MAUSAM, 48, 2 (April 1997), 257-272

551.509.327 : 551.509.313

Deterministic methods for prediction of tropical cyclone tracks

U.C. MOHANTY and AKHILESH GUPTA*

Centre for Atmospheric Sciences,
Indian Institute of Technology, New Delhi, India

सार — उष्णकटिबंधीय चक्रवातों के मार्ग का पूर्वानुमान लगाने के लिए उपलब्ध विभिन्न विषयपरक तकनीकों की परिस्थितिगत समीक्षा इस शोध पत्र में प्रस्तुत की गई है। उष्णकटिबंधीय चक्रवातों की चाल से संबंधित प्रचलित सिद्धांतों के विषय में संक्षेप में बताया गया है। सांख्यिकीय और गतिकीय पद्धतियों वाले निर्धारक निदर्शों की इसमें चर्चा की गई है। चक्रवातों की संरचना और उनकी चाल के पहलुओं को समझने के लिए हाल ही में हुई प्रगति से उष्णकटिबंधीय चक्रवातों के पूर्वानुमान को प्रस्तुत करने में सुधार हुआ है। गतिकीय पद्धतियों से पूर्वानुमान के क्षेत्र में पर्याप्त प्रगति हुई है। विश्व के बहुत से प्रमुख प्रचालनात्मक संख्यात्मक मौसम पूर्वानुमान (एन.डब्ल्यू.पी.) केन्द्रों द्वारा अब विस्तृत पैमाने पर उच्च विभेदन सीमित क्षेत्र निदर्शों (एल.ए.एम.) और भूमंडलीय परिसंचरण निदर्शों के विकसित क्षैतिज विभेदन, भौतिक प्रक्रियाओं के अन्तर्वेशनं, आँकड़ा संग्रहण योजनाओं में सिन्थेटिक और अन्य गैर-पारम्परिक आँकड़ों के उपयोग तथा विश्लेषित चक्रवात केन्द्रों के साथ तद्नुरूपी प्रेक्षणों के आरम्भिक मिलान के लिए नजिंग पद्धति द्वारा प्राप्त हुई है।

उष्णकटिबंधीय चक्रवातों के मार्ग के संबंध में पूर्वानुमान के लिए निर्धारक तरीके में आगे के और सुधारों की संक्षिप्त रूपरेखा तैयार की गई है।

ABSTRACT. The paper presents a state-of-art review of different objective techniques available for tropical cyclone track prediction. A brief description of current theories of tropical cyclone motion is given. Deterministic models with statistical and dynamical methods have been discussed. Recent advances in the understanding of cyclone structure and motion aspects have led to improved prediction of tropical cyclones. There has been considerable progress in the field of prediction by dynamical methods. High resolution Limited Area Models (LAM) as well as Global Circulation Models (GCM) are now being used extensively by most of the leading operational numerical weather prediction (NWP) centres in the world. The major achievements towards improvement of such models have come from improved horizontal resolution of the models, inclusion of physical processes, use of synthetic and other non-conventional data in the data assimilation schemes and nudging method for initial matching of analysed cyclone centres with corresponding observations.

A brief description of further improvement in deterministic approach for prediction of tropical cyclone tracks is outlined.

Key words — Tropical cyclone, Track prediction, NWP models, GCM, Bogus vortex.

1. Introduction

Prediction of the tracks of tropical cyclones is one of the most difficult and challenging problems of current international tropical cyclone research. The focal point of this research is to minimise the forecast errors to the extent that the forecast can be used effectively for issuing appropriate warnings for disaster management purposes. The level of importance is reflected in the large number of forecast techniques

---

Present affiliation : National Centre for Medium Range Weather Forecasting, Mausam Bhavan Complex, Lodi Road, New Delhi-110003, India

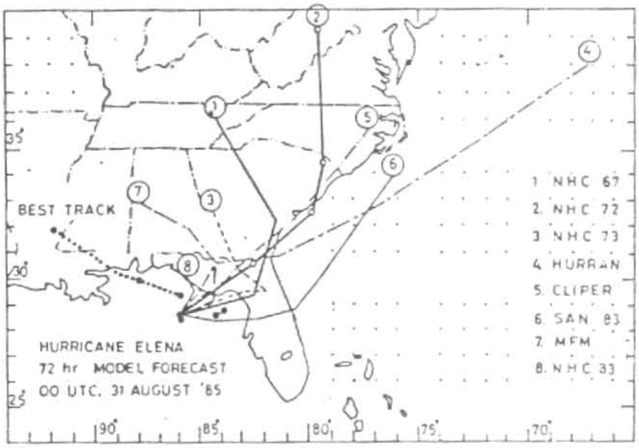

Fig. 1. 72-hr track forecast for hurricane 'Elena' of August 1985 by 8 different models (*Courtesy C.J. Newmann*)

that have been developed using wide range of approaches, from empirical through statistical and dynamical. However, due to complexities of the problem, no single technique has been proved to have outstanding performance over the others. Fig. 1 is a good example of the performance of 8 different operational track prediction models for hurricane 'Elena' of August 1985. All the 8 predicted tracks are in different directions, but the hurricane moved unexpectedly in yet another direction far apart from all the above tracks.

Strong winds, heavy and torrential rains and worst of all, the cumulative effect of storm surges and astronomical tides are the three major elements of tropical cyclone disaster. In the Indian region, the storm surge is the most devastating element. Much of this is contributed by extremely shallow coastal bathemetry of certain segments of the east coast of India and Bangladesh. The track prediction of tropical cyclones in this region is, therefore, of great importance and crucial especially for the purpose of storm surge forecasting as a minor deviation of the landfall point may generate altogether different peak surge height.

Recent analysis of the error statistics reveals that technique development together with observing methods in some basins had resulted in a slow, but steady decrease of forecast errors. There has been significant increase in basic research on tropical cyclone motion aspects in recent years. Moreover, a large number of field experiments on cyclone probing have been conducted in Pacific and Atlantic regions during past few years. At the same time the resolution and initialization of tropical cyclones in numerical models have been considerably improved in recent years. Much more improvements are still possible and are expected in the years to come.

The paper provides a brief description on the deterministic methods used in India and abroad for cyclone track forecasting. For the sake of completeness a brief description on forces (internal as well as external) responsible for the cyclone motion is also presented.

2. Basic principles of cyclone motion

The most important factors which cause a tropical cyclone to move are best represented by the use of barotropic vorticity equation in the form:

$$\partial\zeta/\partial t = \underset{A}{-V\cdot\nabla\zeta}\;\underset{B}{-V n\beta}\;\underset{C}{-(\zeta+f)\,\nabla\cdot V} \qquad (1)$$

Where ζ is the vertical component of relative vorticity, V is the horizontal wind vector, Vn is the meridional wind component (positive towards north), β is the meridional gradient of earth vorticity, and f is the Coriolis parameter or the vertical component of earth vorticity. The tilting, solenoidal and frictional effects have been neglected.

At the first approximation, the cyclonic vorticity is maximum at the centre and decreases with increasing radius. Hence, if the cyclone is moving in a given direction the local rate of change of cyclonic vorticity given by left hand side term of the Eqn. (1), must also increase in the same direction. This vorticity change can only be achieved by processes implicit in the terms on right hand side of Eqn. (1). In the Eqn. (1), the term 'A' represents advection of relative vorticity, the term 'B' the advection of earth vorticity and the term 'C' the vorticity change from divergence or convergence.

2.1. *Enviornmental steering*

The tropical cyclones generally respond like a protected symmetric vortex in a uniform, non-interacting fluid flow. This motion is goverened by the term 'A' of Eqn. (1) and considered as external force responsible for the motion of the cyclones.

The flow simply advects the vortex along and, as a result, the environmental flow is referred to as a steering current. Details of steering current method are discussed in Section 3.3.1.

