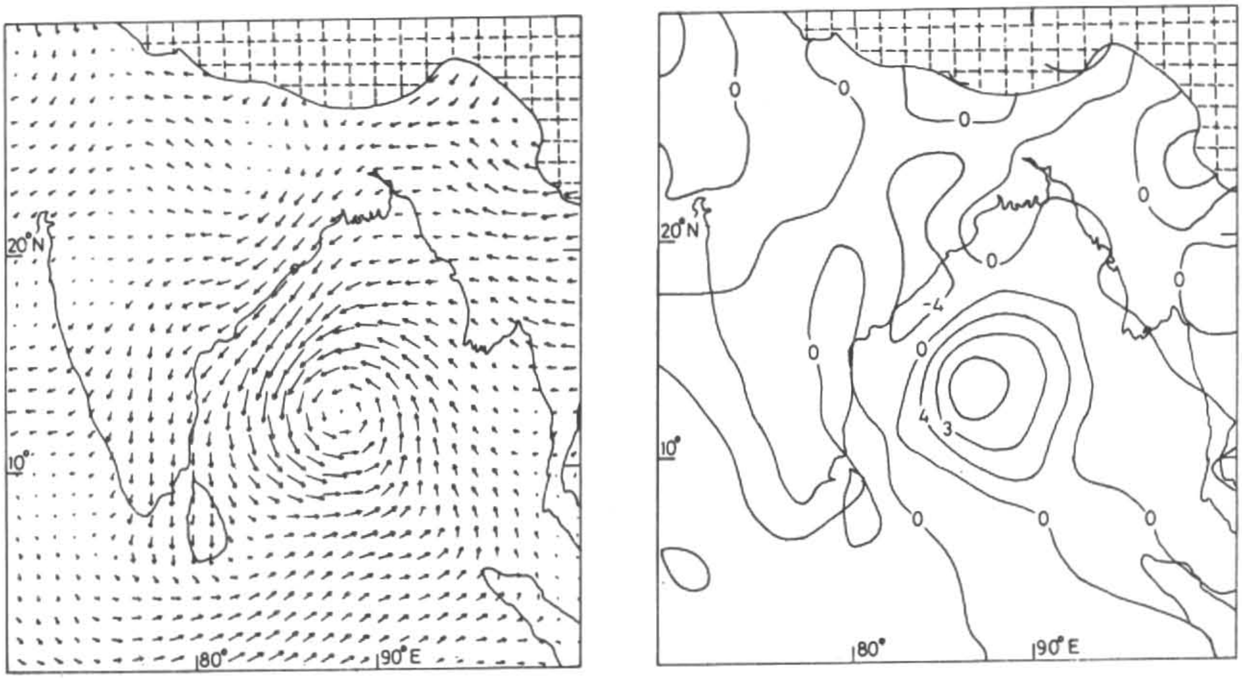


Fig. 1. Observed and predicted (24h, 48h) tracks of the severe cyclonic storm, 7-10 November 1995; The broken curve joining triangles is the track obtained with RH bogus prescription at a level of 60% (see section 4.1.4. for details)

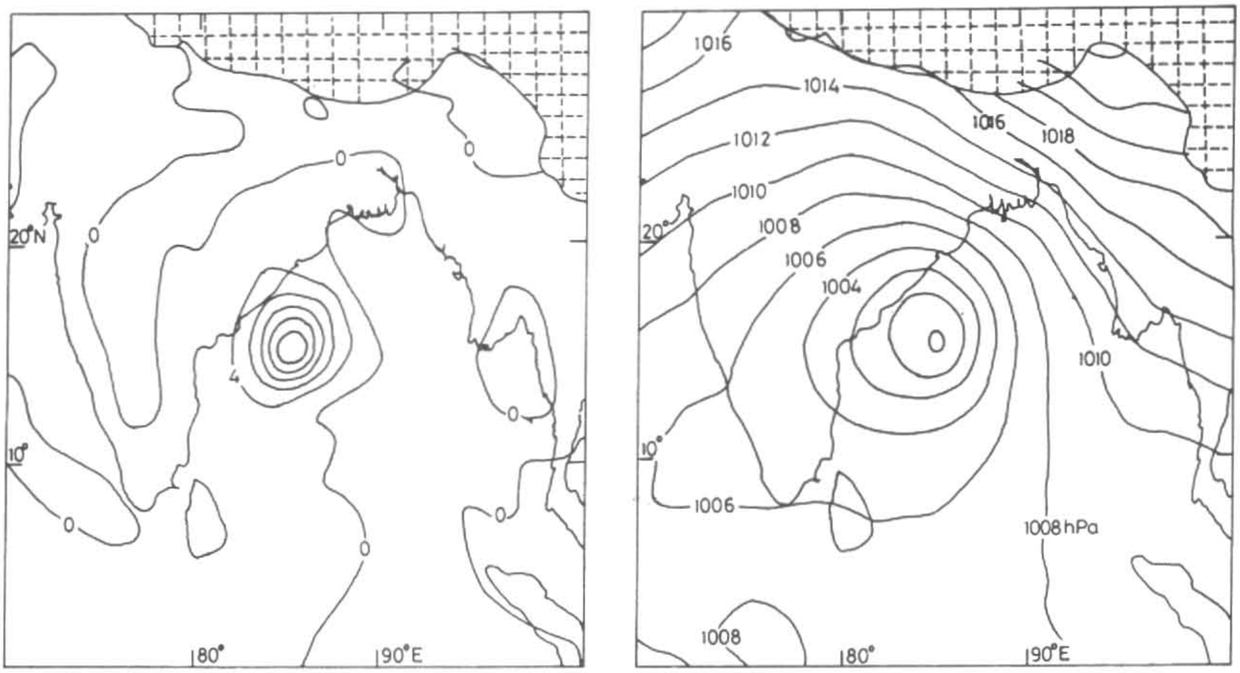
units in the forecast from 8 to 9 November (Fig. 3a) implying that the model was able to predict the intensification of the cyclone. As regards the MSLP field, a well formed low pressure system appears in the forecast (Fig. 3b), though with the lowest central pressure of around 998 hPa being much higher than the observed value of about 984 hPa. The verifying MSLP synoptic analysis of 9 November 1995/00 UTC is shown in Fig. 4. It may be recalled (section 3) that we include only wind observations in the synthetic observational data set; no mass observations either at surface or in upper air are included. As a result, no closed low pressure area was seen in the uninitialized objective analysis (not shown). Inspite of no low pressure area existing in the uninitialized objective analysis, the model has been able to generate a well formed vortex in the MSLP forecast. This lends support to the fact that the model is able to generate its own mass field, the first stage being initialisation itself, and then during the course of integration. However, a full representation of intensity



