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Medium range prediction of tropical cyclogenesis of intense vortices over Indian Seas by a Global Spectral Model

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सार — वर्ष 1995-96 कीं अवधि के दौरान, हिन्द-महासागर में बने छः उष्णकटिबंधीय चक्रवातों के बनने की प्रागुक्ति करने के लिए, राष्ट्रीय मध्यावधि मौसम पूर्वानुमान केन्द्र, नई दिल्ली में प्रयुक्त ग्लोबल स्पेक्ट्रन मॉडल (T-80) के कार्य निष्पादन का मूल्यांकन किया गया है। यह पता चला है कि इस मॉडल में, वायु क्षेत्र में चक्रवात वनने की प्रागुक्ति, कम से कम 72 घंटे पूर्व करने की क्षमता है। तथापि कुछ मामलों में विश्लेषित भ्रमिलताओं की तुलना में पूर्वकथित भ्रमिलताओं की अवस्थितियों में विस्थापन पाया गया है। चक्रवातों के बनने के लिए अनुकूल वायुमंडलीय हालातों के मात्रात्मक आकलन से मॉडल से प्राप्त हुए चक्रवातों के बनने से संबंधित पूर्वानुमानों के मात्रात्मक विश्लेषणों की चक्रवातीय परिसंचरण के आभास के रूप में पुष्टि होती है। इस विश्लेषण से यह भी पता चलता है कि वायु और संहति क्षेत्रों के तदनुरूपी विश्लेषण की तुलना में चक्रवात बनने की परिस्थितियों के प्रामुक्त परिसंचरण सामान्यतः अधिक तीव्र तथा प्रवल होते हैं। प्रामुक्ति की मॉडल क्रमबद्ध त्रुटियों की जाँच करने पर यह पता चला है कि यह मॉडल चक्रवातों के उत्पन्न होने तथा उसके मन्द पड़ जाने की अवस्थाओं की अवधि में और अधिक तीव्र भ्रमिलता की अवस्था में प्रामुक्ति करने के लिए अधिक प्रभावी है। इसके अलावा यह मॉडल तीव्रीकरण की प्रक्रिया के दौरान अपेक्षाकृत भ्रमिलता की कम तीव्रता की प्रामुक्ति करता है।

ABSTRACT. The performance of a Global Spectral Model (T-80) operational at the National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi in predicting the cyclogenesis of six tropical cyclones over Indian Seas formed during 1995-96 has been evaluated. It has been found that the model has the capability to predict cyclogenesis in wind field at least 72 hours in advance although the positions of predicted vortices are seen to be displaced from those of analysed ones in some cases. The quantitative estimates of the atmospheric conditions favourable for cyclogenesis also confirm the conclusions drawn from the qualitative analysis of cyclogenesis predictions of the model in terms of appearance of cyclonic circulation. It also follows from this analysis that the predicted circulations at the cyclogenesis stage are in general more intense and stronger as compared to the corresponding analysis in terms of wind and mass fields. On examining the model systematic errors of prediction it is found that the model has a clear bias for predicting more intense vortex during genesis and weakening stages. On the other hand it predicts relatively less intense vortex during intensification process.

Key words - Global Spectral Model, Optimum, Cyclogenesis, Vortex.

1. Introduction

One of the most outstanding problems of tropical cyclone prediction is to adequately understand and explain the process of tropical cyclogenesis. Our knowledge of the dynamics and structure of mature cyclones has grown, aided by extensive observational analysis and numerical models. However, understanding of the initiation or genesis of the tropical cyclones remains incomplete and speculative. Tropical cyclones have long been observed to develop from pre-existing tropical disturbances (Riehl 1954). Such disturbances generally have persisted for at least a day or two and have active deep cumulonimbus clouds associated with them. Interestingly, as far as operational cyclone work is concerned, the cyclogenesis of tropical disturbances is not considered as important as compared to the track prediction mainly because of the fact that the process of transformation of a tropical disturbance into a tropical cyclone with damaging winds a generally very slow, typically over a period of several days. On the other hand, the intensification of a tropical storm into an intense tropical cyclone can occur within 12-24 hours. Moreover, the area of cyclogenesis is normally much away from the area of interest in the data sparse tropical ocean/seas and therefore enough lead time is available for the cyclone forecaster to watch its further development till it intensifies into a tropical depression.

Intensification of tropical disturbances takes place under certain favourable environmental conditions. Continuous lowering of central pressure results in increase in inward pressure gradient which not only maintains the tropical cyclone, but intensify it, provided there is sufficient evaporation of warm ocean water, deep convective clouds and low vertical wind shear.

Riehl (1954) reviewed early pioneering work on tropical cyclogenesis. Riehl and Malkus (1961) recognize the release of latent heat in deep cumulonimbus convection as the primary energy source for tropical cyclones. The basic mechanism which provides sufficient moist static energy for sustained deep convection, is evaporation from ocean surface. The tropical cyclones, therefore requires a very warm ocean surface and deep cumulonimbus clouds in order to overcome dissipative forces and intensify. Charney and Eliassen (1964) introduce the concept of CISK (Conditional instability of the Second Kind). CISK refers to the growth of weak cyclonic disturbances resulting from low-level frictional convergence (Ekman pumping) which supplies ample water vapour necessary for the disturbance to sustain deep convective clouds. McBride and Zehr (1981) show large differences in the low-level (900 hPa) relative vorticity between composites of pre-tropical storm disturbances and non-developing cloud clusters. Gray (1968), Zehr (1976), and more recently, Lunney (1988) have shown importance of small vertical wind shear through a deep tropospheric layer and the process of ventilation for the development of cyclogenesis. Various case studies suggest that low-level external forcing in the form of wind speed maxima penetrating the circulation of a pre-existing disturbance may initiate tropical cyclogenesis (Lunney 1988, Zehr 1989). Such features are referred to as surges.

Beginning with the work of Kuo (1965) and Ooyama (1969), there have been many studies involving numerical models of tropical cyclones. Anthes (1982) includes a thorough review of tropical cyclone modelling. The numerical simulation often include the early stages of tropical cyclones and therefore are pertinent to tropical cyclogenesis studies. However, the interpretation of the modelling research must also be subject to distinction between cyclogenesis and intensification. Many numerical model simulations begin with initial conditions which are unrealistic with regard to cyclogenesis processes, but may be applicable to intensification. Undoubtedly, recent improvement in numerical models and available data initialization, show great promise in their applicability to tropical cyclogenesis.

A tropical disturbance passes through various stages of intensification before it attains a hurricane intensity. The obvious question that can be raised is : At what stage the cyclogenesis occurs? Is it at the stage of a low level cyclonic circulation? or a tropical depression? or can it be at the stage of a tropical storm? The conceptual model of tropical cyclogenesis defines two distinct stages of cyclogenesis (Zehr 1992). The beginning of Stage 1 marks the onset of the enhanced convection associated with early convective maximum and formation of a low level circulation with a distinct center. It is at the end of Stage 1 and the beginning of Stage 2 that a tropical depression forms. The end of stage 2 is marked by the formation of a tropical storm. It is at this stage that the process of tropical cyclogenesis is said to be completed. Further evolution to a mature severe cyclonic storm is attributed to the intensification process.