2.2. *The beta effect*

The so-called beta effect was first introduced by Rossby (1948) to explain the propensity for cyclones to drift poleward with time. A phenomenon which is commonly referred to as the Rossby drift in his honour. Rossby used a beta plane approximation and considered a symmetric wind field superimposed on a symmetric pressure field. Since the Coriolis force is larger on the poleward side than on the equatorward side, a poleward directed force is exerted on the cyclone. This force will be greater for larger cyclones than for smaller ones, so that the former will drift poleward faster. Rossby' reasoning was however, incorrect, in that, even if we could superimpose a symmetric wind and pressure field, geostrophic adjustment processes would rapidly bring the two into balance and thus remove the unbalanced poleward force. Though, the Rossby Drift theory was a failure, it led to an alternative hypothesis described in the section 2.4.

The correct beta effect can be readily seen in term 'B' of Eqn. (1). This indicates that only meridional flow will advect earth vorticity. A cyclonic vortex has equatorward flow on its western side and poleward flow on its eastern side. Since the earth vorticity increases cyclonically towards the poles, this will produce a differential advection of vorticity with a maximum increase of cyclonic vorticity to the west, and of anticyclonic to the east of the vortex centre. If there is no superimposed environmental flow, the vortex will then propagate to the west in a direct analogy to the higher latitude Rossby waves. This was shown in more rigorous treatments by Kasahara (1957) and Holland (1983). Holland showed that the inclusion of vortex scale convergence changes the propagation to a direction of slightly poleward of westward.

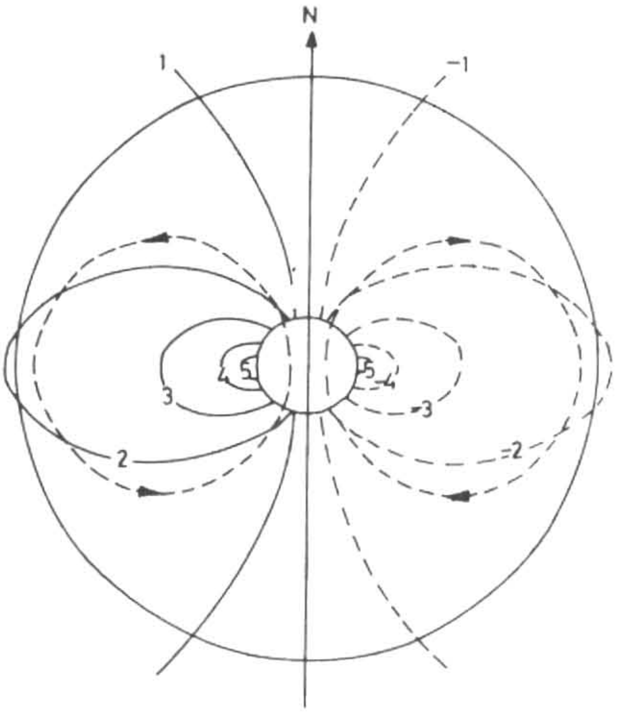

Fig. 2. Field of instantaneous rate of change of relative vorticity ($\partial\zeta/\partial t$), in arbitrary units, centred on a symmetric, nondivergent cyclone on a northern-hemisphere beta plane with no basic flow (Holland 1983). Heavy dashed lines show the induced secondary circulation resulting from the vorticity change.

2.3. *The combined steering plus beta effect propagation*

Kasahara (1957) and Holland (1983) have shown that cyclones embedded in a uniform flow will deviate to the west (or slightly poleward of west if typical large-scale values of convergence are used) because of the above described beta effect propagation. Holland (1983)'s method was to specify a vortex and uniform flow and derive analytic solution for linear cyclone from Eqn. (1). The propagation speed is determined by the size of the envelope of 'effective radius', which in turn is determined by the size and outer wind strength of the cyclone. This shows that the tropical cyclone motion is quite sensitive to size or outer core wind strength changes, but is almost independent of the core region intensity. A small cyclone will have almost negligible westward propagation speed, whereas a large cyclone could be propagating towards the west at a relatively much higher speed. This clearly shows that the large cyclone will move more independent of the environmental flow than will a small cyclone. These results are in good agreement with observations and have been confirmed by numerical modelling experiments.

2.4. *The poleward Rossby drift*

Anthes (1982) proposed that the observed tendency for tropical cyclones to drift polewards was due to a second order, non-linear adjustment of the basic current to the outer region distortion. This can be

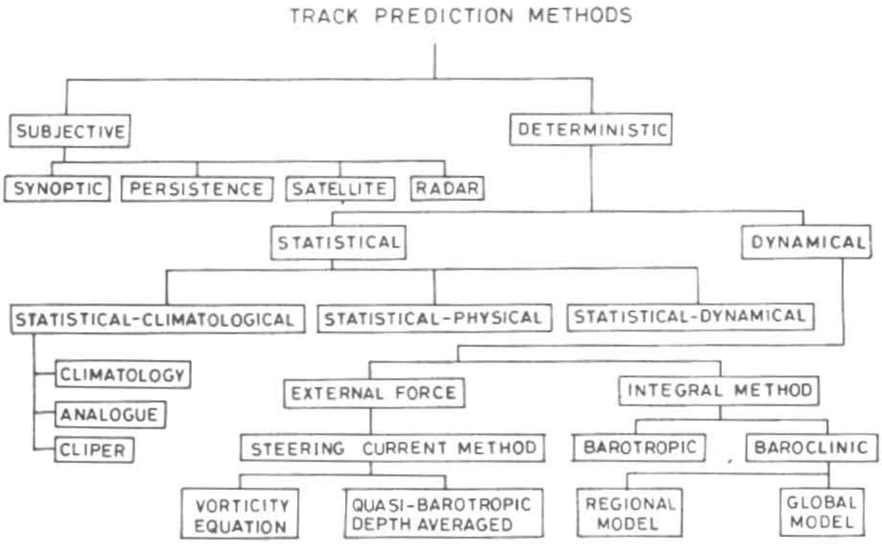

Fig. 3. Methods of tropical cyclone track prediction

described by considering a symmetric, non-divergent cyclone on a northern-hemispheric beta plane with no basic current. Then the instantaneous time rate of change of relative vorticity given by term 'B' in Eqn. (1) is shown in Fig. 2. In addition to propagating the vortex to the west, these vorticity changes will produce a vortex distortion with an accumulation of cyclonic vorticity to the west and anticyclonic vorticity to the east. This distortion produces two opposing secondary circulations, counterclockwise to the west and clockwise to the east, as shown by the dashed lines in Fig. 2. The resulting southerly flow over the vortex will advect it poleward. Introducing convergence into the cyclone will rotate the field in Fig. 2 in a clockwise direction, so that the generated steering current will be from more southwesterly direction. Thus the poleward Rossby drift may be explained by non-linear development of an induced poleward steering current.

2.5. *Surface frictional effects*

The effects of surface friction on cyclone motion have been studied analytically by Kuo (1969). The frictional dissipation increases with the square of the wind speed. Since a northern-hemispheric cyclone embedded in an environmental flow over the open ocean has stronger winds on the right, it will experience a greater frictional dissipation in the right, compared to the left semicircle. Kuo found that this produces a small motion deviation (around 5 deg.) to the right.

3. Track prediction techniques

The tropical cyclone track prediction techniques are grouped into the following two categories: subjective and deterministic. Synoptic, satellite, radar methods etc. come under subjective techniques. Statistical and dynamical methods are broadly categorised as objective or determinstic techniques. Fig. 3 shows different methods of track prediction under each of these categories. In this paper we shall confine our discussions to only deterministic methods. Table 1 gives a list of some of the important work carried out on different aspects of track prediction techniques in India and abroad.

3.1. *Statistical methods*

Statistical models are widely used to provide the objective guidance on the storm track forecast at various forecast centres. The basic approach of these statistical techniques is to use historical data to formulate some sort of prediction alogorithm by which the tropical cyclone motion (predictand) over some future time interval is found to be statistically related to some current parameters (predictors), environmental or otherwise. The sources of predictors are from one or more of the four original information: climatology, persistence, environmental data and numerically forecast fields data.