(a)

(b)

Figs. 2(a&b). Wind flow (a) and relative vorticity (b) analysis at 850 hPa on 8 November 1995, 00 UTC with synthetic data included. (Rel. Vort. in units of 4×10^{-5} s^{-1})



(a) (b)

Figs. 3(a&b). 24h forecast relative vorticity at 850 hPa (a) and mean sea level pressure (b) valid for 00 UTC of 9 November 1995

changes could be expected only from a better horizontal and vertical resolution.

Fig. 5 contains the time evolution plots of 6 hourly forecast relative vorticity maxima based on 8/00 UTC initial conditions. The two curves correspond to evolution of central vorticity maxima under two different conditions of initial humidity bogus; this will be discussed in a subsequent section. The upper curve is the one which is of concern at the moment, which shows that the vorticity peaks at 24-30 forecast hour and thereafter falls. The drop in vorticity maxima follows after the cyclone makes landfall in the forenoon of 9 November (after about 30 hours from the initial time). The intensity changes, both positive and negative, have thus been projected well by the model.

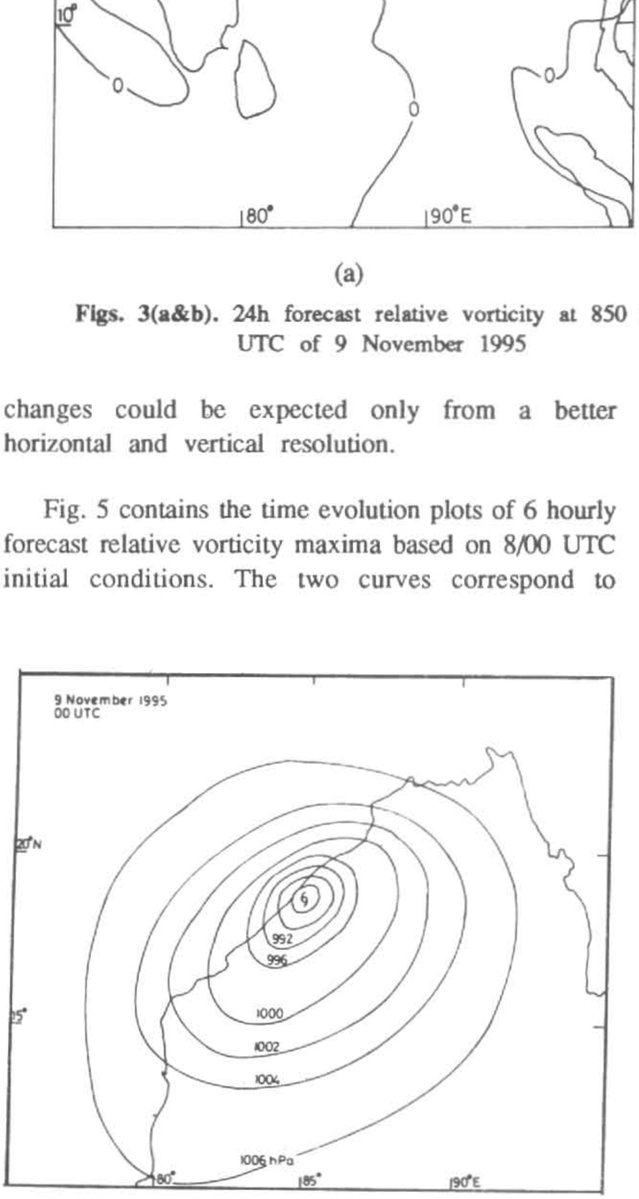


Fig. 4. Verifying mean sea level pressure analysis on 9 November 1995, 00 UTC

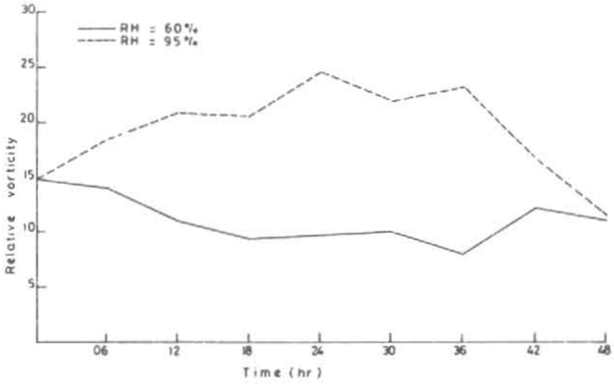


Fig. 5. Evolution of 6 hourly forecast relative vorticity with RH bogus prescription at near-saturation level of 95% (upper curve) and 60% (lower curve)

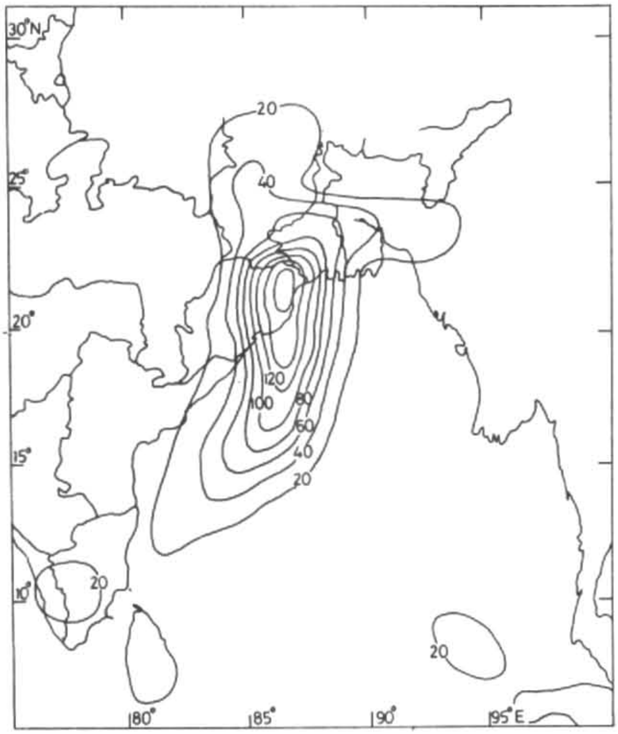


Fig. 6. 24-hr rainfall forecast valid for 00 UTC of 10 November 1995 based on initial conditions of 9 November 1995