The numerical models often do not capture the early stage of cyclogenesis and are more suited to intensification processes. No numerical models have yet adequately simulated the important detailed changes which take place during genesis (Gray 1979). However, recent improvement in the numerical models in terms of improved physics and resolution have shown good promise in this direction. The aim of this paper is to evaluate performance of a Global Spectral Model (T-80) in predicting the first stage of cyclogenesis (the formation of a tropical depression) and present quantitative estimates of favourable environmental conditions in the T-80 analyses and forecasts.

2. The model and data assimilation

The National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi was established and dedicated to the nation in March, 1989 with the major objective of developing medium range weather prediction models for monsoon region and agrometeorological advisory services for the farming community in India. With the supercomputing facility available at Centre, it became possible to run a Global Spectral Model for operational weather prediction for the period of 3 days and beyond. The global data assimilation and forecasting system of the NCMRWF are adapted from the National Centre for Environmental Prediction (NCEP) previously known as National Meteorological Centre (NMC), Washington, D.C, USA. The Medium Range Analysis Forecast System (MAFS) of the NCMRWF consists of (*i*) data processing, quality control and non-conventional data utilisation, (*ii*)data assimilation, (*iii*) model integration, (*iv*) post processing and diagnostics and (*v*) preparation of location specific forecasts for agrometeorological advisories.

2.1. *Analysis scheme*

A global spectral interpolation (SSI) scheme of analysis is used for preparing initial data sets for forecast model. Details of the scheme are given in the studies of Parrish and Derber (1992); Bansal *et al.* (1994). In this scheme observational residual (observation-first guess at observation location) are analysed in spectral space. The analysis variables used in the current version of the SSI are the sigma level spectral coefficients of the amplitudes of empirical orthogonal functions of vorticity, unbalanced part of divergence, unbalanced temperature, unbalanced log of surface pressure and the specific humidity. The distinction of balanced and unbalanced variables is way of implicity including a linear balance relationship. The basic concept of SSI is to minimise an objective function defined in terms of deviations of the desired analysis from the first guess field, which is taken as the six hour forecast, and the observations, weighted by the inverse of forecast and observation errors respectively.

One significant feature of the scheme is that the analysis variables are closely related to the most commonly used variables in the operational models like sigma level coefficients of spherical harmonic expansions of vorticity, divergence, temperature, log of surface pressure, and the specific humidity. It makes use of forecast error covariance in spectral space. Since the analysis variables in this scheme are defined spectrally, the analysis is carried out as a single global problem and not approximated locally as is done in multivariate optimum interpolation (OI). This has a major advantage of not producing discontinuities in the solution resulting from the data selection procedure required in the grid point by grid point approximation used by traditional optimum interpolation. It is known that there is no well-defined mass-wind relationship over tropics, unlike the geostrophic relationship which determines the extra-tropical flow. The SSI incorporates the mass and wind balance in the analysed fields by the appropriate choice of analysis variables. Since the analysis variables deal with the sigma levels and they are closely related to the model variables, it reduces the scope of losing information between the final analysis output and the model input field. It has been shown by Parrish and Derber (1992) and also by Bansal *et al.* (1994) that the analysed increments in SSI are smooth and it gives a better root mean square fit to the observations than OI. Further, it was found that the mass and motion fields are more balanced in this case and initialization changes the analysed fields to a much lesser extent compared to OI especially in tropics. As such initialization steps has been removed from the present scheme. An interesting feature of SSI is that it is possible to use any type of observation as long as it can be derived in terms of the model variables.

2.2. *Forecast model*

The forecast model is based on the primitive equations for vorticity, divergence, virtual temperature, log of surface pressure, and the specific humidity. These equations include horizontal and advection terms, forcing terms and diabatic heating source/sink terms, which represent physical processes. The model uses the spectral method of horizontal representation of variables and the finite difference representation in the vertical having 18 equal spaced levels cast on terrain following sigma coordinate system. The horizontal resolution of the model is 80 waves represented in triangular truncation, in gaussian grid representation there are 256 grid-points in east-west and 128 in the north-south which corresponds to roughly 160 km. The model has the state of art physical parameterization packages. They include deep cumulus convection of Kuo type, large scale heating in a stably stratified environment, the surfaces layer based on stability dependent bulk aerodynamic, in planetary boundary layer above the surface layer, the eddy transport is formulated by use of Richardson number dependent vertical diffusion process. The radiation parameterization is treated separately for short and long wave computations. Diagnostic cloud scheme based on predicting relative humidity, vertical motion and convective rain is also included for computing interactive clouds for radiation computations.

The mountains are represented as resolved mean orography at the model resolution. The mean monthly climatological fields of vegetation cover index, roughness length, soil moisture, snow cover, and the sea surface temperature are used as lower boundary conditions during the time integration of the model. The details of various aspects of the model are documented in Sela (1980), Kanamitsu (1989) and Kanamitsu *et al.*(1991).

The current MAFS is operational from 1st June 1994 to produce regularly 5-days global forecasts.

3. Prediction of cyclogenesis by T-80 model

There were total 6 cyclonic storms over the north Indian Ocean, 3 each in 1995 and 1996 during non-monsoon months (pre-and post- monsoon seasons: April-May and October-December). Out of these, 2 formed in the Arabian Sea and 4 in the Bay of Bengal. All these storm are taken for the present study for evaluating performance of T-80 model in predicting the first stage (formation of a tropical depression) of cyclogenesis. Fig.1 gives the best-fit tracks of all these six storms. For the present study, the cyclogenesis in the model analysis and prediction is taken as a clearly identified closed cyclonic circulation in the lower tropospheric level (here 850 hPa) within the inter-tropical convergence zone (ITCZ) over the Bay of Bengal or Arabian Sea. Though, the above definition appears to be too inadequate to clearly separates out cyclogenesis of developing and non- developing cases, yet, it undoubtedly depicts the model's capability to capture such feeble cyclonic circulations in its analysis and forecast fields. Some quantitative estimates of favourable atmospheric conditions for cyclogenesis have also been presented to substantiate model prediction of cyclogenesis.