The relative importance of three predictive sources (climatology, persistence and environmental fields) in reducing the variance of storm motion varies from

TABLE 1

Different methods/techniques/models of tropical cyclone track prediction

Type of method	Method	Technique/Model	References
Statistical	Statistical-Climatological	Climatology	Lourensz, 1981; Crutcher and Hoxit, 1974; Martin, 1974
		Analogue	Hope and Neumann, 1971; Jarrell and Somervell, 1970; Datta and Gupta, 1975; Jarrell *et al.*, 1975; Annette, 1978; Mohanty, 1980
		CLIPER	Neumann, 1972; Sikka and Suryanarayana, 1972; Neumann and Mandal, 1978; Kivganov and Mohanty, 1979 (a)
	Statistical-Physical	NHC-67, NHC-72, TOPEND, AUSTCYC 7075, Stepwise Screening	Kivgnav and Mohanty, 1978; Mohanty, 1979; Neumann, 1972
	Statistical-Dynamical	NHC-73,NHC-83,NHC-90	Neumann and Lawrence, 1975; Neumann,1988
Dynamical	External force	Steering current method	Kasahara,1957; Kivganov and Mohanty, 1979 (b); Holland, 1984; Pike 1987; Elsberry, 1986
	Integral method	Barotropic model	Kasahara, 1957; Das and Bose, 1958; Dutta and Pradhan, 1968; Sikka, 1975; Singh and Saha, 1978; Ramanathan and Bansal, 1977; DeMaria *et al.*, 1992; Holland *et al.*, 1991
		Baroclinic model	**Regional Model** Harrison, 1969; Miller, 1969; Ookochi, 1978; Harrison and Fiorino, 1982; Mathur, 1974; Hovermale and Livezey, 1977; Elsberry and Peak, 1986; Prasad, 1990; Iwasaki *et al.*, 1987; Mathur 1991; Puri *et al.*, 1992; Chen *et al.*, 1995; Kurihara *et al.*, 1993 **Global Models** Andersson and Hollingsworth, 1988; Mathur, 1991; Krishnamurti *et al.*, 1993

basin to basin. The studies on the relative predictive potential of three sources suggest that the Australian basin is statistically most difficult amongst all basins. On the other hand, the North Indian Ocean (the Bay of Bengal and Arabian Sea) are the easiest of all.

The statistical methods are broadly categorised into three groups: Statistical-climatological, statistical-physical/synoptic and statistical-dynamical.

3.1.1. *Statistical-climatological methods*

Observations, that tropical cyclones in certain regions and seasons move along similar tracks, have given rise to a range of climatological techniques for forecasting motion. These techniques may be grouped into four categories: climatological mean motion, analogue, Markov chain method and combined persistence and climatology techniques.

(a) *Climatological technique*

The simplest approach is to calculate the mean motion of all tropical cyclones in a few degrees latitude/longitude square (Marsden square) for a specified time period. One method is to use means and standard deviations of meridional and zonal motion for 5° Marsden squares by the calendar month; the standard deviations give an indicator of the uncertainty in the climatological forecast. A variation on this method is to develop histograms for specified direction and speed ranges and to present these as cyclone roses on charts for display in the forecast office.

The climatological tracks can be used to calculate the probability of a tropical cyclone being in a specified area at each of the standard forecast time periods. A very effective variation on this method is to generate a scatter plot of the 12, 24, 48 and 72 hour positions of cyclones that moved through the current storm location. This plot may contain all tropical cyclones or some subset, such as those within a certain time or motion window for the current storm. Such plots effectively indicate potential bifurcation regions where storms have a tendency to move in one of two (or more) preferred directions. This knowledge is useful for identifying potential for large forecast errors and for interpreting other techniques, such as CLIPER.

(b) *Analogue technique*

The analogue technique is based on the assumption that a given cyclone is expected to move with the mean speed and direction of all storms that have occurred in that region within some time interval close to the current day. This is another type of climatological prediction. Although, an experienced foecaster keeps a note of such information in his mind in his day-to-day work, objective method of selecting such analogues was required. These techniques were developed for Atlantic by Hope and Neumann (1971), for western North Pacific by Jarrell and Somervell (1970), for the eastern North Pacific by Jarrell *et al.* (1975), and for the Australian region by Annette (1978).

The important aspect of such technique is the specification of analogues in terms of tolerance in space and time. Depending on the data set and accuracy required, these limits of tolerance can be relaxed. The complication arises when more than one family of storms is associated with a given area and time of the year. In such situation, a simple mean of both the tracks is taken.

Analogue method consists of searching for all tropical cyclones in the historical record that occurred within a present spatial, seasonal and translational velocity range of the cyclone to be forecast (Hope and Neumann 1971). The forecast track is derived as the mean of all cyclones. The scatter in analogue track provides an objective indicator of the uncertainty in the forecast.

For Indian region Datta and Gupta (1975), modified their earlier scheme for prediction of tropical cyclone tracks by analogue technique. In this scheme, after selecting the analogues a predicted velocity was arrived at for each analogue by giving time dependent weightages to the velocities of analogue and existing storms. From the different forecast positions probability ellipses were drawn for different probabilities for each of the forecast hours. The scheme also incorporates a programme to calculate the probability of existing storm striking a particular coastal area. This scheme is currently in use in India for issuing advisories during the storm situations.

(c) *Markov chain method*

The Markov chain approach provides transition probabilities between speed and direction ranges, known as "bins", based on the climatological characteristics of previous cyclones in the region and time of year. The selection of bins is constrained in that each must contain a similar proportion of cyclones with sufficient number to allow a stable prediction. The Markov chain technique provides useful indications of the likelihood of changes in speed and direction and thus the degree of consideration given to persistence. Though, this is a new concept, yet it is not found to be of much use for prediction of tropical cyclone tracks.

A variation on this approach, used by JTWC (J. Martin, personal communication), is to keep all cyclone tracks in a data base on a personal computer, then to search for the analogue by any criterion specified by the forecaster. This method provides a degree of flexibility in the analogue selection criterion and provides a ready, objective answer to the types of climatological questions that often arise in forecast discussion.

(d) *Combined persistence and climatology*

A combination of persistence and climatology provides the best basic forecast technique and the basis for comparing forecasts from different regions. In recent years the CLIPER technique (Climatology and PERsistance, Neumann 1972) has gained widespread acceptance. CLIPER consists of regression equations to predict the zonal and meridional displacement of a tropical cyclone for set time periods, usually 12, 24, 36, 48 and 72 hours. The equations are developed by some form of stepwise regression with the set of predictors including current and past position, intensity, motion and Julian date of climatological days. Generally with these limited number of predictors polynomial equations upto 3rd order are used. The selection criteria are based on the amount of variance explained from the climatological cyclone record and additional methods are used to further stabilise and enhance the final result (Neumann 1972). As a general outcome, persistence predictors are given the highest weightage for the 24 hours or so, and climatology dominates at longer time periods.

For Indian seas, Sikka and Suryanarayana (1972) developed a scheme of prediction of tropical storms based on climatology and persistence. The authors found higher errors in position and/or direction of movement vector when the storm is in the recurvature stage or when it shows sudden acceleration or deacceleration. Neumann and Mandal (1978) developed a set of regression equations using same elements as predictors that are typically used for selecting storms in analogue methods, namely, the day number, initial latitude and longitude, average meridional speed during post 12 and 24 hr, average zonal speed, past 12 and 24 hr. The predictands were: latitudinal and longitudinal displacements at 12 hourly steps upto 72 hour. Probability ellipses are also produced in this scheme. The major difference from the analogue method was while the analogue method uses the clusters of predicted positions obtained from the different analogue storms, this method used the prediction errors to construct the probability ellipses. The scheme was superior to the analogue method in the sense that firstly because of its computational simplicity and secondly because it is quite likely that the analogue method may produce no forecast due to non-availability of matching pattern, this method will always produce a forecast. Kivganov and Mohanty (1979a) developed a method based on empirical predictors only (*i.e.*, climatology and persistence) which was similar to CLIPER technique. The method was developed based on the climatological information for the period and tested for cyclones of subsequent years.

