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Current status of tropical cyclone track prediction techniques and forecast errors

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सार – पिछले कुछ दशकों में भूमंडलीय उष्णकटिबंधीय चक्रवातों के पूर्वानुमान में होने वाली त्रुटियों में उन्नत आँकड़ा संग्रहण तकनीकों, सतत मॉडल विकास, उच्च विभेदनों और भ्रमिल विशिष्टता के फलस्वरूप काफी कमी आई है। यह देखा गया है कि समूचे विश्व में पूर्वानुमान की त्रुटियों में प्रत्येक समय के अनुभवों के आधार पर प्रतिवर्ष 1 से 2 प्रतिशत तक की कमी आई है जिनके परिणामस्वरूप लम्बी अवधि (48 घंटे से अधिक) के पूर्वानुमानों में अत्यंत तीव्र गति से सुधार हो रहा है। अटलांटिक और प्रशांत महासागर जैसे बेसिनों में यद्यपि विभिन्न कारणों से पूर्वानुमान की त्रुटियों में काफी अधिक कमी हुई है तथापि भारतीय क्षेत्र में यह प्रवृत्ति काफी साधारण रही है। इस क्षेत्र में पूर्वानुमान की त्रुटियों में कमी आने का एकमात्र कारण भारत मौसम विज्ञान विभाग (भा. मौ. वि. वि.) और राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केन्द्र (एन. सी. एम. आर. डब्ल्यू. एफ.) जैसे प्रचालनात्मक एन. डब्ल्यू. पी. केन्द्रों द्वारा उनके क्षेत्रीय और भूमंडलीय मॉडलों के विश्लेषण में संश्लेषित भ्रमिलता का अधिकाधिक प्रयोग हो रहा है। अंतर्राष्ट्रीय उष्णकटिबंधीय चक्रवात अनुसंधान में इस तथ्य पर अब अधिक बल दिया जा रहा है कि विशेष रूप से बहुत कम समय में ही अपारम्परिक आँकड़ों के अधिक उपयोग, मेसोस्केल विश्लेषणों, भ्रमिल विशिष्टता के लिए संश्लेषित आँकड़ों के उपयोग से और उच्च मॉडल विभेदन में भौतिक प्राचलीकरण के निष्पादन द्वारा उष्णकटिबंधीय चक्रवात के मार्ग का पूर्वानुमान अधिक सटीक बन सके। चक्रवातों के लैंडफॉल के संबंध में पहले से चल रही हरीकेन डब्ल्यू. आर. एफ. परियोजना पर विशेष रूप से चल रहे अनुसंधान और प्रचालनात्मक कार्यों से आने वाले वर्षों में भारतीय क्षेत्र को लाभ होने की संभावना है। तथापि, भारतीय क्षेत्र द्वारा मॉडल के विकास के समन्वित प्रयासों के अलावा मॉडल के विश्लेषण के लिए पारम्परिक और अपारम्परिक आँकड़ों की अधिकतम उपलब्धता तथा उन्नत आँकड़ा संग्रहण तकनीक के उपयोग को अधिक प्राथमिकता दी जानी चाहिए।

ABSTRACT. Thanks to advanced data assimilation techniques, continuous model development, higher resolutions, and vortex specification, there has been considerable progress in the reduction of global tropical cyclone forecast errors during past few decades. It has been observed that world-wide rate of reduction of forecast errors was of the order of 1%-2% per year for all time horizons, with most rapid improvement at longer durations (beyond 48 hours). While other basins like Atlantic and Pacific oceans reported greater rate of decline of these errors due to various factors, the trend has been quite modest for Indian region. The only factor responsible for reduction of errors in the region was the greater use of synthetic vortex by operational NWP centres like India Meteorological Department (IMD) and National Centre for Medium Range Weather Forecasting (NCMRWF) in their Regional & Global model analyses. The current emphasis of international tropical cyclone research is to achieve greater accuracy of TC track prediction, especially in the short range, by maximizing the use of non-conventional data, meso-scale analysis, use of synthetic data for vortex specification, and the performance of physical parameterization at higher model resolution. The current research and operational emphasis of the ongoing Hurricane WRF project for land falling cyclones, is expected to benefit the Indian region in the years to come. Nevertheless, the Indian region needs to assign higher priority to the greater availability of conventional & non-conventional data and use of advanced data assimilation technique for model analysis besides its concerted efforts on model developments.