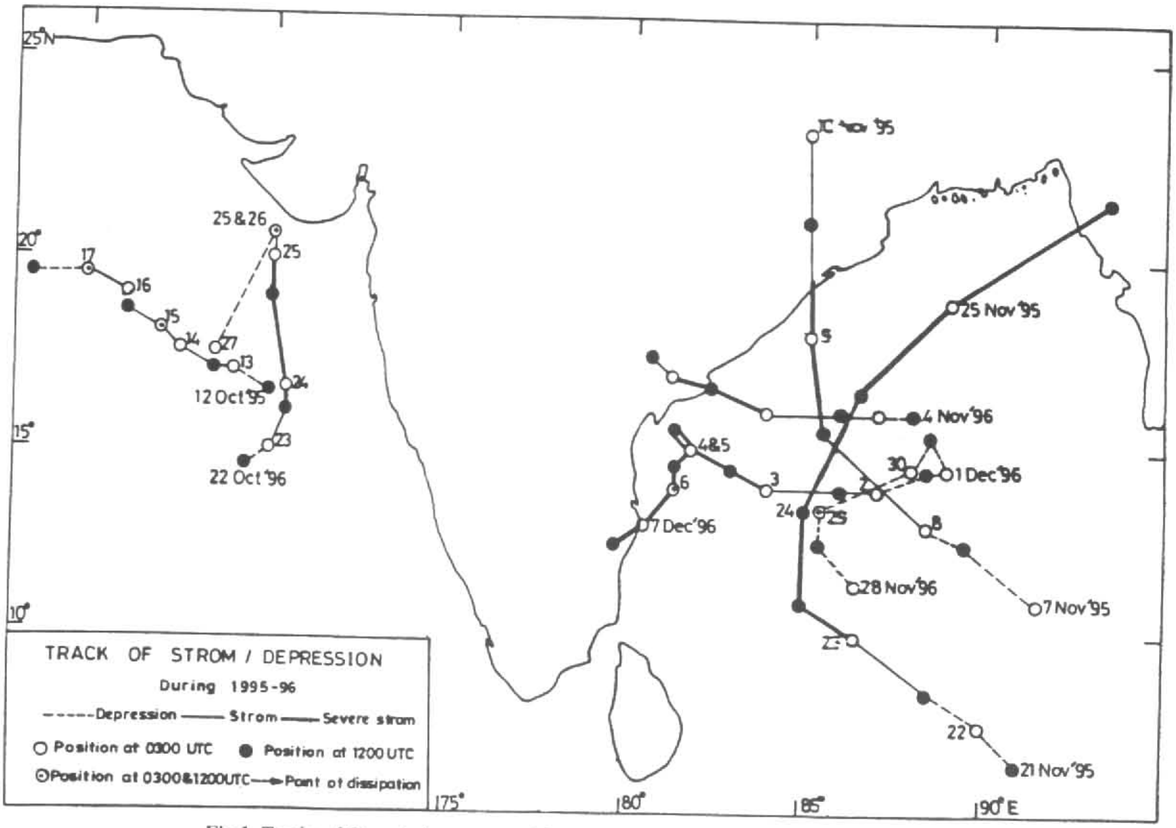


Fig.1. Tracks of 6 tropical storms considered for study during 1995-96 over Indian Seas

3.1. *Qualitative prediction of cyclogenesis in terms of cyclonic circulation in the wind field*

(a) *Arabian Sea Cyclone of 14-17 October 1995*

The genesis of the cyclone took place from a well marked low pressure area which moved across central peninsula and emerged into the Arabian Sea on 12 October 1995. In order to evaluate model performance in predicting the genesis of the system, 850 hPa wind and contour fields for 24, 48 and 72 hr predictions valid for 00 UTC of 12 October are chosen for comparison with the analysis valid for 00 UTC of same day (Not shown). It may be noted that all the three predictions show a well defined cyclonic circulation and their positions are closely matched with that in the analysis. While 24 and 48 hr predicted circulations are located nearly over the same place as in the analysis. 72 hr prediction shows center of the circulation close to land and the shape of the circulation somewhat elongated extending from central Arabian Sea to central peninsula. It is seen that predicted circulations have associated minimum contour value of the geopotential heights 4-11 m lower than that in the analysed circulation. This shows that the predicted circulations are slightly more intense compared to analysed one. A close examination of the wind fields associated with the circulations, however, shows that the winds in the analysed circulation, especially in the northwestern sector, is stronger compared to those in the predicted ones.

(b) *Bay of Bengal severe cyclonic storm with a core of hurricane winds of 7-10 November 1995*

The system had its origin in the south central Bay of Bengal as a depression in the morning of 7 November, 1995. The prediction of its genesis in the model has therefore been verified for 00 UTC of this date. Figs. 2(a-d) show 850 hPa wind and contour fields in the analysis, 24, 48 and 72 hr forecasts valid for 00 UTC of 7 November 1995. It may be seen that the circulation in the model analysis is poorly defined with a broad circulation extending over the entire south Bay of Bengal. On the other hand, the predicted circulations, especially in 48 and 72 hr, are much stronger and intense both in the wind and contour fields. The associated minimum value of geopotential heights in the 48 and 72 hr forecasts are 1447 m and 1458 m respectively as compared to 1480 m in the analysed and 24 hr predicted circulations. Wind fields, particularly in the northern sector, were quite strong in the circulations of 48 and 72 hr forecasts as compared to those in the analysis and 24 hr forecasts. The positions of the vortex in the 48 and 72 hr forecasts were slightly to the west of those in the analysis and 24 hr forecast.

(c) *Bay of Bengal severe cyclonic storm with a core of hurricane winds of 21-25 November 1995*

This storm had emerged into the south-east Bay of Bengal from the east and concentrated into a depression at 1200 UTC of 21 November 1995. In order to examine the model's capability to predict its genesis, the analysis, 24, 48 and 72 hr forecasts valid for 00 UTC of 21 November were chosen. Similar to earlier cases, the predicted vortices appear to be much more intense and strong as compared to the one in the analysis. The wind fields, particularly in 48 hr forecast, are very strong in the forecasts as compared to analysis. The associated winds are reaching upto 20-30 m/s in 48 hr forecast. The contour fields are also very deep in the forecasts. The minimum value of geopotential heights associated with the vortices in the forecasts are 30-60 m lower than that in the analysis. The position of the circulations in the forecasts, especially in 48 and 72 hr, are slightly to the west of analysed position. It may be mentioned that the positions of the initial vortex in the model analyses beginning from 21 to 24 November 1995 were very much south of the best-fit positions.

(d) *Arabian Sea severe cyclonic storm of 23-28 October 1996*

This system had originated from the remnant of a low pressure area which moved from the Bay of Bengal. The system emerged into the central Arabian Sea and developed into a depression by mid- day of 22 October 1996. It is noted that the positions of the vortex in all the three forecasts are in good agreement with that of analysed one, although the orientation of the wind and contour fields is somewhat different in each of these forecasts as compared to analysis. The strength of winds associated with the circulation in the forecasts is also agreeing well with that in the analysis. However, the minimum geopotential heights associated with the predicted vortices are 3-12 m lower than that in the analysis.