TABLE 2

Forecast Difficulty level (FDL) in km in six different ocean basins of the world

Basin	Mean storm latitude	24 hr Fcst	48 hr Fcst	72 hr Fcst
SW Pacific (Australian)	20.1°S	241	503	728
North Atlantic	27.6°N	210	463	680
Northwest Pacific	20.4°N	184	416	632
SW Indian	18.4°S	161	339	500
Northeast Pacific	17.9°N	144	295	431
North Indian	15.7°N	117	230	328
Mean of all basins		176	374	550

*After Pike and Neumann (1987)

It has been widely accepted by all forecast offices in the world to use CLIPER as their basic forecast tool. Although a large computer is needed to develop the original equations, the forecasts can be made on any computing system, in essentially zero time. CLIPER also provides a convenient and consistent benchmark for indicating the skill of other forecast techniques.

Neumann (1981) introduced the concept of forecast difficulty level (FDL) to assess forecast improvements over the North Atlantic basins. The concept is based on the use of residual errors of CLIPER to provide a threshold skill level and a basis for determining forecast difficulty. The value of FDL is proportional to operational forecast errors. The idea behind development of this parameter is to normalise all forecasts by the CLIPER errors to provide homogeneous indication of forecast skill. Pike and Neumann (1987) presented FDLs for all the tropical cyclone basins in the world (Table 2). It may be seen that maximum values of FDL are observed for Australian/southeast Indian and southwest Pacific regions. The North Indian Ocean has the lowest magnitude of the FDL. This implies that under similar circumstances the cyclones are easiest to predict in the North Indian Ocean compared to any other basins in the world. However, it may be noted that the FDL relates to only the intrinsic nature of the cyclone tracks. The operational factors, such, as accuracy of fixing the cyclone centres will affect the persistence forecasts. This is particularly important for cyclones of North Indian Ocean which are relatively weak and therefore the accurate fixing of their centres is difficult.

In recent years, there have been considerable advancements in the development of advanced statistical techniques using physical and dynamical parameters as inputs to the statistical models. These techniques generated a lot of interest among cyclone forecasters as some of them are found to have skills much better than climatological or analogue techniques.

3.1.2. *Statistical-physical models*

In this approach, the physical factors responsible for the movement of tropical cyclones are taken into account through synoptic observations in and around the storm's field. The contribution of environmental field relative to climatology and persistence in explaining the variance of cyclone motion varies in different regions. Significant differences occur between the zonal and meridional components. Climatology is found to be almost insignificant as a predictor of meridional motion in the Atlantic, but is good predictor for zonal motion. Although, the persistence is a good predictor for short-range prediction, it contributes considerably less at 72 hr. The synoptic information, by contrast, contributes more at longer time intervals for Atlantic region. Synoptic information is also found important for Australian region, but the contribution decreases with time.

One of the earliest Statistical-Synoptic models is the NHC-67 model. Regression equations were developed using data from 1945-65. Apart from past 12 hr movement, the predictors included 1000, 700 and 500 hPa heights and 24 hr height changes, as well as 700-500 and 1000-700 hPa thickness, at 120 grid points centred on the storm. Additional predictors, evaluated at only selected grid points, included the geostrophic wind components and vorticity at 1000, 700 and 500 hPa, thermal winds based on the 700-500 and 1000-700 hPa thickness, and average height changes at the three levels.

Mohanty (1979) used synoptic predictors such as sea level pressure fields, geopotential fields at 700 and 500 hPa and the 1000 to 700 hPa and 700 to 500 hPa thickness computed over a 5 deg. lat./long. moving coordinate to obtain prediction for the cyclones of the Bay of Bengal. Other parameters taken are geostrophic steering currents at 700 and 500 hPa surfaces and the preceding 12 hour track of the storm. Kivganov and Mohanty (1978) developed a physical-statistical method of forecasting post-monsoon storms in the Bay of Bengal. They used coefficients of empirical orthogonal functions of meteorological fields and the past 12 hr storm movement as predictors. A minimum number of predictors with maximum amount of prediction information were selected by stepwise regression technique. Another method based on empirical predictors only (*i.e.*, climatology and persistence) was developed by Kivganov and Mohanty (1979a) which was similar to CLIPER technique developed for other regions. Mohanty (1980) developed a scheme in which three independent forecasts derived from the above three methods are obtained and then used as basic predictors to derive a new set of prediction equations. In order to consider the non-linear effects, a third-order polynomial with 3 basic predictors and 16 additional predictors are generated. A stepwise screening regression procedure is used to eliminate the predictors which fail to provide the prescribed minimum incremental reductions of variance (0.1%). Mohanty (1994) summarises the performance of different objective methods discussed above in predicting the tracks of the post-monsoon cyclones (Fig. 4). It is found that the method using combination of three independent forecasts from three different models provides the best forecast.

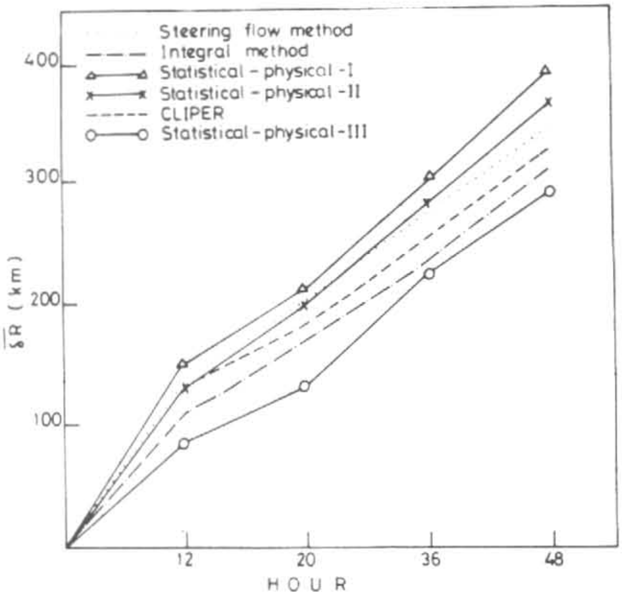

Fig. 4. Performance (average magnitude of vector error) of different objective methods in predicting the tracks of post-monsoon cyclones in the Bay of Bengal (Mohanty 1994)

3.1.3. *Statistical-dynamical model*

These models use numerical outputs from a numerical model in addition to the predictors used by the Statistical-Synoptic Models. One of the earliest models of this kind was NHC-73 model developed by Neumann and Lawrence (1975). The predictors included as input to this model were: Output from CLIPER model, current 1000, 700 and 500 hPa height fields and 24, 36 and 46 hr height predictions from NMC, Washington numerical prediction model. The above model uses an overlapping areal stratification of the dependent data set into 52 zones across the tropical Atlantic.

NHC-73 model was insufficiently robust to withstand changes in the numerical model packages which provided input. With the lessons learned from the above model, NHC-83 was designed with sufficient robustness to withstand resonable changes in the statistical characteristics of the large scale numerical model. Nevertheless, changes to the large scale model have caused some problems with NHC-83 model also. The model which was introduced operationally for the 1983 hurricane season, has outperformed other models in use at NHC by a rather wide margin till 1988. Nevertheless, long-term operational use of the model has disclosed certain design weaknesses.

Two approaches to potential improvement are suggested. The first involves maintaining the basic integrity of the NHC-83 model but using deep-layer mean winds rather than deep-layer mean geopotential heights as the main source of predictive information. The second method involves retaining the geopotential heights as predictors but revising the model based upon an evaluation of NHC-83 error patterns. NHC-90 is based on second approach. Early results of the performance of the model suggest that it is likely to outperform NHC-83.

While the performance of such models is better than the other statistical models, there are certain limitations of these techniques. Inclusion of numerical products as input to the model makes it very complicated. Moreover, the prediction from these models cannot be made until the output from numerical model is available for a large number of tropical cyclones from past records. This demands operational run of the same NWP model for a longer time. Further, the success depends on quality of objecive analysis and subsequent forecast of tropical cyclone environment with NWP model. This delay may be 6 hour or more. The accuracy of the numerical models for tropics is questionable. While developing the model, actual analysis fields from numerical model are used. However, in an operational mode, serious problems can crop up from errors and biases in the numerical output.