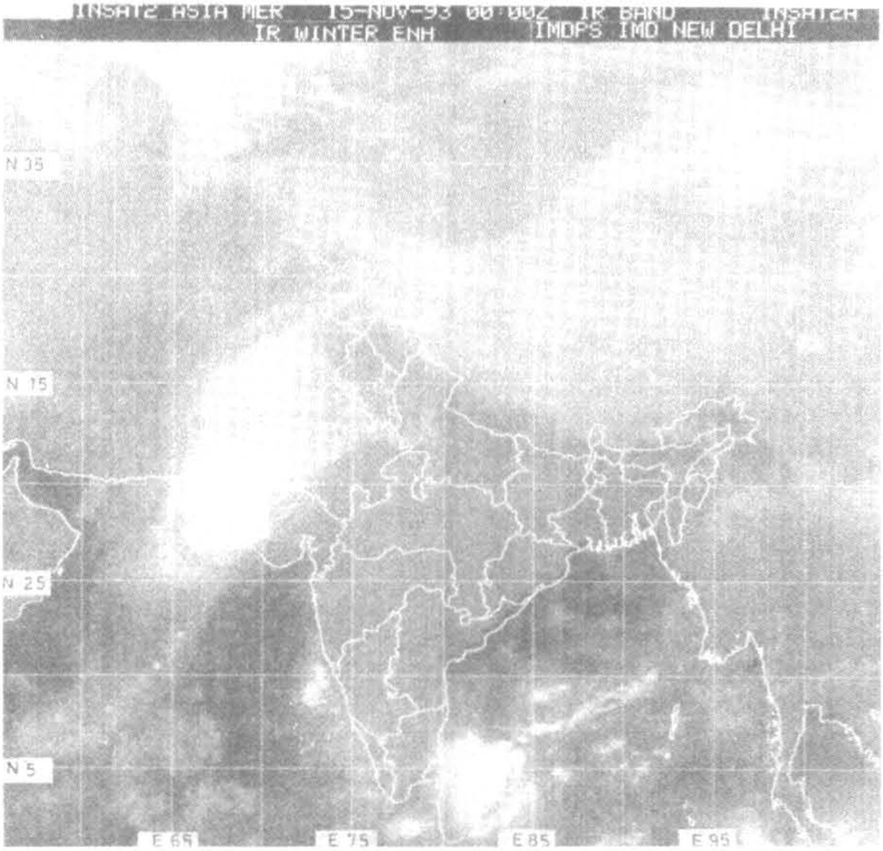


Fig. 7. INSAT cloud photograph of 9 November 1995, 0500 UTC

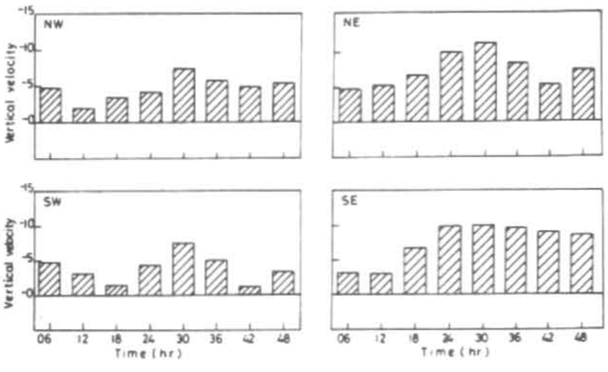


Fig. 8. Evolution of vertical velocity with time in model integration in four quadrants around the moving storm with RH bogus prescription at 95% level

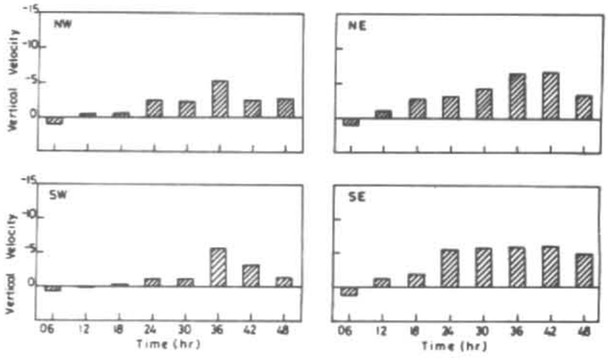


Fig. 9. Evolution of vertical velocity with time in model integration in four quadrants around the moving storm with RH bogus prescription at 60% level

4.1.3. *Rainfall prediction*

The 24h predicted rainfall pattern as produced by the model based on the initial conditions of 9 November and ending at 00 UTC of 10 November is shown in Fig. 6. A comparison of the predicted rainfall pattern with satellite cloud photograph of 9 November 1995/05 UTC presented in Fig. 7, shows a good correspondence of predicted rainfall pattern with the cloud mass. The rainfall pattern shows a southward extending band of precipitation which appears to be matching with the feeder band seen in the cloud imagery over Bay of Bengal though not exactly coinciding with it.

4.1.4. *Sensitivity experiment on the impact of initial humidity field*

It is a well known fact that the principal driving force in tropical cyclone genesis and movement is cumulus convection. Apart from the environment steering, the contribution of vorticity tendency due to convective processes is another significant factor in the cyclone movement. The role of deep cumulus convection and associated divergence has been shown to be an important contributor to storm track forecasts (Krishnamurti *et al.* 1992). Krishnamurti and Oosterhof (1989) have also demonstrated that improvements in Kuo type cumulus parameterization resulted in good track forecasts of a super typhoon. Japan Meteorological Agency (JMA 1992) have shown a positive impact on typhoon track forecasts by changing the cumulus parameterization scheme from Kuo to Mass Convective Adjustment (MCA) type. The idea of giving these descriptions here is to highlight the importance of convection processes in cyclone track predictions, which in turn heavily depend on the initial moisture analysis. We felt motivated to examine the impact of initial humidity field on track forecast in our case. With this end in view, a sensitivity experiment was run in which the bogus relative humidity observations within the cyclone field were as usual prescribed at near saturation value of 95% in one case and at a medium level of 60% in the other case, all other conditions remaining identical. The experiments were set off on the initial conditions of 8 November/00 UTC. The focus of the impact study would be 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.

Referring back to Fig. 1 the storm track resulting from 60% RH run is shown by curves joining the triangles. One can notice a large deviation in the predicted track which takes the cyclone northwestward with a speed much slower than actual, resulting in a very large position error at 48h (nearly 500 km), which is in sharp contrast to the 95% RH case, where the position error is just around 100 km at 48h.