Key words – Tropical cyclone, Track forecast, Data assimilation, North Indian region, Dynamical model.

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 these 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 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.

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

TABLE 1

Forecast Difficulty Level (FDL) in km for different Ocean basins for different forecast hours

Ocean Basin	FDL (in km)		
	24 hr	48 hr	72 hr
SW Pacific	230	500	725
N. Atlantic	200	450	670
NW Pacific	180	400	620
SW Indian	150	320	450
NE Pacific	130	270	400
North Indian	100	210	300

disaster. In the Indian region, the storm surge is the most devastating element of TC impact. Much of this is contributed by extremely shallow coastal bathymetry 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.

2. Tropical cyclone 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 categorized as objective or deterministic techniques. Mohanty and Gupta (1997) and Gupta (1999) have described these techniques in details. The techniques developed in India in the last 4 decades are based on different approaches like (*i*) statistical, (*ii*) analogue, (*iii*) persistence and climatology (*iv*) statistical physical and statistical dynamical models. Table 1, after Pike and Neumann (1987) presents data on Forecast Difficulty Level (FDL) statistics for 24 hr, 48 hr and 72 hr tropical cyclone tracks in different ocean basins. It is observed that for all the three time periods FDLs are lowest in the North Indian Ocean showing not too erratic behaviour of tropical cyclones in this basin.

The performance of the dynamical models for track prediction in the North Indian Ocean is discussed below.

2.1. *Dynamical models*

Although, the dynamical 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.

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.

(*i*) *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. In India a large number of work using barotropic model are available [Das and Bose (1958), Sikka (1975), Singh and Saha (1976, 1978), Ramanathan and Bansal (1977)].

(*ii*) *Baroclinic models*

Baroclinic models are expected to improve predictions of the steering flow, especially beyond 36 hour when baroclinic effects become more evident. In these models, the effect of vertical shear be represented better both in the tropical cyclone structure and in the environment. 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.

(a) *Regional baroclinic models*

Regional Baroclinic models came into use from 1969 (Harrison, 1969). The work of Mathur (1974) is good example of the approach emphasizing the tropical cyclone simulation.