3.2. *Dynamical models*

Numerical tropical cyclone track prediction models have recently proven to be successful in the operational prediction of tropical cyclone motion. The forecast errors of large-scale motions with global models have also improved considerably in recent years. Much of this success is contributed by increase in computer power, developments in numerical techniques, improved understanding of physical processes and improvements in observing systems and objective analysis and initialization. While the improvements in predictions in mid-latitudes have been quite dramatic, the numerical forecast improvements in tropics have been more modest. Perhaps, the most important factor is the relatively poor data coverage in the tropics compared to mid-latitudes. Moreover, the horizontal gradients of meteorological properties such as temperature and geopotential heights in the tropics are of the same order as the measurement inaccuracies. Inadequate understanding of the dynamics and thermodynamics of tropical circulations, especially about physical processes involved in the release of latent heat energy and its contribution to large-scale dynamics are some of the important factors contributing to problems of numerical forecast for tropics. It also follows that moisture measurements are more important in the tropics than in mid-latitudes, and yet the rawinsonde moisture observation may be representative of only a small area around the station. Convective-scale processes have been typically parameterized in terms of large-scale circulations However, it is not clear whether the basic assumption of parameterizability is applicable for the smaller scale tropical circulations or not.

In spite of the above stated limitations, use of NWO models for prediction of tropical cyclone tracks have a long history of more than four decades. Just after the first attempt of NWP development, work has been carried out in Japan and USA to use NWP models for tropical cyclones. The numerical prediction of tropical cyclone tracks are broadly divided into two categories: Steering concept (external forcing) and Integral concept (both external and internal forcings).

3.2.1. *Steering current method*

Techniques to estimate the "steering current" in which a tropical cyclone is embedded has arisen from the notion that tropical cyclones are equivalent to corks in the stream, and that an accurate determination of stream flow will provide excellent forecasts. Research over the past several decades has shown that this simplistic picture is inaccurate and that interaction between the tropical cyclone and its environment has a marked impact on motion. Nevertheless, upto 80% of the variance of tropical cyclone motion can be explained by the large scale environmental flow and its estimation provides valuable support for track prediction. Operational techniques for determining an appropriate steering flow include space mean approaches, such as MUSIC technique (MULtilevel

Steering by Integrated Current) used in several Asian countries. The major difficulties arise from removal of the cyclone circulation and in determining the appropriate level or layer mean.

Holland (1984a) examined the relationship between tropical cyclone motion and the environmental flow using composite cyclones. He estimated the basic current by averaging over a 1-7° latitude radial band surrounding the cyclone and found significant and consistent track deviations. In the mean, cyclones tend to move polewards and westwards of this basic current. For example, low latitude, westward-tracking cyclones move faster and slightly poleward of the basic current, those moving to the northeast move slower and to the west. These findings are in qualitative agreement with the theoretical studies discussed above. The theoretical studies also support the forecaster experience that very large cyclones tend to move more independently of the environmental flow than do small systems.

Geopotential heights have been used in some studies to estimate the environmental flow. Although, these produced similar results to direct wind observations, height fields are quite smooth and unreliable in the deep tropics and modern wind analysis methods are becoming quite accurate.

Kivganov and Mohanty (1979b) proposed a hydro-dynamical method of prediction of tropical cyclone tracks in the Bay of Bengal. In this method, the cyclonic storm is represented by a constant circular vortex stream described in terms of the maximum sustained wind and the radius of the storm's eye. A depth averaged barotropic flow is assumed. The vortex representing tropical cyclone is eliminated from the initial stream function analysis leaving only a steering wind field in the region of the cyclone. The cyclonic vortex motion is estimated by the steering current which is determined by a numerical model using quasi-solendial approach.

Removal of a symmetric cyclone is not recommended for operational applications, as this does not always provide a good indicator of the environmental flow. The cyclone may be asymmetric and non-linear asymmetries in the environment will be partially removed. A better approach is to use an appropriate filter to remove the cyclone scales, preferably only in the vicinity of the cyclone.

The appropriate level or layer mean to be used to indicate the steering current has been debated widely. The most consistent observational result is that the 700 or 500 hPa level provides the closest approximation. A more consistent and stable relationship is found for layer means. However, Holland (1984b) argued against the inclusion of outflow and inflow layers and recommended the layer from 850-300 hPa. Many forecast offices consider that deeper layer-mean, *e.g.* 850-200 hPa, are best for forecasting. This apparent conflict with observational and theoretical results probably arises from the lack of good mid-level observations in the vicinity of most of the tropical cyclones. In these cases, the inclusion of 200 hPa analyses, with their observations from satellite cloud drift winds and commercial aircraft may provide a more stable analysis.

3.2.2. *Integral method*

In this method, the tropical cyclone vortex is considered as inseparable part of the large scale flow and thus free interaction of the cyclonic storm with its outer environment is allowed. Although, these techniques were in use in most of the countries affected by the cyclones for past four decades, with the availability of advanced computer resources in recent years, there has been a greater emphasis to employ complex NWP models to predict the tropical cyclone tracks. Considerable advances have been achieved in the prediction of mid-latitude circulation systems with numerical models during past one decade. On the other hand, the advances in accuracy of the prediction of tropical systems have been relatively much slower due to various reasons. Nevertheless, a good progress has been achieved in understanding the structure and dynamics of movement of tropical cyclones. These advances provide a basis for improved track predictions with dynamical models.

The barotropic models which were first developed in the beginning of NWP era, are still in use at several tropical cyclone forecasting centres. The Regional baroclinic models continue to be the primary dynamical track prediction tool. Due to considerable improvement in the horizontal resolution and the availability of supercomputing facility at most of the NWP centres, the global models are becoming popular these days for tropical cyclone track prediction.

3.2.2. (a) *Barotropic models*

Barotropic models are useful for tropical cyclone prediction because of their simplicity in nature, less computational requirement and easy to have higher resolution to resolve the storm structure and the interaction between the vortex and its environment. However, the environment also evolves due to baroclinic processes, specially during recurvature in association with mid-latitude trough. Thus a barotropic model can be useful for situations in which the lower tropospheric flow in tropics is more barotropic, and for limited periods of times before baroclinic processes significantly influence the environmental circulation.

Kasahara (1957) made one of the earliest studies on tropical cyclone track prediction using barotropic models. In this study, the prediction for steering flow is obtained by separating the vortex field from the total flow. By solving the equation which includes interaction terms between the hurricane and the steering flow, the prediction of movement of the vortex is obtained.

In India, the first study on the prediction of movement of low pressure systems by dynamical methods was by Das and Bose (1958). Authors computed 24 hr forecast of two monsoon depressions on the basis of barotropic model of Charney and Estoque's baroclinic model. Dutta and Pradhan (1968) used dynamical methods to predict the tropical storm movement. Sikka (1975) used a barotropic vorticity equation applied to the non-divergent part of the wind flow at 500 hPa to predict tropical cyclone movement. He used the wind flow over a large area as he found it difficult to define the vortex field and to remove it from the total field because the paucity of data over the Indian Sea area. The study shows that the storm's displacement is better predicted than its direction of movement. Recurvature is predicted generally 24 hr after its occurrence. Singh and Saha (1976) performed numerical experiments with a primitive equation barotropic model for prediction of a depression and a storm. The basic input was the observed wind from which the stream function was obtained and from the computed stream function field the values of two horizontal components of wind vector were derived. These wind components were used as inputs to the balance equation to obtain the height fields. Ramanathan and Bansal (1977) used a premitive equation barotropic model to predict storm tracks. They treated the vortex in three different ways. The first method was to treat it as an integral part of the total flow which was integrated. They found a westward bias in the predicted tracks. The vortex was taken as symmetric one in this method. In the second method, the total field was subjected to double Fourier analysis and residual was taken as the basic field. The vortex was treated as a point which was advected each hour with successive value of the new *u* and *v* of the basic field during the integration at the advected centre points. Though the method provided good forecast, in many cases the difficulty arose when the basic flow became so weak that the vortex advection was practically nil. In the third method, the basic flow was obtained similar to the second method, but the vortex was assigned certain characteristic with a wind maximum symmetrically around a centre. This had further improved the performance, but the vortex movement remained generally slower than actual. Singh and Saha (1978) repeated their earlier experiment on the same set of tropical storm and monsoon depression but used an improved quasi-Lagrangian advection scheme. This led to some improvement in 48 hr forecast but rapid deterioration was noticed beyond this period.