In order to investigate the evolution of various dynamical parameters, which could account for such wide deviations in storm tracks in the two cases, the distribution of the vorticity maxima at the center and average vertical motion and integrated moisture flux divergence in four quadrants around the moving vortex were examined. The average values were computed within a radius of 2° lat/long. from the grid point of the vorticity maxima at the particular forecast hour to represent conditions close to the central core area of the cyclone. The objective is to evaluate the distribution of these parameters in different sectors in view of the known asymmetries in the field of a cyclone. The following features are observed:

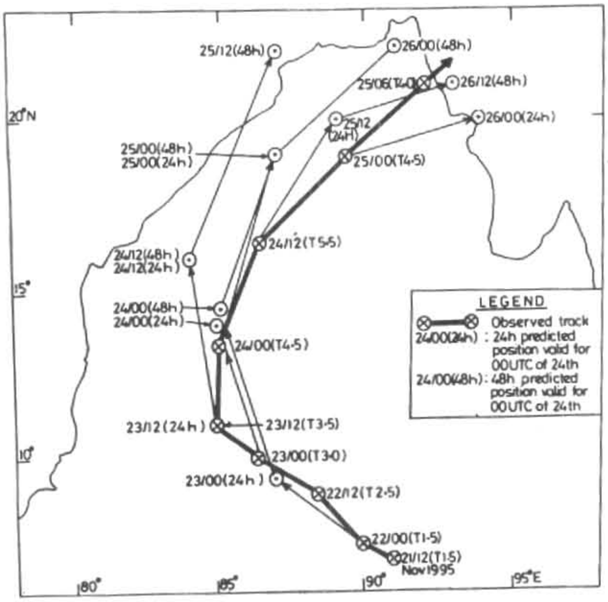


Fig. 10. Observed and predicted (24h, 48h) tracks of the severe cyclonic storm, 21-25 November 1995

(a) *Evolution of vorticity field*

The 6 hourly evolution of the relative vorticity maxima in the 60% RH case is shown alongside 95% RH case in Fig.5. The contrast in the two cases is striking. 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.

(b) *Vertical motion and integrated moisture flux divergence field*

The evolution of vertical motion field, as the model integration proceeds, is presented in Fig. 8 for the 95% RH case and Fig. 9 for 60% RH case. The experiment revealed that in the former case there is a sustained rise in the vertical motion with time. The maximum values occur in the northeast quadrant at hour 30 after the initial start. The values fall thereafter, as the cyclone makes the landfall. On the other hand with the initial humidity field prescribed at 60% level, the model clearly has a spin up problem as the vertical motion fails to take off even after many hours of integration; in fact the direction of vertical motion is found to be downward in the first 6-12 hours. The integrated moisture flux divergence (1000-300 hPa) also showed a similar behaviour (not shown).

The experiment thus clearly establishes the dominant role of initial humidity field and the attendant convection which contributes a great deal in moving the vortex.

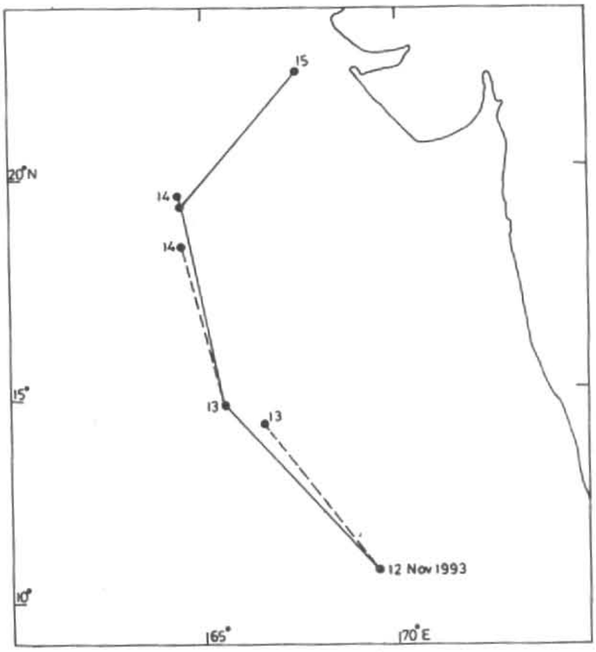


Fig. 11. Observed and predicted (24h, 48h) tracks of the severe cyclonic storm, 12-15 November 1993

4.2. *Severe cyclonic storm, 21-25 November 1995*

This case was of a recurving storm and offered an opportunity to test the performance of the model in predicting recurvature. The storm originated in the southeast Bay of Bengal as a T 1.5 vortex on 21 November evening. It moved initially in a northwesterly direction for the next two days, *viz*, upto 23rd evening. After that date it took a rather sharp turn northeastward and continued moving in that direction till it hit Bangladesh in the forenoon of 25 November. The system intensified till 24th evening when it reached a peak intensity of T 5.5. Thereafter, it weakened slightly.

The observed and predicted tracks starting from the initial conditions on each day out to 48 hours are presented in Fig. 10.

It is seen that the predicted positions are quite close to the observed positions in the initial portion of the track, say upto 24th morning. Thereafter, the deviation between the observed and predicted positions increased. Nevertheless, the important point to note here is that the model was able to predict recurvature of the system very well in 48 hour forecasts beginning on 23rd and 24th. In later stages, however, the storm accelerated very much and the model failed to keep pace with its unusual speed of movement, though maintaining the right direction of movement.