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

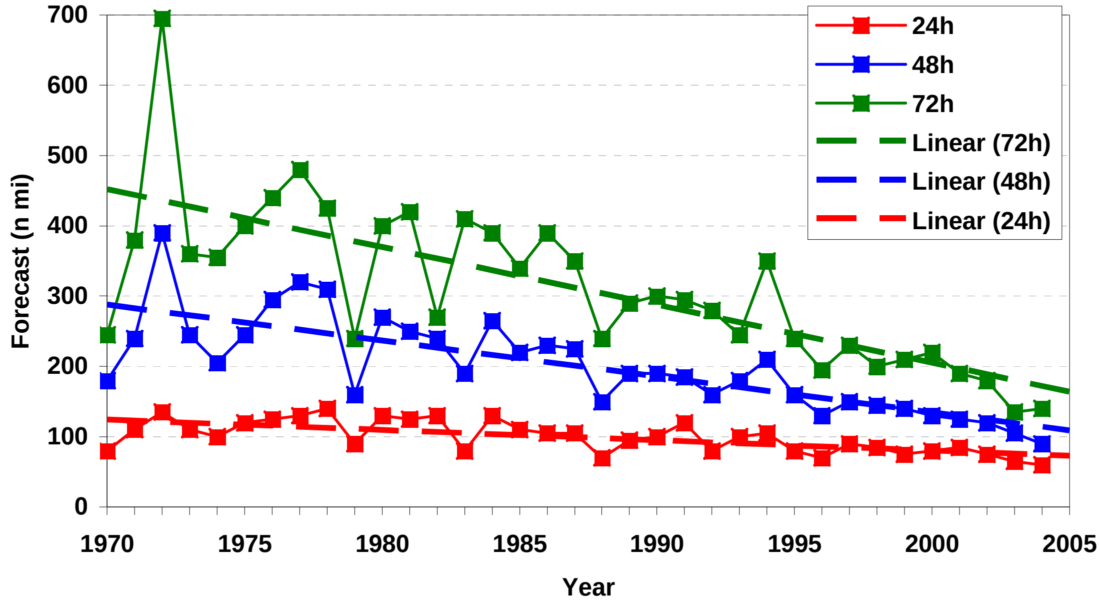

Fig. 1. National Hurricane Centre's annual average track forecast errors over North Atlantic region for the period 1970-2004

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 Centre for Environmental Prediction (NCEP). Elsberry and Peak (1986) summarised the development of these models.

In India, there has been some progress in recent years towards the use of limited area model for prediction of tropical cyclones in the Indian Seas. Prasad *et al*. (1997), proposed a scheme for generating synthetic observations in tropical cyclone field for initializing a limited area primitive equation model and tested on a 1° × 1° resolution 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. They found that there is a significant improvement of the predicted track by this model compared to a barotropic primitive equation model. Many versions of baroclinic models have been developed by researchers in Japan and USA.

(b) *Global baroclinic models*

One of the serious demerits of Limited Area Models (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 mechanisms that determines movement of the cyclone. The main advantage of the global baroclinic models 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. It has been first noted by Manabe *et al*. (1965) that tropical cyclone like vortices do form in coarse resolution global circulation model. They simulated tropical disturbances in their model with a horizontal resolution of 400 km and have shown that increase of horizontal resolution from 400 km to 200 km grid made the structures of the disturbances more realistic. Bengtsson *et al*. (1982) examined tropical cyclone vortices in the operational forecasts performed at the European Centre for Medium Range Weather Forecast (ECMWF).

Recent developments 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 (1993) indicates substantial reduction of systematic errors in the ECMWF model due to finer resolution and inclusion of more realistic parameterization schemes for physical processes. Krishnamurti and Oosterhof (1989) reported systematic improvements in the formation and motion of the storms when the models with increasing horizontal resolution *viz*., T21, T31, T42, T63 and T106 were employed for tropical cyclone prediction. Krishnamurti *et al.* (1993) summarise the improvements related to the