(e) *Bay of Bengal severe cyclonic storm with a core of hurricane winds of 4-7 November 1996*

The system had its genesis as a depression in the central Bay of Bengal around 1500 UTC of 4 Nov, 1996. The analysed circulation is very weak and extending over entire central and north Bay of Bengal. The model forecasts upto 72 hr valid for the same date shows relatively weaker circulation as compared to analysed one. Wind fields associated with analysed vortex were upto 10-15 m/s, especially in the northwestern sector. On the other hand wind fields in the 48 and 72 hr predictions show maximum winds of the order of 5-8 m/s only. Similarly, the contour fields in the forecasts were relatively poorly developed as compared to that in analysis. These results are in contrast with those of earlier cases discussed in the section in which both wind and contour fields were relatively stronger in the forecasts as compared to analysis.

(f) *Bay of Bengal severe cyclonic storm with a core of hurricane winds of 28 November-6 December 1996*

This system originated as a well marked low pressure area in the evening of 27 November 1996. For verifying model prediction for the genesis of the system, the analysis and forecasts upto 72 hr for the 850 hPa wind and contour fields valid for 00 UTC of 27 November were chosen. It is observed that the wind fields associated with the circulation are quite diffused and broad in the analysis. One can however, identify a weak circulation within the east-west shear line extending from the south central Arabian Sea to the south-east Bay of Bengal along 6°N latitude. The positions of the vortex in the 24 to 72 hr forecasts are more or less agreeing with the analysed position. However, the wind and contour fields in the forecasts are much stronger and well defined as compared to those in the analysis. The minimum value of geopotential heights in the forecasts are 3-18 m lower than that in the analysis.

These results clearly demonstrate that the T-80 model has the capability to not only capture the initial vortex in the analysis, but also to predict its genesis at least 72 hr in advance. The fact that the Bay of Bengal and the Arabian Sea are nearly data void regions with almost negligible upper air soundings and meagre surface data coverage, these results assume considerable importance for the operational cyclone forecasters and numerical modelers. The above analysis also shows model bias for more intense vortex in the prediction as compared to the analysis in most of the cases.

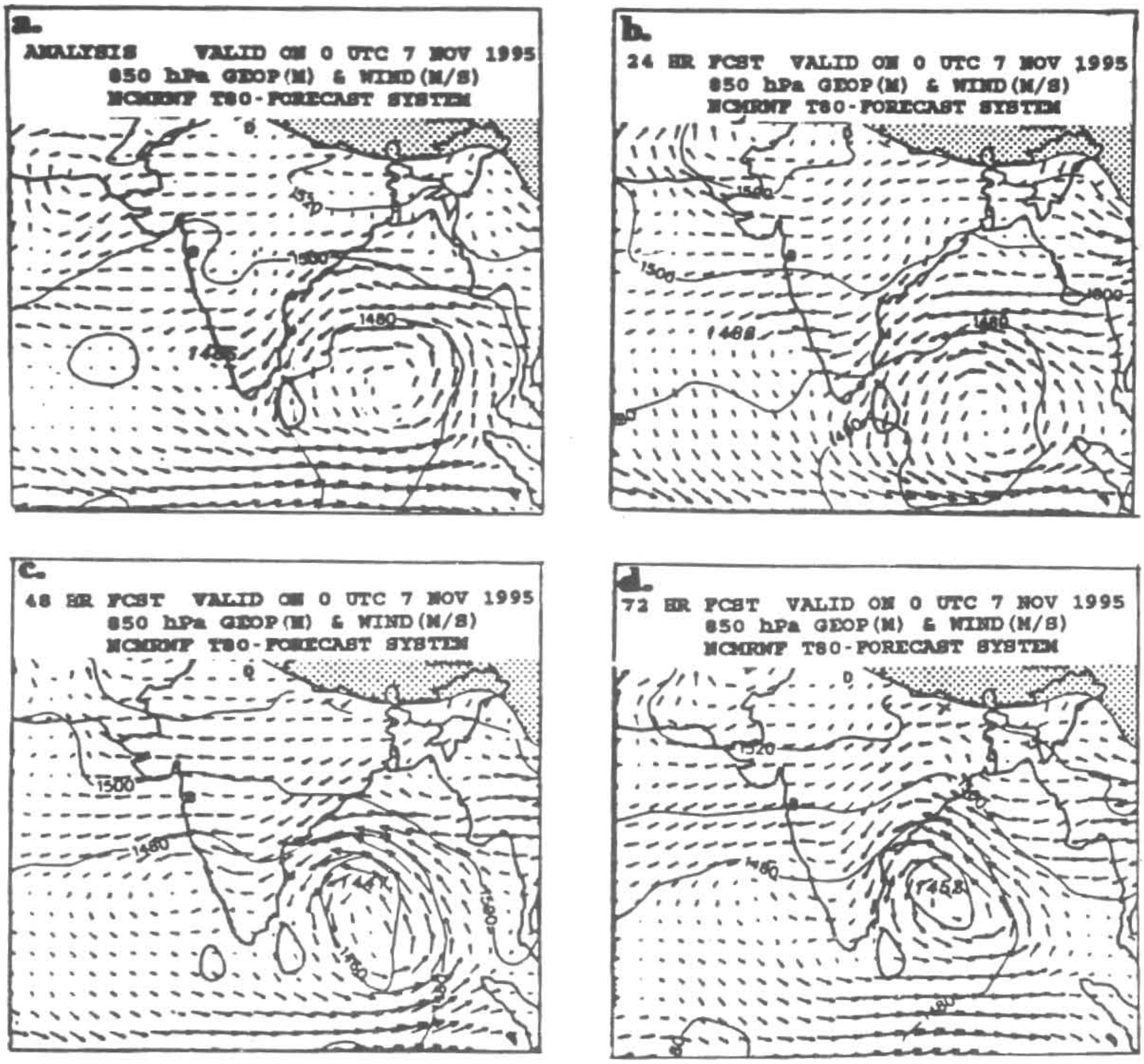
3.2. *Quantitative estimates of cyclogenesis prediction by the model*

The section 3.1 describes the qualitative analysis of cyclogenesis observed in the analysed and predicted wind field associated with 6 storms. However, such analyses are not adequate enough to establish and study the performance and capability of the model in predicting the process of cyclogenesis. In order to study this in detail, the quantitative estimates of different dynamical variables such as relative vorticity, divergence, total precipitable water content, specific humidity, temperature, etc., are computed and analysed. For the sake of brevity, discussion relating to only one case (Bay of Bengal storm of 7-10 November 1995) is presented in this section as almost similar results are observed for other cases.