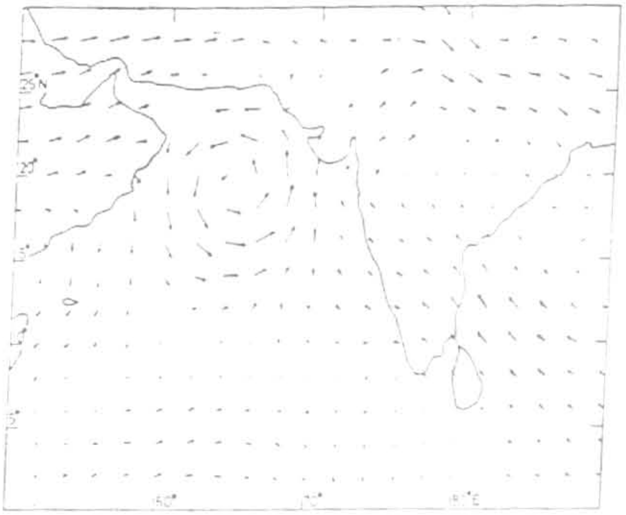


Fig. 12. Wind analysis at 500 hPa on 14 November 1993

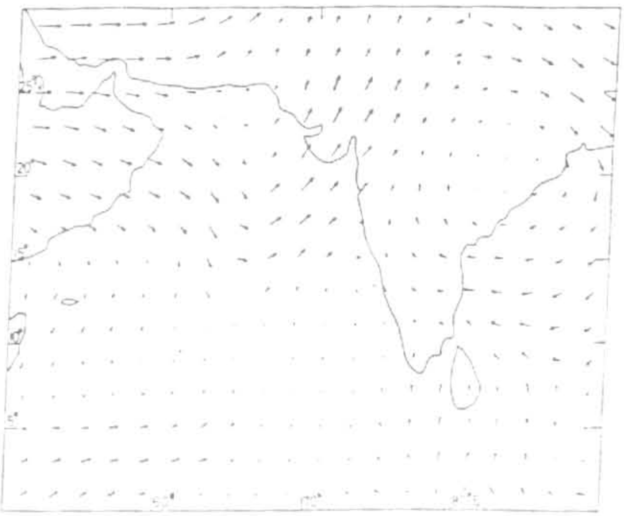


Fig. 13. 24 h predicted wind field at 500 hPa valid for 15 November 1993, 00 UTC

4.3. *Severe cyclonic storm, 12-15 November 1993 in Arabian Sea*

This is the only case of a cyclone tracked in the Arabian Sea out of the eleven cases reported here. This system originally developed in the Bay of Bengal, which moved westward and emerged into the Arabian Sea. The remnant of the Bay depression (8-9 November 1993) reintensified in the east Arabian Sea on 12 November. Moving initially in a northwesterly direction it further intensified into a cyclonic storm on 13th. Thereafter, the cyclone changed its track from northwesterly to northerly. It attained the intensity of a severe cyclonic storm with a core of hurricane winds and peak satellite intensity of T4.0 on 14th. After 14 November the disturbance showed an unusual behaviour. It recurved northeastward and weakened rapidly over the sea.

The model shows good 24h track forecast based on initial conditions of 12 and 13 November; the predicted direction of movement nearly coincides with the actual on both the days, though the speed of movement is slightly underpredicted (Fig. 11). The intensification of the system from 12 to 14 November was brought out well by the model. An interesting aspect of this case was that the model forecast from the initial condition of 14 November showed weakening of the system. The storm did weaken beginning from 14-15 midnight and eventually ended up as a well marked low pressure area over northeast Arabian Sea off Gujarat-Sind coast by the morning of 16th. The 500 hPa forecast wind flow pattern exhibited a degeneration of the vortex into a trough in westerlies (Figs. 12 & 13). This implied that the flow was getting evolved into a shear type pattern which is detrimental to sustenance of a tropical cyclone. A support for this observation is provided by the satellite photographs (Figs. 14 & 15) of the cyclone on 13 and 14 November, which show a marked change in the cloud texture from that of a well formed vortex on 13th to that of a shear pattern on 14th. To that extent it would be quite justified to infer that the model in this case could capture even weakening of the cyclone over the sea.