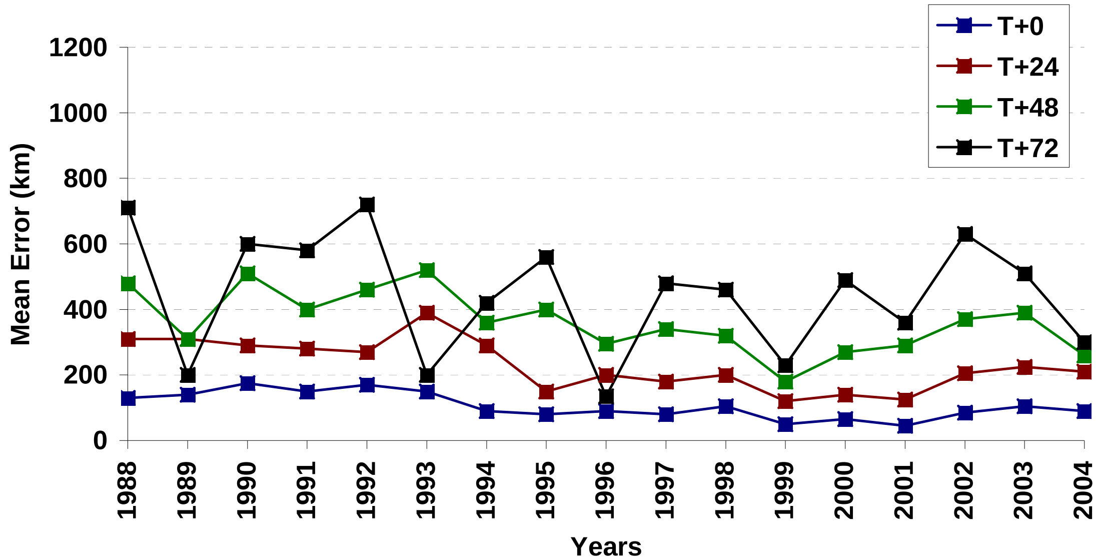

Fig. 2. Mean forecast errors for North Indian Ocean (NIO) region based on the statistics available with Joint Typhoon Warning Centre (JTWC), Guam, USA for the period 1988-2004

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.

In general, a cyclone vortex is either missing or is seen to be poorly represented both in position and intensity, in the global analysis. In order to provide proper representation of the vortex in the initial analysis, synthetic or bogus technique has come into frequent use by several leading NWP centres in the world. Japan Meteorological Agency (Ueno and Ohnogi, 1992), United Kingdom Meteorological Office, National Centre for Environmental Prediction (NCEP), USA, etc. have operationalized the synthetic data scheme for cyclone forecasting.

In India, not much work has been done using global models. The National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi is running a 18-layer Global Spectral Model (T-80) adapted from NCEP, USA. Gupta (1999) have reported encouraging results on the impact of insertion of synthetic vortex in the model analysis on the prediction of tracks of a few intense tropical storms of Indian region.

3. Current status of errors of tropical cyclone track prediction models

Forecasts of TC motion have improved steadily over the last three decades, mostly due to a combination of better observations, especially the satellite (Soden *et al*. 2001) and dropsonde (Burpee *et al*. 1996; Tuleya and Lord 1996; Aberson and Franklin 1999) data; improvements in dynamical models (Kurihara *et al*. 1998); and improved understanding of physical processes and mechanisms that govern the motion of TCs (Emanuel 1999). During past 3 decades, forecast track errors from numerical prediction systems have decreased by approximately 25% at 24 hours, 35% at 48 hours and 50% at 72 hours (McAdie and Lawrence, 2000). Annual rate of improvement was, 0.8% at 24 hour, 1.7% at 48 hour and 1.9% at 72 hour forecasts. Leslie *et al*. (1998) suggest improvements of 30% are still possible. Fig. 1 shows that National Hurricane Centre's annual average track forecast errors over North Atlantic region for the period 1970-2004, depicting a clear decreasing trend in track forecast errors in past 3 decades. These trends are more evident and steep for 48 and 72 hr forecasts. The 96 hr and 120 hr forecast errors during past 5 years are found to be very close to that of 48 hr forecast errors of mid- eighties.

Fig. 2 is the similar plot for North Indian Ocean (NIO) region based on the statistics available with Joint Typhoon Warning Centre (JTWC), Guam, USA. JTWC regularly issues tropical cyclone track forecasts for North Indian Ocean. It may be seen that unlike north Atlantic region, NIO region does not show any discernible trend in the reduction of forecast errors during past 18 years. Slight reduction in the errors in 24 and 48 hr forecast is observed which is attributed to use of synthetic vortex in the initial field. The region continues to face with inadequacy of non-conventional data which are crucial for tropical cyclone prediction and the forecast error for 48 hour forecast has hovered around 200 km since 1995.

TABLE 2

Mean Track Forecast Errors (in km) from UKMO Global Model for 3 seasons prior to northern summer 2002 for six ocean basins: North East Pacific (NEP), North Indian Ocean (NI), North Atlantic (NA), North West Pacific (NWP), Australian (AUST) and South West Indian Ocean (SWI). The number of forecasts in each category is shown in bracket