3.2.1. *Distribution of certain dynamical and thermodynamical parameters*

(a) *Wind field*

Figs. 3(a & b) show the 850 hPa analysis and 72 hr predicted wind distribution valid for 00 UTC of 7 November 1995. Isotacks of 5, 10, 15 m/sec are drawn and the areas with wind speed 10 m/sec or more are hatched. It may be seen that both in the analysis and forecast, winds are stronger to the north of the circulation center. The winds are however,



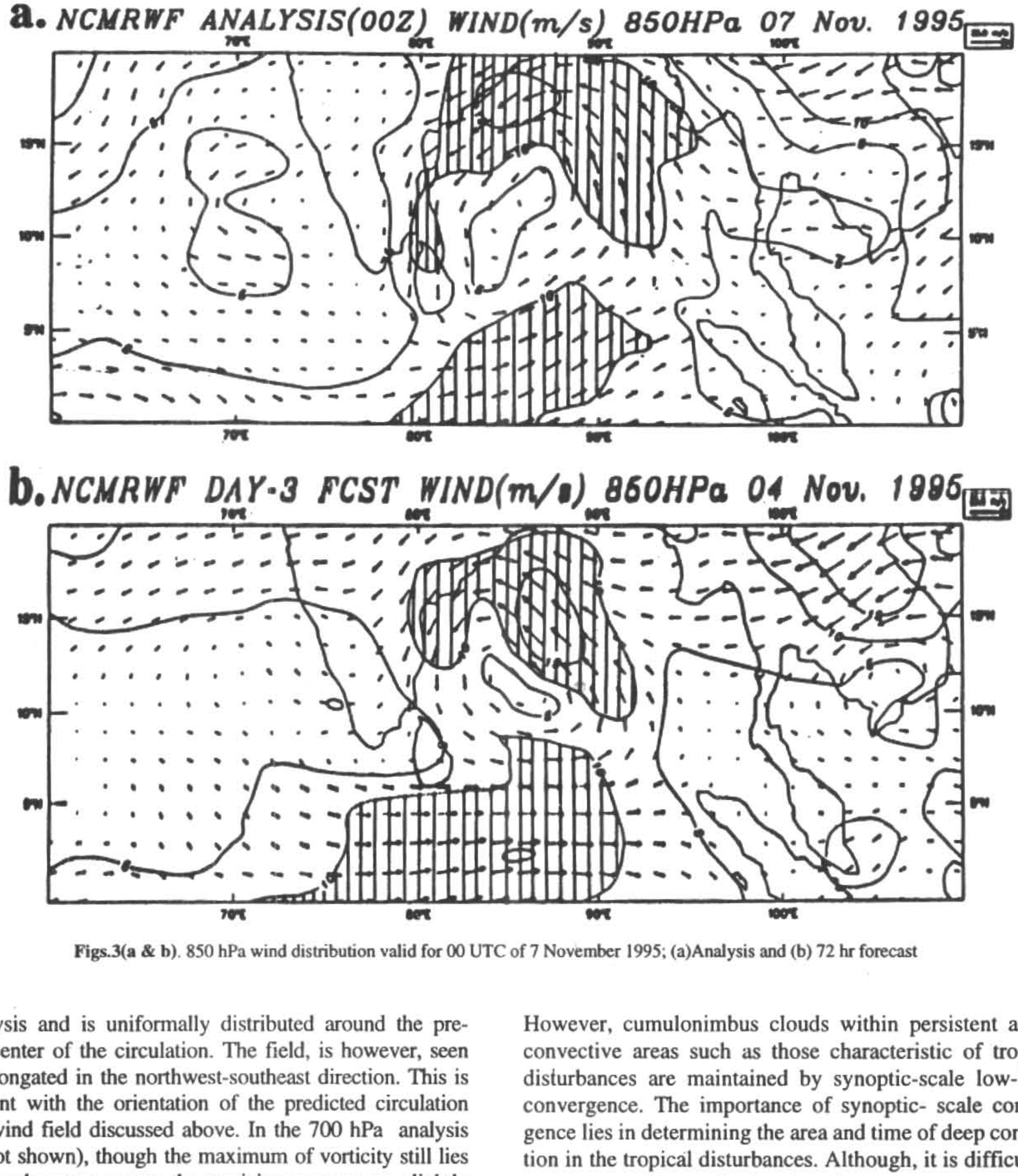
Figs.2(a-d). 850 hPa wind and contour fields valid for 00 UTC of 7 November 1995; (a)Analysis, (b)24 hr forecast; (c)48 hr forecast and (d)72 hr forecast

relatively stronger in the forecast compared to those in the analysis. The areas of winds with speed 10 m/sec or more in the analysis are nearly matching with those in the 72 hr forecast. The significant difference between the analysis and forecast fields lies in the fact that in the analysis winds are converging from southern (more precisely southeastern) sector whereas in the 72 hr forecast these are converging from northwestern sector. Moreover, the circulation in the analysis is oriented in the north-north- east to south-south-west direction whereas in the forecast the same is oriented in the northwest southeast direction.

(b) *Relative vorticity field*

Role of synoptic-scale low-level vorticity in the formation of a tropical disturbance is known since long (Riehl 1954). Weak disturbances with small ($<1.0 \times 10^{-5} sec^{-1}$) associated low-level relative vorticity are less likely to undergo cyclogenesis than the stronger ones (Zehr 1992). In addition, disturbances which are moving into an environment with negative low-level vorticity are less likely to undergo cyclogenesis than those moving into a positive relative vorticity area. Therefore, the low-level vorticity is of critical importance to tropical cyclogenesis.

Considering the importance of its role in the cyclogenesis, relative vorticity fields at 850 and 700 hPa are produced for the storm of 7-10 November, 1995 and presented in Figs. 4 (a & b) are the 850 analysis and 72 hr forecast of relative vorticity fields valid for 00 UTC of 7 November 1995. The regions with relative vorticity value $4 \times 10^{-5} sec^{-1}$ or more are hatched. It may be seen that 850 hPa vorticity field in the analysis is relatively weak and its maximum lies in the southeastern sector. In the 72 hr forecast field, however, the vorticity is stronger compared