5. Forecast errors

In addition to looking at the forecast model performance in cyclone track prediction in a qualitative manner as done in the preceding section, it is customary to express the forecast performance quantitatively in terms of forecast errors. Forecast errors 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. In this case the absolute displacements (position errors) and direction displacement (DD) errors for 24h forecasts (also 48h forecasts in the 1995 cases) were measured on each day of forecasts. The individual day's errors are presented in Table 2. The mean 24h position errors work out to about 170 km for 38 cases. It would also be seen from Table 2 that in a majority of cases the DD errors are positive (predicted track to the right of actual track), meaning thereby that there exists some poleward/rightward bias in the model predicted tracks. The mean DD errors for positive and negative cases considered separately work out to about ± 20°. The

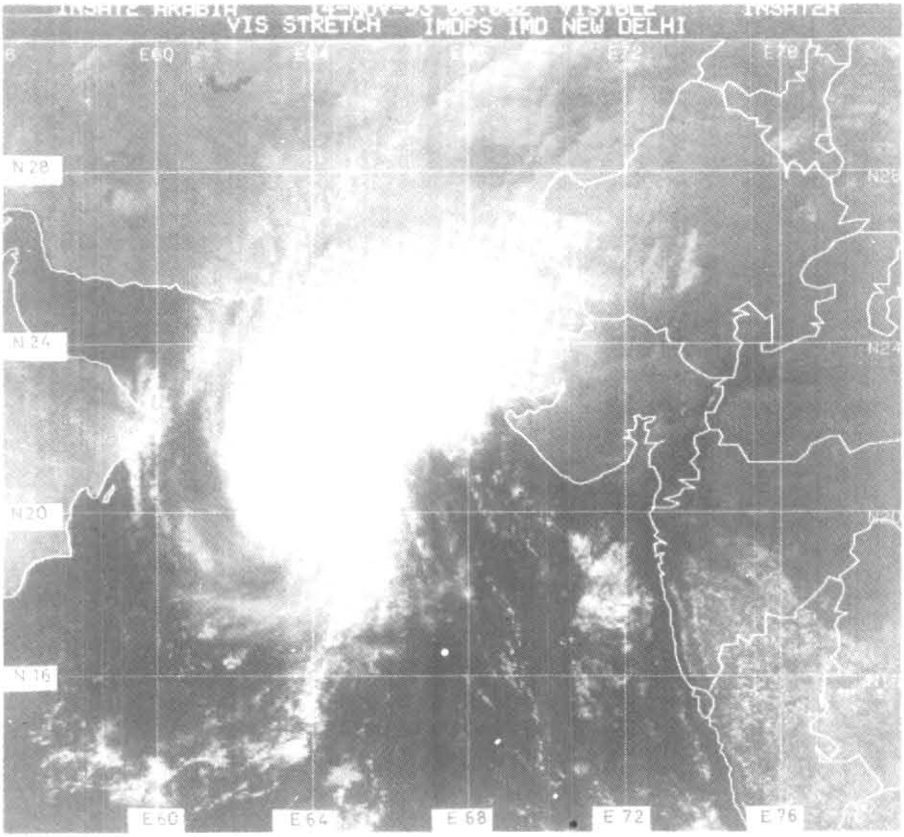


Fig. 14. INSAT 2A satellite imagery on 14 November 1993, 0600 UTC

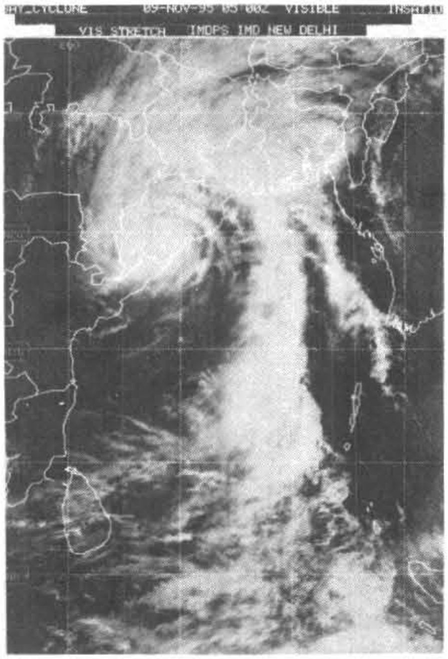


Fig. 15. INSAT 2A satellite imagery on 15 November 1993, 0000 UTC

TABLE 2

24-hr forecast errors of cyclone track predictions

S. No. (1)	Valid date (2)	Position displacement (km) (3)	Direction displacement (deg) (4)
1.	7 May 1990	160	− 25
2.	8 " "	100	− 10
3.	9 " "	320	+ 20
4.	26 April 1991	100	− 20
5.	27 " "	120	+ 15
6.	28 " "	150	+ 20
7.	29 " "	200	+ 30
8.	30 " "	240	− 5
9.	12 Nov. 1991	160	+ 20
10.	13 " "	110	+ 10
11.	15 " "	80	− 10
12.	5 Nov. 1992	200	+ 30
13.	6 " "	70	− 30
14.	7 " "	250	− 65
15.	12 Nov. 1992	230	+ 30
16.	13 " "	300	+ 40
17.	14 " "	220	+ 35
18.	15 " "	100	0
19.	17 " "	230	− 20
20.	18 " "	230	+ 5
21.	19 " "	280	+ 25
22.	20 " "	100	+ 10
23.	13 Nov. 1993	110	+ 5
24.	14 " "	100	− 3
25.	2 Dec. 1993	120	+ 20
26.	3 " "	100	+ 10
27.	4 " "	200	+ 20
28.	5 " "	190	+ 10
29.	30 Apr 1994	90	− 15
30.	1 May "	90	+ 20
31.	2 " "	400	+ 25
32.	3 " "	150	+ 20
33.	8 Nov. 1995	200	− 30
34.	9 " "	150	0
35.	10 " "	200	0
36.	23 Nov. 1995	50	0
37.	24 " "	50	0
38.	25 " "	250	− 30
Mean		167	± 20

Note : +ve/−ve direction displacement error means predicted track to the right/left of actual track

Mean direction displacement error calculated separately for +ve and −ve values

mean 48h position error in respect of the 1995 cases works out to about 210 km (for 5 cases).