Hurricane Research Division (HRD), USA model (DeMaria *et al.* 1992) and BMRC, Australia model (Holland *et al.* 1991) are the two recent barotropic models which have shown good results. The HRD model (called VICBAR) utilizes a nested grid with high resolution near the centre and coarser grid at greater distances. In the operational version, the inner grid resolution is 50 km. The model uses the cubic spline approach for analyses on nested grid. In this operational case, the analysis is of layer average (850-200 hPa) winds and heights using the prior 12 hours global forecast fields as background. A crucial part of the analysis is the specification of the fields near the storm where inadequate observations exist to specify the steering and the storm structure.

The VICBAR model is run whenever a named tropical cyclone (V max > 33 kt) exist in the Atlantic region. It has been noticed that the performance of VICBAR model matches closely with the advance statistical-dynamical models, *e.g.*, NHC-83 and NHC-90. In addition, this barotropic model is superior to the limited area baroclinic model (Quasi-Lagrangian Model - QLM) up to 36 hours, and is comparable beyond 36 hours. In general, the model performance diminishes beyond 72 hours.

The BMRC barotropic model (BARO) was aimed at cyclone track prediction on a workstation and can be integrated so quickly that it is feasible to do multiple integration. Thus the forecaster can use the model interactively to test various scenarios that might apply in particular situations. The basic advantage of using a barotropic model is to have multiple integration of the model in a given period compared to a single integration of a more complex baroclinic model.

3.2.2. (b) *Baroclinic models*

Baroclinic models are expected to improve predictions of the steering flow, especially beyond 36 hour when baroclinic effects become more evident. The vertical shear effects in the tropical cyclone structure and in the environment will be represented better. However, the real key to the success of these baroclinic models is the specification of the initial conditions to represent the location, structure, initial motion of the tropical cyclones and parameterization of physical processes in the model.

The baroclinic models are mainly of two types : (*i*) Limited-area/regional models (LAM) for specific region with a capability to integrate over a shorter time period (1-2 days) and (*ii*) General circulation models (GCM) for the entire globe with capability to integrate for a longer time period as they are not influenced by artificial lateral boundary conditions such as those imposed in LAM.

(*i*) *Regional models*

The earliest work on baroclinic models were by Harrison (1969) and Miller (1969). These research groups developed multi-layer, primitive equation models with a parameterization of number of important physical processes. It was demonstrated that tropical NWP models were not only computationally and numerically feasible, but that some tropical cyclone features could even be predicted. After these initial attempts at real data forecasting, the future efforts split into two aspects: the synoptic-scale or steering aspects on the motion problem and other concentrating on the tropical cyclone scale. The recent study on synoptic-scale aspect is by Harrison and Fiorino (1982). The work of Mathur (1974) and Hovermale and Livezey (1977) are good examples of the approach emphasizing the tropical cyclone simulation. The advantage of synoptic approach is that the computational savings achieved through a simple treatment of the tropical cyclone allowed a greater number of cases to be run which can be useful for operational purposes.

The earliest baroclinic models which were made operational for tropical cyclone track forecasts include, Moving Nested Grid (MNG) model for Japan by the Japan Meteorological Agency (JMA), the One-way influence Tropical Cyclone Model (OTCM) and the Nested Tropical Cyclone Model (NTCM) by the U.S.Navy Fleet Numerical Oceanography Centre (FNOC) and a Movable fine-mesh Model (MFM) for tropical cyclones threatening U.S. coastal areas by the National Meteorological Centre (NMC). Elsberry and Peak (1986) summarised the development of these models.

In India, there has been good progress in recent years towards the use of limited area model for prediction of tropical cyclones in the Indian seas. Prasad (1990) proposed a scheme for generating synthetic observations in tropical cyclone field for initializing a limited area primitive equation model and tested on a coarse resolution ($2^\circ \times 2^\circ$) forecast model. Mohanty *et al.* (1989) used a multi-layer primitive equation limited area model appropriate to a meso-scale quasi-hydrostatic baroclinic system to predict the track of monsoon depression. He found that there is a significant improvement of the predicted track by this model compared to a barotropic premitive equation model.

The single objective of the earlier dynamical models was to predict the future positions. The developments of new models were intended to improve cyclone-related precipitation forecast as a seconday objective. Moreover, intensity predictions are also expected to improve with the development of these high resolution baroclinic models, although the resolution is still not adequate enough to represent the details of inner core wind distribution.

Some of the other recent baroclinic models for prediction of tropical cyclone tracks are : Typhoon Model (TYM) for western North Pacific (Iwasaki *et al.* 1987), Quasi-Lagrangian Model (QLM) for U.S. (Mathur 1991), BMRC model for Australia (Puri *et al.* 1992), Taiwan Model (Chen *et. al.* 1995) and Geophysical Fluid Dynamics Laboratory (GFDL) model (Kurihara *et al.* 1993). The development and testing of baroclinic models are underway in several other countries.

(*ii*) *Global baroclinic models*

One of the serious demerits of LAM is their poor prediction of large scale features due to unrealistic lateral boundary conditions. This is particularly important for tropical cyclone track prediction since large scale steering current is one of the most essential mechanism that determines movement of the cyclone. The main advantage of the global baroclinic models

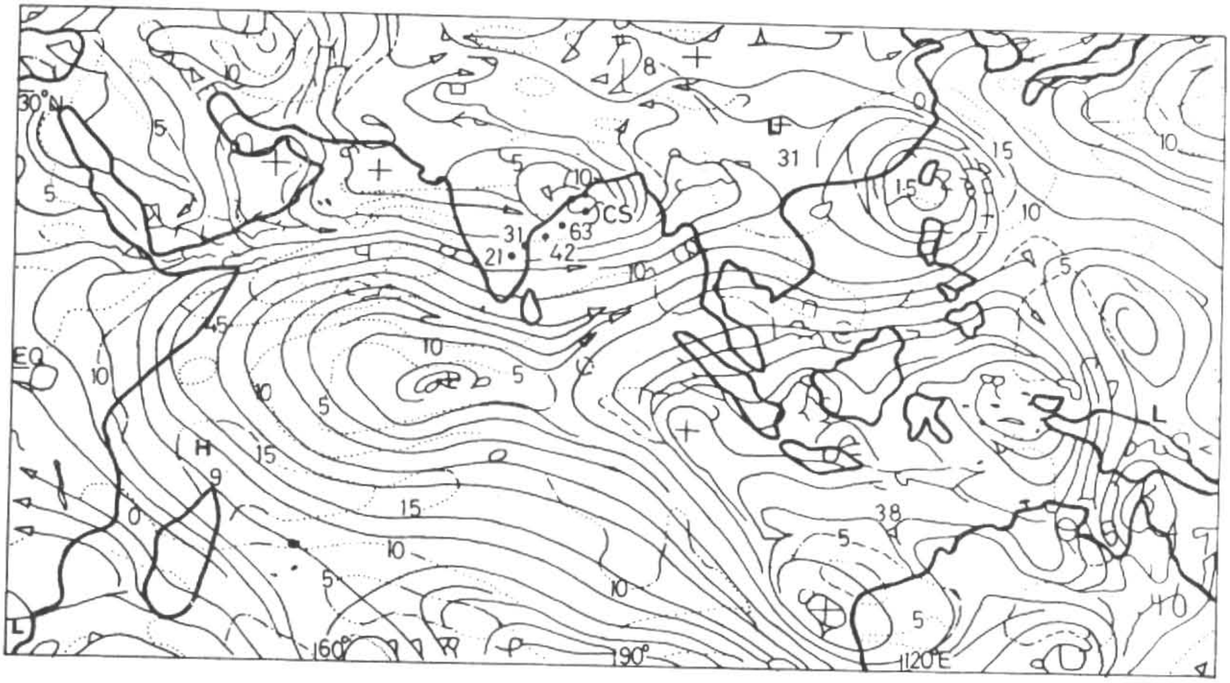

Fig. 5. Predicted positions at day 5 for several forecast experiments. The black dots along the east coast of India denote the positions of the global model at different resolutions T21, T31, T42, T63, T106, and T170. The flow field shown as streamlines is the observed field on day 5 (Krishnamurty *et al.* 1996)

relative to the limited-region, baroclinic models is that it does not require lateral boundary conditions that eventually limit the useful forecast interval. However, till recently the most serious problem associated with global models was the specification of initial cyclone field.