Basin	Forecast Period				
	24	48	72	96	120
NEP	102 (258)	188 (181)	290 (123)	434 (88)	606 (61)
NI	130 (54)	220 (36)	313 (20)	305 (11)	278 (6)
NA	132 (330)	241 (257)	332 (194)	384 (145)	476 (111)
NWP	134 (517)	251 (397)	371 (279)	508 (195)	679 (118)
AUST	160 (207)	269 (142)	382 (91)	476 (53)	632 (30)
SWI	157 (270)	276 (224)	370 (181)	475 (137)	580 (99)

Table 2 shows mean track forecast errors from the UKMO global system for the three latest seasons up to northern summer 2002 for each of the six TC basins. The basins are ordered top to bottom in terms of absolute skill in the 48-hour forecast. The number of forecasts is indicated in brackets. These statistics document current state-of-the-art for each basin in terms of guidance from an individual numerical forecast system. Because relatively few forecasts are made beyond 72 hours, the statistics at these longer lead times are less robust. Forecasts in the northern hemisphere are more skillful than those in the southern hemisphere, reflecting the data availability issue and also possibly the greater variability in motion, and hence difficulty, in the southern hemisphere. Performance is best in the NE Pacific and worst in the SW Indian Ocean. Since persistence in the motion affects the degree of difficulty in the forecast, verification against CLIPER (Bessafi *et al*., 2002) is needed to help define the source of this difference. The generally skillful performance over all basins likely reflects the improved use of synthetic TC and remotely-sensed observational data. There is some evidence that error growth is largest in the first 24 hours, suggesting improvements in initialization are still possible.

Although it is apparent from this table that North Indian Ocean errors are second lowest after North east Pacific region. However, these figures are not normalized with reference to the degree of forecast difficulty which needs to be looked into carefully to assess the actual performance of the model in different basins. In order to examine the potential track forecast skill of UKMO model for each basin, the errors in various ocean basins are normalized with reference to FDL figures given in Table 1. The Table 3 gives these figures for various basins.

TABLE 3

Mean potential track forecast errors (in km) from UKMO Global Model for 3 seasons prior to northern summer 2002 for six ocean basins

Basin	Forecast Period		
	24	48	72
NEP	124	237	371
NI	197	360	522
NA	110	194	268
NWP	128	228	323
AUST	116	201	289
SWI	172	303	406

It is clearly evident from Table 3 that in terms of performance, the potential forecast errors are largest for North Indian Ocean and lowest for North Atlantic Ocean. As mentioned earlier, the possible reason for poor performance in the North Indian Ocean could be the availability of inadequate non-conventional data over the region.

3.1. *Performance of Numerical Models used by operational agencies in India for TC prediction in the Indian region*

India Meteorological Department (IMD) and National Centre for Medium Range Weather Forecasting (NCMRWF) are the two agencies in India which run Regional and Global models on operational basis. IMD is running 3 Regional/ Meso-scale numerical models *viz.*, Florida State University (FSU) Semi-implicit semi-lagrangian 100 km resolution model, NCEP's Quasi Lagrangian Model (QLM) with 40 km resolution and MM5 meso-scale model with 30 km resolution. IMD invariably uses bogus vortex in the initial analysis for each tropical cyclone case in the North Indian region. Table 4 gives 7 year track prediction errors by QLM model for 20 tropical cyclone cases over NIO region for the period 1998-2004. The 7 year average forecast errors for 24 hr, 36 hr and 72 hr periods were 140 km, 202 km and 315 km respectively. It may be mentioned that the errors from QLM model were much lower than those obtained using Persistence and Climatology methods.

NCMRWF runs 2 global models on operational basis *viz.*, T-80 with 160 km horizontal resolution and T-170 with 75 km resolution. It also runs 3 Regional/Mesoscale models in real time. The centre is running T-80 model for past over a decade since 1994 on operational basis. The error statistics for all 33 tropical cyclones during the period 1995-2004 are available. The mean track prediction errors (without bogus vortex in the initial field) for 24 hr, 48 hr and 72 hr periods are found to be 374 km, 638 km and 814 km respectively. There have been large along

TABLE 4

Track prediction errors (in km) for 20 tropical cyclones over North Indian Ocean using QLM model, Persistence and Climatology during 7 year period (1998-2004)