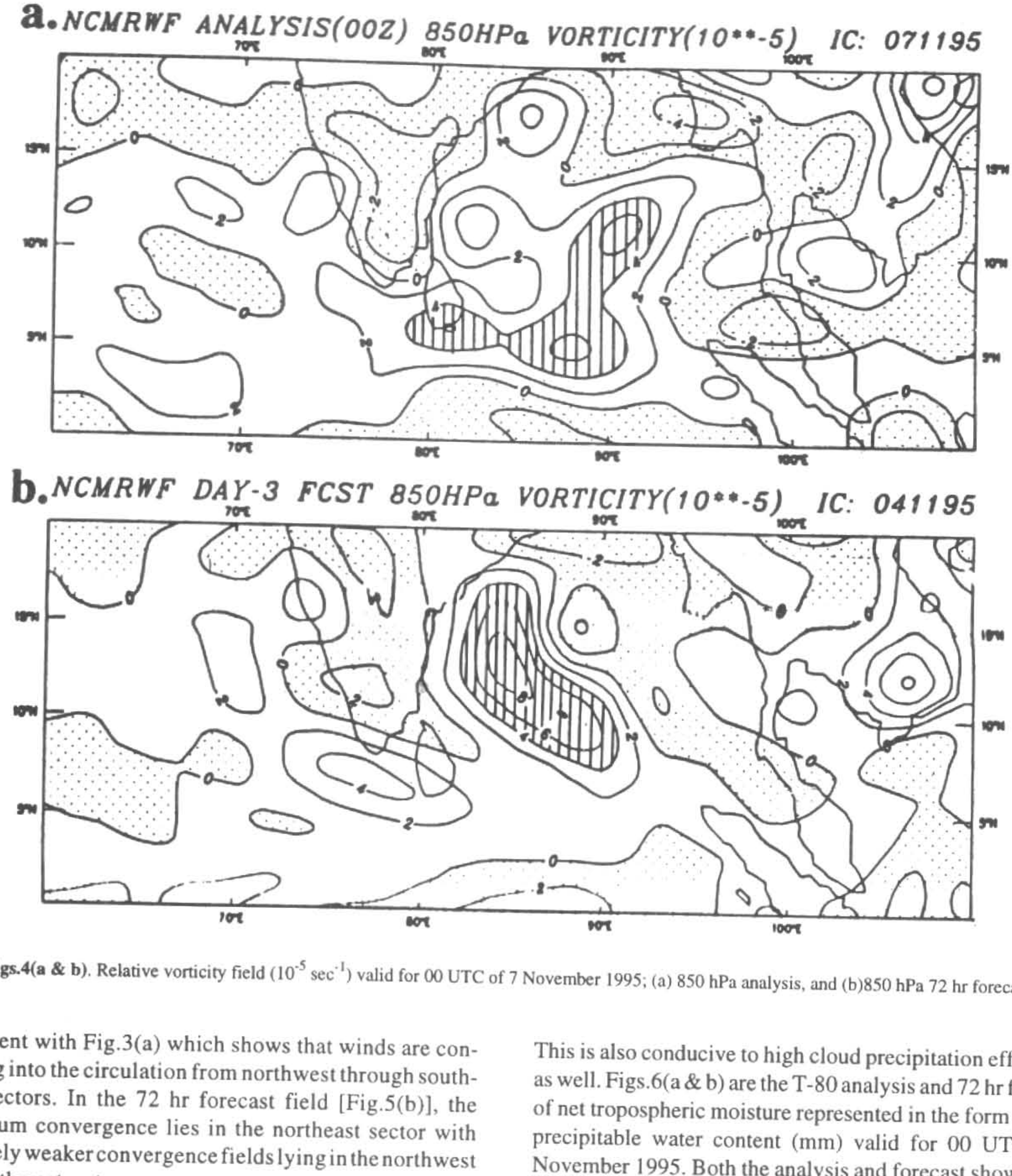
Figs.3(a & b). 850 hPa wind distribution valid for 00 UTC of 7 November 1995; (a)Analysis and (b) 72 hr forecast

to analysis and is uniformally distributed around the predicted center of the circulation. The field, is however, seen to be elongated in the northwest-southeast direction. This is consistent with the orientation of the predicted circulation in the wind field discussed above. In the 700 hPa analysis field (not shown), though the maximum of vorticity still lies in the southeastern sector, the vorticity contours are slightly more organised. However, 72 hr predicted field at 700 hPa shown nearly identical magnitude and distribution of vorticity around the center as observed for 850 hPa.

(c) *Divergence field*

In the tropics, synoptic-scale low-level convergence is generally very small. It is well known that the low-level convergence helps in initiating process of deep convection. Deep cumulus convections commonly observed over warm ocean are initiated by localized low-level convergence. However, cumulonimbus clouds within persistent active convective areas such as those characteristic of tropical disturbances are maintained by synoptic-scale low-level convergence. The importance of synoptic- scale convergence lies in determining the area and time of deep convection in the tropical disturbances. Although, it is difficult to measure small magnitude of such convergence over the tropics, observations show that it is an important forcing mechanism for tropical cyclogenesis (Zehr, 1992).

In order to study its role in the present case, divergence fields are computed and analysed. Figs.5(a & b) are the 850 hpa analysis and 72 hr forecast of divergence valid for 00 UTC of 7 November, 1995. Positive field indicates divergence and negative convergence. Convergence areas are shaded. It may be seen from the above figures that the areas of strong convergence in the analysis lies in the northwest to southwest quadrants. This is