The most important problem associated with the large scale models in predicting the tropical cyclone is the discrepancies of the detailed structures of tropical cyclones between the predicted and the observed, due to coarse horizontal resolutions. Tropical cyclone models are characterised by the very fine resolution of the order 10 to 50 km which is too fine to be attainable in the large scale models due to computer power limitations.

Recent developments towards the improvement of global models have yielded improved tropical cyclone forecasts. These efforts were mainly in two directions: to increase the resolution of the models and to include appropriate and more accurate parameterization schemes of the physical processes available. Miller (1992) indicates substantial reduction of systematic errors in the ECMWF model due to finer resolution and inclusion of more realistic parameterization schemes for physical processes.

Another important problem in connection with tropical cyclone forecast by global models is the representation of initial cyclone fields. The ECMWF researchers, Andersson and Hollingsworth (1988) were one of the first group to study methods of inserting synthetic observations into a global model to represent tropical cyclones. The ECMWF however, does not use such observations in their operational model. The JMA was the first to introduce synthetic observations into an operational global model. The Fleet Numerical Meteorology and Oceanography Centre (FNMOC) began inserting synthetic observations in their global model during 1990. United Kingdom Meteorological Office (UKMO) have also introduced bogussing procedures in their global model. Lord (1991) described the bogussing system for the U.S. NMC which uses the position and structure information transmitted from the tropical cyclone warning centres. The procedure is based on the scheme proposed by Mathur (1991). In summary, all the important global model centres except ECMWF insert synthetic observations to at least define the position of the tropical cyclone. All these centres insert the synthetic observations during the analysis, which blends these observaions with actual observations in and around the tropical cyclone to provide the initial conditions for the global model.

Krishnamurti *et al.* (1993) summarises the improvements related to the tropical cyclone life cycle and track forecast through the physically-based initialization system that has been developed to make use of the diverse data sources, and especially the satellite-based rainfall rates. The FSU global model is typically integrated with T170 horizontal resolution, which is surpassed only by the ECMWF T213 model. Krishnamurti *et al.* (1996) have tested the effect of horizontal resolution for tropical cyclone prediction with spectral models of different horizontal resolutions (Fig. 5). Systematic improvements in the formation and motion of the storms are achieved for several case studies when the horizontal resolution is improved and an additional vertical level within the surface layer is utilized to improve the surface flux calculations.

There have been considerable improvement of track prediction forecast by these global models mainly through the improvement in the resolution, improvement of the accuracy of parameterization schemes for physical processes and the use of synthetic observations. These advances in the global model suggest that useful track forecast upto 5-day can be achieved in certain cases with advanced global models. However, more complete and systematic evaluation of these models for tropical cyclone forecasting are needed.

3.3. *Expert systems*

Besides statistical and dynamical models as described above, in operational set-up another objective approach in use for making final operational forecast is the Expert System. This system is used for integrating various methods of forecast available to the forecaster. The traditional check list used in different forecast centres to suggest logical steps to be followed in the event of a tropical cyclone is rudimentary form of an expert system. More complex decision trees also have been developed for interactive use on workstation or personal computer. The Joint Typhoon Warning Centre (JTWC) has a technique called TAPT (Typhoon Acceleration Prediction Technique) which uses surrounding wind fields to estimate the potential for rapid or delayed acceleration associated with poleward oriented or recurving tropical cyclones. Guidelines are provided for duration of acceleration, maximum acceleration and typhoon path.

One area of considerable potential for meteorological applications is the use of visualization techniques. Specific patterns, such as satellite imagery, could be recognised objectively and entered into decision trees. A sequence of satellite imagery and cyclone track could be used to develop new motion forecast algorithms.

Greater complexities can be achieved by the use of high order expert systems, such as neutral networks. These accept a set of input data and results from historical events, such as past tropical cyclone tracks, then iteratively calculate the potential paths via a series of cases and branch points. They require massive computing facilities to develop, however, and have not been shown to be better than standard statistical and dynamical techniques.

4. Concluding remarks and future prospects

Track prediction has been focal point of the tropical cyclone research all over the world. Accurate prediction of cyclone motion is extremely crucial for cyclone forecasting and warning work. Availability of a large number of subjective and objective techniques reflects the level of importance and concern of the cyclone forecasters.

There has been considerable progress in recent years towards the development of track prediction models. There are two important areas where significant progress has been achieved in past one decade. These were: improvement in the global circulation models in terms of its resolution, improvement of the accuracy of parameterization schemes for physical processes and use of synthetic and non-conventional data in the data assimilation schemes and improvement in the statistical-dynamical techniques.

Further improvements in the track prediction will come from several areas, including : research, improved observations, numerical models and statistical techniques. Continued research is required to develop proper understanding of the processes involved in the cyclone motion. Improvement in observations are essential for building appropriate knowledge of the structure and anomalous behaviour of the cyclones. Improvement in numerical models will provide further improvements in forecast skill.

With the advent of advanced super-computing techniques, much more improvement in the resolution of global model is expected in the years to come. This is quite evident from the improved performance of ECMWF's high resolution T-213 model. Parameterization of physical processes appropriate to intense tropical convection in the global model is yet another area where considerable improvement is needed. Other areas where improvement is required are the extensive data coverage over the data void regions through non-conventional observations and synthetic cyclonic vortex data generation, and the use of nudging technique for initial matching of analysed cyclone centres with the corresponding observations and physical initialization of input data. Expert systems using neutral network technique is another area through which a lot of improvement is expected. Better assimilation of the cyclone and its environment and the use of coupled atmosphere-ocean models can bring in substantial improvement in the model performance. Coupling numerical model and statistical forecast can also provide further improvements. A significant improvement of performance is expected from a new approach known as Ensemble technique which combines some estimate of the forecast skill with different forecasts. This is done by a method known as Monte-Carlo method of integrating a numerical model many times whilst introducing slight changes in the initial analyses. Alternatively, the forecast from several centres can be combined in a manner which indicates the degree of forecast uncertainty and overall improvement of the prediction of the tracks of tropical cyclones.

References

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

Annette, P., 1978, "Optimum prediction of the movement of tropical cyclone track (1974) by linear extrapolation", *Mon. Wea. Rev.*, **106**, 1619-1921.

Anthes, R.A., 1982, "Tropical Cyclones : Their evolution, structure and effects", *Meteor. Mongr.*, **19**, Amer. Meteor. Soc., Boston, MA, 208 p.

Chen, D. R., Yeh, T.C., Huang, K.N., Peng, M.S. and Chang, S.W., 1995, "A new operational typhoon track prediction system at the Central Weather Bureau in Taiwan, Preprints 21st Conf. Hurr. Trop. Meteror., Amer. Meteor. Soc., Boston, MA 02108, 50-51.

Das, P.K., and Bose, B. L., 1958, "Numerical prediction of the movement of Bay depressions". *Indian J. Met. Geophys.*, **9**, 1-4, 225-232.

Datta, R.K. and Pradhan, S.K. 1968, Proc. WMO/IUGG Sym. on NWP, Tokyo, 1968.

Datta, R.K. and Gupta, R.N., 1975, "Tracking tropical storms in the Bay of Bengal and calculation of probabilities of its striking east coast by storm analogue technique", *Indian J. Met. Hydrol. Geophys.*, **26**, 344-348.

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

Elsberry, R.L. and Peak, J.E., 1986, "An evaluation of tropical cyclone forecast aids based on cross-track and long-track components", *Mon. Wea. Rev.*, **114**, 142-155.