Year	24 hr FCST			48 hr FCST			72 hr FCST
	QLM	PERS	CLIM	QLM	PERS	CLIM	
1998	143 (2)	206	216	224	234	299	-
1999	119(3)	341	205	248	497	250	-
2000	100 (3)	208	264	173	333	383	-
2001	106 (3)	269	204	183	373	402	-
2002	150 (2)	191	131	115	247	278	425
2003	187 (3)	267	231	251	382	358	280
2004	176 (4)	141	221	223	242	215	240
Mean	**140 (20)**	**232**	**210**	**202**	**330**	**312**	**315**

track errors (539 km) for westward moving systems and large cross track errors (902 km) for northward moving cyclones. It has been seen that for lower intensity systems (Cyclonic storms and Severe Cyclonic storms), the model has shown faster movement as compared to observed speed of movement whereas for intense systems (Very Severe Cyclone and Super Cyclone), the model has shown faster movement in 46% cases and slower movement in remaining 54% cases. Gupta (1999) has shown that after using bogus vortex in the initial field there is a reduction of track forecast errors by 40% in 48 hr and 72 hr forecasts and upto 70% in 24 hr forecast. The Table 5 shows the mean error (in km) from T-80 model for 24 hr, 48 hr and 72 hr forecasts for 6 tropical cyclones of North Indian Ocean during 1995-96 with and without bogus vortex in the initial field. It has been seen that the position of the initial vortex in the operational analysis is out be several km in most of the cases. These displacements in some of the cases were as much as 500 km. The large errors of track prediction of tropical cyclones using operational model, are largely attributed to initial vortex problem. The model run with bogus vortex in the initial field, reduced these errors and hence improvement in the forecast errors.

4. Tropical cyclone track forecast by operational centres: Consensus forecast

Consensus tropical cyclone track forecasts using TC track forecasts from regional and global models are becoming increasingly popular in recent years. The two major Tropical Cyclone operational centers in US *viz*., National Hurricane Centre (NHC) and Joint Typhoon Warning Centre (JTWC) have been using this method of TC forecast guidance for past few years (Goerss *et al*., 2004). Forecasters at NHC routinely utilize consensus forecast aids (*e.g*., GUNA) formed using the interpolated TC forecasts from GFDL model (GFDI) and the Global

TABLE 5

Mean error (in km) from T-80 model for 24 hr, 48 hr and 72 hr forecasts for 6 tropical cyclones of North Indian Ocean during 1995-96 in the operational and Bogus runs

24 hr FCST		48 hr FCST		72 hr FCST	
OPR	BOG	OPR	BOG	OPR	BOG
429	132	759	418	902	594

Forecast System (AVNI) run at NCEP, the Navy Operational Global Atmosphere Prediction System (NOGAPS) and the UK Meteorological Office global model (UKMO). A second consensus aid (CONU) was also developed using interpolated TC track forecasts from the GFDL model (GFDL, Rennick, 1999) run at FNMOC along with those from the aforementioned models. The average track forecast errors for 2001-03 Atlantic hurricane seasons using CONU were of the order of 61 nm, 112 nautical miles (nm), 165 nm, 214 nm and 271nm for 24, 48, 72, 96 and 120 hour forecast periods respectively. As expected, these errors were relatively much less compared to the errors from individual models. The JTWC's consensus aid utilizes interpolated version of 8 models: NOGAPS, UKMO, JMA, NCEP, MM5 (run by US Air Force), GFDL (GFDL model run by FNMOC using NOGAPS) and COAMPS. Table 6 shows track forecast errors for the NW Pacific for the 2002 season upto September. The range of forecast errors for the individual models are also shown in the table. It is interesting to note that consensus forecast errors are much lower than the lowest errors from individual models.