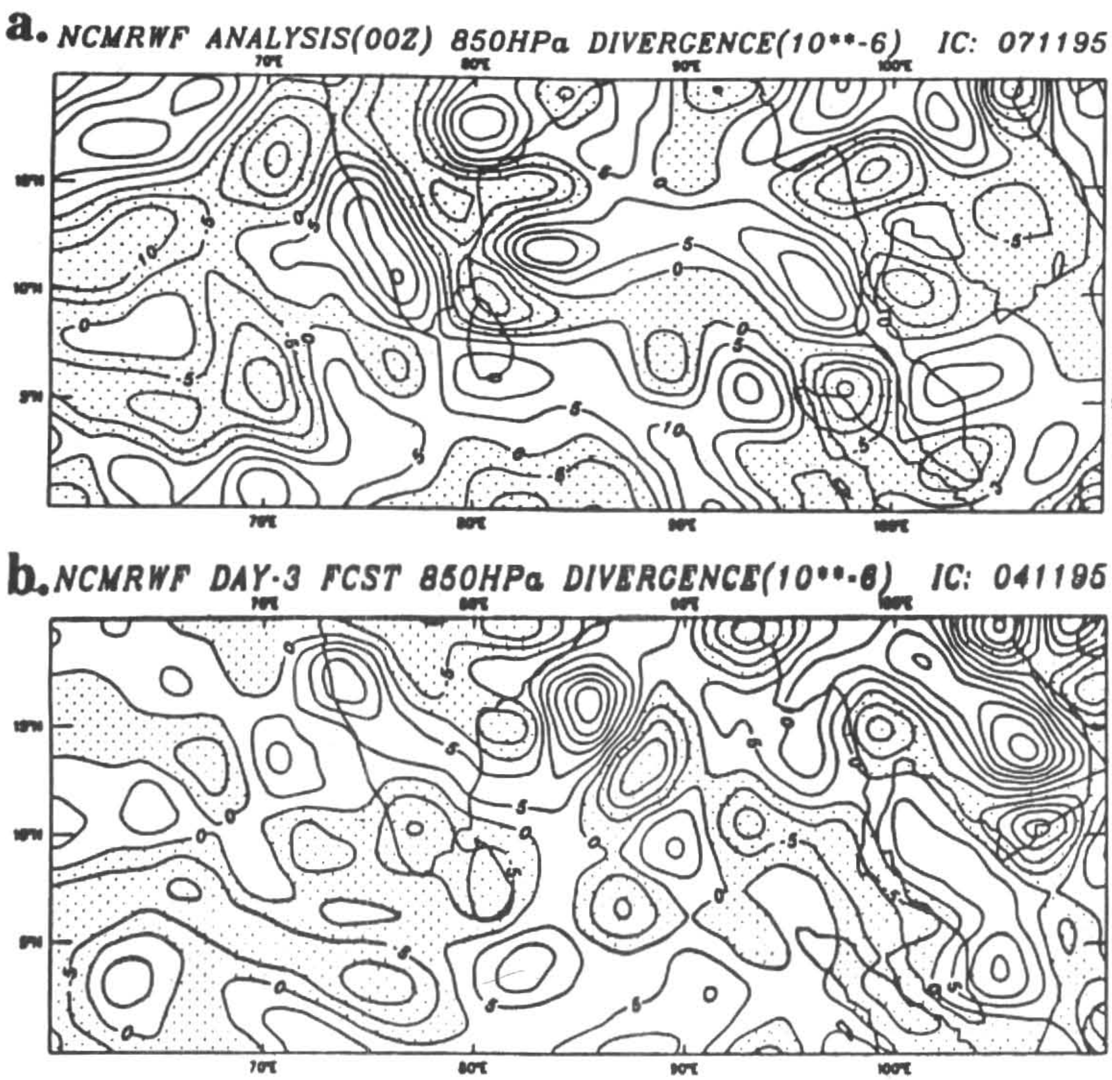


Figs.4(a & b). Relative vorticity field (10^{-5} sec^{-1}) valid for 00 UTC of 7 November 1995; (a) 850 hPa analysis, and (b) 850 hPa 72 hr forecast

consistent with Fig.3(a) which shows that winds are converging into the circulation from northwest through southwest sectors. In the 72 hr forecast field [Fig.5(b)], the maximum convergence lies in the northeast sector with relatively weaker convergence fields lying in the northwest and southwest sectors.

(d) *Moisture field*

The role of moisture in initiating and maintaining the synoptic-scale disturbance is well known. Gray (1979) has demonstrated that the presence of higher than average middle tropospheric level humidity is more conducive for tropical cyclone formation. The high humidity at the middle troposphere adds to the amount of moisture convergence in a given column. This is also related to moist air entainment as it is less growth-inhibiting than the dry air entrainment. This is also conducive to high cloud precipitation efficiency as well. Figs.6(a & b) are the T-80 analysis and 72 hr forecast of net tropospheric moisture represented in the form of total precipitable water content (mm) valid for 00 UTC of 7 November 1995. Both the analysis and forecast show maximum moisture content of the order of 50-55 mm to the south and southwest of storm's center. Large gradient of moisture field is observed in the western sector indicating convergence of relatively less moist winds from the continent. Winds from southern sector are however more moist which is expected due to evaporation from sea surface. However, in the 72 hr forecast, there is another area of high moisture content extending from northeast to southeast of storm's center. The vertical E-W cross-section of specific humidity along storm's latitude (~ 12°N) in the analysis and 72 hr forecast valid for 00 UTC of 7 November, 1995 has been



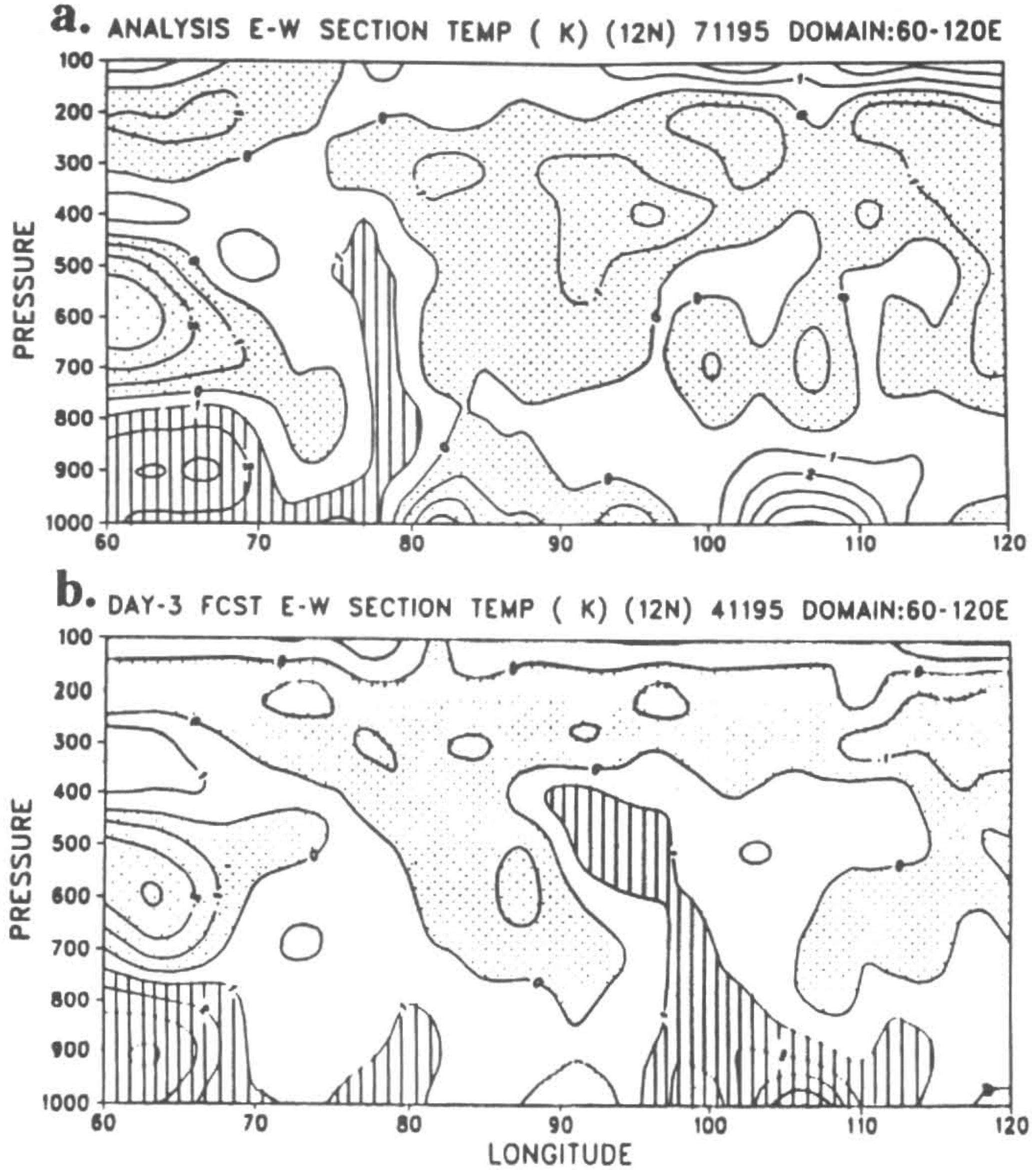
Figs.5(a & b). 850 hPa divergence field (10^{-5} sec^{-1}) valid for 00 UTC of 7 November 1995; (a)Analysis and (b) 72 hr forecast

prepared. Higher values of specific humidity are observed to the west of storm's center where convergence and total precipitable water content are also higher as discussed above. The specific humidity values of 3 gm/kg or more were observed upto middle tropospheric levels. In the lower levels of values upto 24 gm/kg can be noticed. In the 72 hr forecast, high q values are seen both in the western and eastern sectors. This is also consistent with the predicted convergence and net moisture fields which show high convergence in northeastern and northwestern sectors and high moisture content in northeast to southeast of storm's center.