The skill of a cyclone track prediction model is usually measured in terms of forecast error relative to CLIPER (Neumann and Pellisier 1981, Thompson *et al.* 1981) or to a persistence forecast. Forecast skill is defined as:

$$\frac{\text{CLIPER PE} - \text{Model PE}}{\text{CLIPER PE}} \times 100\%$$

where, PE = Position error (5)

Positive skill indicates that model forecast is better than CLIPER and *vice versa*. The forecast skill of the present model relative to CLIPER in the case of November cyclones worked out to 64% for 24h and 76% for 48h forecasts (IMD 1996). It may be worth mentioning here that the so called forecast difficulty level as inferred from CLIPER models by Pike and Neumann (1987) is the least in the north Indian Ocean as compared to all other basins. It would, therefore, be quite pertinent to state in this context that the positive skill of dynamical model in the north Indian Ocean, as seen here, is of great significance.

The slow and poleward/rightward bias that has been witnessed in the experiments reported here, seems to be a phenomenon common to some other models also being run at other centres. For instance, in respect of the models run by United Kingdom Meteorological Office, a similar slow and poleward bias has been reported (UKMO 1993). The Japan Meteorological Agency (JMA 1992) have also reported similar biases in their models used for typhoon forecasting and have attributed these errors possibly to cumulus parameterization scheme and the typhoon bogus data.

The forecast errors in our study compare well with similar results for 24h forecasts reported by some other workers, *e.g.*, Mathur (1991) in respect of Atlantic hurricanes by the NMC QLM, which are 182 km and 180 km respectively for the 1988 and 1989 hurricane seasons. Likewise, the 24 h forecast errors reported by Japan Meteorological Agency in respect of their Typhoon model are respectively 187 km in 1988 and 185 km in 1989, and for Asia spectral model, 182 km in 1989 (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 48h forecasts for different ocean basins (UKMO 1995).

6. Conclusion

The study has demonstrated the capability of limited area model in giving successful cyclone track forecasts by ensuring a proper representation of the cyclone vortex in the initial input fields with the aid of synthetic data. Such data are generated by an empirical scheme depending on a few initial parameters of cyclone structure and preliminary synoptic information. An encouraging result of the study is the successful track forecasts even in the case of recurving cyclones, where a change in the direction of movement has been predicted well by the model, with a lead time of 48 hours; prediction of recurvature by dynamical models has been recognized as a difficult problem. Intensity variations have also been captured by the model.

A sensitivity experiment carried out in this investigation to see the impact of initial humidity analysis in the field of the cyclone revealed that prescription of near saturation values of humidity bogus is a crucial factor for the model to produce a good track prediction. Prescribing a low value of humidity bogus at a medium level of 60% resulted in a large deviation of the predicted track from the actual path and the system losing its intensity in the forecast as against saturation RH case where the vortex gained intensity after initial start and gave a track forecast very close to the observed one. This gives support to the well accepted view that humidity analysis is of crucial importance in tropical numerical weather predictions, particularly in the case of tropical cyclones.

The forecast error computations brought out that the skill of the limited area model in our area is as good as anywhere else.

It needs be mentioned that the cyclone forecast problem is a complex one because of the several physical processes which influence the cyclone development and motion. This is partly due to the mathematical complexity of the problem which involves the interaction of a vortex with its surrounding flow (environment). From the observational perspective, data are usually too sparse around tropical cyclones which would make it possible to carry out meaningful computations of dynamic and thermodynamic quantities that might reveal the physical processes involved. A proper and better perception of the physics of the cyclone motion and its incorporation in the numerical models is required for better forecasts. There is scope for improvement in the forecast model performance by refining the model grid to a much finer resolution, by adopting an appropriate convection scheme, by improving the bogussing scheme, and introducing storm asymmetry etc. It is also known that the β-effect coupled with the convergence/divergence in a vortex and/or the environmental flow has a profound influence on the cyclone motion. Analysis of the initial divergence field and the environmental flow and their evolution during the course of integration of the model are the most important influences. Both are difficult to analyze in the absence of real data in the vicinity of cyclones and are likely to constitute major sources of forecast errors in operational cyclone track predictions by numerical models. The systematic biases observed in the forecast models in respect of tropical cyclone movement need investigation in the framework of these influences.

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