5. Current international operational & research issues and future directions

Developments in data assimilation and numerical models will continue, independent of the TC forecast problem. Ongoing improvements to 3D and 4DVAR

TABLE 6

Mean forecast track errors (km) for the NW Pacific upto September 2002 for consensus of 8 models and for individual models

Forecast duration (hrs)	24	48	72	96	120
Consensus Error (km)	128	216	289	387	503
Range of individual model errors (km)	140-181	240-303	335-459	435-527	592-666

assimilation methods (Zou *et al*., 2001), with the inclusion of new data sources, and the use of physical initialization procedures (Krishnamurti *et al*., 1997) will continue to produce improvements in the definition of the large scale environment and outer structure of storms (and hence in track forecasts). For those basins fortunate enough to have aircraft reconnaissance, availability of dropsonde data and eventually advanced NWP targeting strategies should result in further significant improvements in track forecasting (Aberson and Franklin, 1999).

The question of vortex specification remains open. Its use is possibly dependent on the application. For short-term track and intensity forecasts it would seem to be necessary in the near future. For longer-term forecasts it may not be required and may even have a negative impact. Careful diagnosis of its impact on short to medium range prediction should be undertaken. With increases in resolution, the question also arises of how much real TC structure can or needs to be represented in initial conditions. The issue of vortex initialization (Zou and Xiao, 2000), particularly for intense storms, and even without a synthetic vortex, will become increasingly important and needs to be studied.

Some of the priorities of US Weather Research Program on tropical cyclones are : to reduce landfall track and intensity errors by 20%, increase warning lead-time to 24 hours and beyond with 95% confidence, make skillful forecasts of gale force wind radii out to 48 hours with 95% confidence, extend quantitative precipitation forecast to 3 days and improve skill of day-3 forecasts to improve inland flooding and finally to extend track forecasts to 5 days with an average error less than 250 nautical miles (Willoughby *et al*., 2005).

The Weather Research and Forecast model (WRF) is being developed as part of collaborative effort between National Centre for Atmospheric Research (NCAR), USA; Operational Centres such National Centre for Environmental Prediction (NCEP), Forecast systems laboratory and the Air Force weather agency; and Government laboratories and universities to produce meso-scale model that can be used both operationally and for research. The WRF for Tropical Cyclone known as Hurricane WRF (HWRF) is part of this most important developmental work. A large number of groups in USA and outside are working on Hurricane WRF project. The focus of the project includes developing very high resolution model suitable for hurricane core, advanced data assimilation, and appropriate physics suiting to high resolution.

6. Priorities for Indian region

The fact that trend of error reduction in the Indian region is far slower than that over rest of the world, calls for setting up priorities on various research & operational issues on urgent basis. The data scarcity over the Indian Ocean and adjoining region poses a major problem in defining the large-scale flows associated with tropical weather systems. The simulation of large scale flow and associated rainfall prediction by NCMRWF assimilation-forecast system were compared to that of other major operational Numerical Weather Prediction (NWP) centers (Basu *et al*., 1999). The study revealed that although most of the large-scale monsoon features are captured well, yet the predicted rainfall is under-estimated compared to observations and predictions by other NWP centers. Various studies have already shown that quality initial analysis over data sparse region has an important role in defining the initial vortex.

In the Indian region, the availability of both conventional and non-conventional data has been the major issue. There has been no aircraft reconnaissance flight or drop-sonde observation over the region for tropical cyclone probing. Indian region needs to have a NEXRAD type network of Doppler Radars along east and west coasts of India and also over the coastal areas of the adjoining countries. The data from these radars could be used for advanced data assimilation system in real time. At present such radars are available only at 4 locations in India *viz*., Kolkatta, Machilipatnam, Sriharikota and Chennai and one location in Bangladesh *viz*., Dhaka. A set of crucial observations over the data void ocean region is being planned for future series of India's satellites such as INSAT-3D, Oceansat and Meghatropiques. It is expected that by using these data in the advanced data assimilation system, considerable improvement in the model analysis could be achieved which may lead to significant decrease in forecast errors. However, concurrent to the improvement of model analysis, concerted efforts are required to improve model resolution and physics. These developments could lead to phenomenal reduction in forecast errors in the region in the years to come.

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