Harrison, E.J., Jr., 1969, "Experiments with a primitive equation model designed for tropical application", M.S. Thesis, Naval Postgraduate School, Monterey, CA, 54p.

Harrison, E.J., Jr. and Fiorino, M., 1982, "A comprehensive test of the Navy nested tropical cyclone model", *Mon. Wea. Rev.*, **109**, 646-650.

Holland, C.J., 1983, "Tropical cyclone motion: Environmental interaction plus a beta effect", *J. Atmos. Sci.*, **40**, 428-442.

Holland, G.J., 1984 (a), "Tropical cyclone motion: A comparison of theory and observations", *J. Atmos. Sci.*, **41**, 68-75.

Holland, G.J., 1984 (b), "On the climatology and structure of tropical cyclones in the Australian/southwest Pacific region: I. Data and tropical storms", *Aust. Met. Mag.*, **32**, 1-16.

Holland, G.J., Leslie, L.M., Ritchie, E.A., Dietachmayer, G.S., Klink, M. and Powers, P.E., 1991, "An interactive analysis and forecasting system for tropical cyclone motion", *Wea. Forecasting*, **6**, 415-423.

Hope, J.R. and Neumann, C.J., 1971, "Computer methods applied to Atlantic Area Tropical Cyclone climatology", Mariners Weather Log, **15**, 272-278.

Hovermale, J.B. and Livezey, R.E., 1977, "Three-year performance characteristics of the NMC hurricane model", Preprints 11th Conf. Hurr. Trop. Meteor., Amer. Meteor. Soc., Boston, MA 02108, 121-125.

Iwasaki, T., Nakano, H. and Sugi, M., 1987, "The performance of a typhoon track prediction model with cumulus parameterization," *J. Meteor. Soc. Japan*, **65**, 555-570.

Jarell, J.D., and Somervell, W.L. Jr., 1970, "A computer technique for using typhoon analogs as a forecast aid" Naval Weather Research Facility Technical Paper No. 6-70, 47 p.

Jarrell, J.D., Mauck, C.M and Renard, R.L., 1975, "The Navy's analog scheme for forecasting tropical cyclone motion over the Northeastern Pacific Ocean", Technical Paper No. 6-75, Naval Environmental Prediction Research Facility, Monterey, CA, 27 p.

Kasahara, A., 1957, "The numerical prediction of hurricane movement with the barotropic model", *J. Met.*, **14**, 386-402.

Kivganov, A.F. and Mohanty, U.C., 1978, "On the physical statistical method for forecasting the movement of tropical storms in the Bay of Bengal", *Meteor. Hydrol.* **5**, 19-25.

Kivganov, A.F., Mohanty, U.C., 1979 (a), "On the application of nonlinear regression analysis to forecast the movement of tropical cyclones in the Bay of Bengal", *Tr. Hydrometeorol. Centre, USSR*, **125**, 47-58.

Kivganov, A.F., Mohanty, U.C., 1979 (b), "Hydro-dynamical method of forecasting the trajectories of tropical cyclones in the Indian Seas", *Meteorol. Climatol. Hydrol.* **15**, 9-15.

Krishnamurti, T.N., Bedi, H.S., Yap, K.S., Oosterhof, D., 1993, "Hurricane forecasts in the FSU models", *Adv. Atmos. Sci.*, **10**, 121-131.

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., 1969, "Motions of vortices and circulating cylinder in shear flow with friction", *J. Atmos. Sci.*, **26**, 390-398.

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

Lord, S.J., 1991, "A bogussing system for vortex circulation in the National Meteorological Centre global model", *Preprints, 19th Conf. Hurr. Trop. Meteor.*, Amer. Meteor. Soc., Boston, MA 02108, 328-330.

Mathur, M.B., 1974", A multiple grid primitive equation model to simulate the development of an asymmetric hurricane (Isbell, 1964)", *J. Atmos. Sci.*, **31**, 371-392.

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

Miller, M.J., 1992, "The analysis and prediction of tropical cyclones by the ECMWF global forecasting system: Progress, problems and prospects". *Tropical Cyclone Disasters*, J Lighthill, Z. Zhemin, G. Holland, and K. Emanuel (Eds.), Peking University Press, 220-231.

Miller, B.I., 1969, "Experiments in forecasting hurricane development with real data", ESSA Tech. Memo., ERLTM-NHRL, 85, 28 p.

Mohanty, U.C., 1978, "Tropical cyclones in the Bay of Bengal and objective methods for prediction of their movement", Ph.D. thesis, Odessa Hydro-Meteorological Institute, USSR.

Mohanty, U.C., 1979, "Statistical method of forecasting tropical cyclones", *Meteorol. Climatol. Hydrol.*, **15**, 16-22.

Mohanty, U.C., 1980, "An objective method of forecasting the movement of tropical cyclones in the Bay of Bengal based on a number of statistical models", WMO symposium on probabilities and statistical methods in weather forecasting Nice, France (Geneva, WMO), 359-364.

Mohanty, U.C., Paliwal, R.K., Tyagi, A. and John, A., 1989, "Evaluation of a multi-level primitive equation limited area model for short range prediction over Indian region", *Mausam*, **40**, 34-42.

Mohanty, U.C., 1994, "Tropical cyclones in the Bay of Bengal and deterministic methods for prediction of their trajectories, Sadhana", Acad. Proc. in Engg. Sci., Vol. 19, Part 4, 567-582.

Neumann, C.J., 1972, "An alternative to the HURRAN tropical cyclone forecast system", NOAA Tech. Memo NWS SR-62, 24 p.

Neumann, C.J., 1985, "Trends in forecasting the tracks of Atlantic tropical cyclones: An update through 1984, "Preprints, 9th AMS conference on Probability and Statics in Atmospheric Science, American Meteor. Soc., Boston, 109-115.

Neumann, C.J. and Lawrence, M.B., 1975, "An operational experiment in the statistical-dynamical prediction of tropical cyclone motion", *Mon. Wea. Rev.*, **103**, 665-673.

Neumann, C.J. and Mandal, G.S., 1978, "Statistical prediction of tropical storm motion over the Bay of Bengal and Arabian Sea", *Indian J. Met. Hydrol. Geophys.*, **29**, 487-500.

Ookochi, Y., 1978, "Preliminary test of typhoon forecast with a moving multi-nested grid (MNG)", *J. Meteor. Soc. Japan*, **56**, 571-583.

Pike, A.C., and Neumann, C.J., 1987, "The variation of track forecast difficulty among tropical cyclone basins", *Wea. Forecasting*, **2**, 237-241.

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

Puri, K., Davidson, N.E., Leslie, L.M. and Lagan, L.W., 1992, "The BMRC tropical limited area model", *Aust. Meteor. Mag.*, **40**, 81-104.

Ramanathan, Y. and Bansal, R.K., 1977, "On the application of a primitive equation barotropic model for the prediction of storm tracks in the Indian region", *Indian J. Meteor. Hydrol. Geophys.* **28**, 2, 169-176.

Rossby, C.G., 1948, "On displacements and intensity changes of atmospheric vortices", *J. Mar. Res.*, 175-187.

Sikka, D.R., 1975, "Forecasting the movement of tropical cyclones in the Indian seas by non-divergent barotropic model", *Indian J. Meteor. Geophys.*, **26**, 323-325.

Sikka, D.R. and Suryanarayana, R., 1972, "Forecasting the movement of tropical storms/depressions in the Indian region by a computer oriented technique using climatology and persistence", *Indian J. Meteor. Geophys.*, **23**, 35-40.

Singh, S.S. and Saha, K.R., 1976, "Numerical experiments with a primitive equation barotropic model for prediction of movement of monsoon depressions and tropical cyclones", *J. Appl. Meteor.*, **15**, 805-80.

Singh, S.S. and Saha, K.R., 1978, "Numerical experiment with primitive equation barotropic model using quasi-Lagrangian advection scheme to predict the movement of monsoon depressions and tropical cyclone", *Indian J. Meteor. Hydrol. Geophys.*, **29**, 1&2, 367-374.