(e) *Thermal field*

It has been shown by several workers that tropical cyclone development is more favoured when the diabatic heating is greater in the lower than in upper tropospheric levels (Yamasaki 1968, Koss 1976, Davies and De Guzman 1979), Kuo (1965, 1974) has demonstrated that the temperature difference between cloud and environment can be taken as vertical form function in the Kuo scheme which in fact redistributes the diabatic heating with a low level maximum. This suggests that the lower tropospheric environment around the low-level cyclonic circulation is expected to be warmer than surrounding for favourable development of the circulation into a tropical cyclone.

Figs. 7(a & b) are the analysis and 72 hr forecast of E-W vertical cross-section of temperature anomaly along storm latitude (~ 12°N) valid for 00 UTC of 7 November 1995. It may be noticed that in the analysis the positive temperature anomaly (warming) of nearly 1°K is observed in a vertical column lying 6-7° lat./long. west of storm center which extends upto middle tropospheric levels. 72 hr forecast on the other

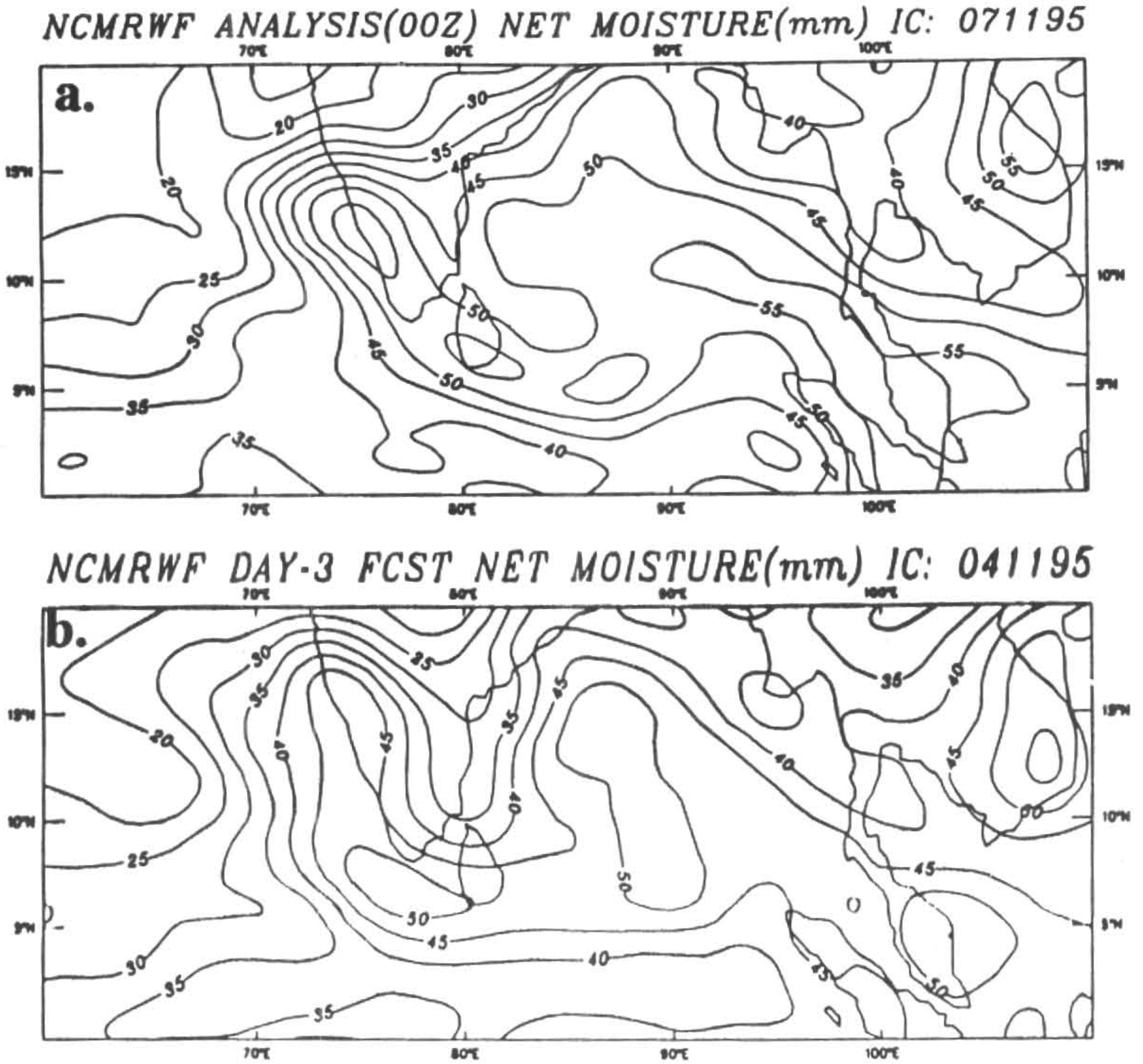


Figs.6(a & b). 850 hPa Net moisture content (mm) valid for 00 UTC of 7 November 1995; (a)Analysis and (b) 72 hr forecast

hand shows relatively more pronounced temperature anomaly to the east of storm center extending upto middle troposphere in addition to weak positive temperature anomaly to the west of storm center which confines to lower troposphere (~800 hPa). An interesting point which emerges from the analysis of these Figures is that both the analysis and 72 hr forecast show warm anomaly to the east and west of the storm center in the lower levels. Middle and upper tropospheric temperature anomalies over the storm center remain largely negative (cooling) in both analysis and forecast.

3.2.2. *Genesis parameter*

A extensive work on physical climatology of tropical cyclogenesis by Gray (1975 and 1979) revealed that there are six most important factors responsible to cyclogenesis. These are: above average low-level vorticity and middle level moisture, conditional instability through a deep layer, a warm and deep oceanic mixed layer, weak vertical wind shear of the horizontal winds and a location at least a low degrees poleward of the equator (a significant value of planetary vorticity). These six parameters are not independent of each other. In the tropics, regions of high sea-surface temperatures are invariably correlated with conditional instability due to the weak horizontal temperature gradients in the middle levels. High humidities in the middle levels also tend to occur in regions with warm waters, and virtually all areas with widespread deep convection are associated with mean ascending motion and are moist aloft. The rela-

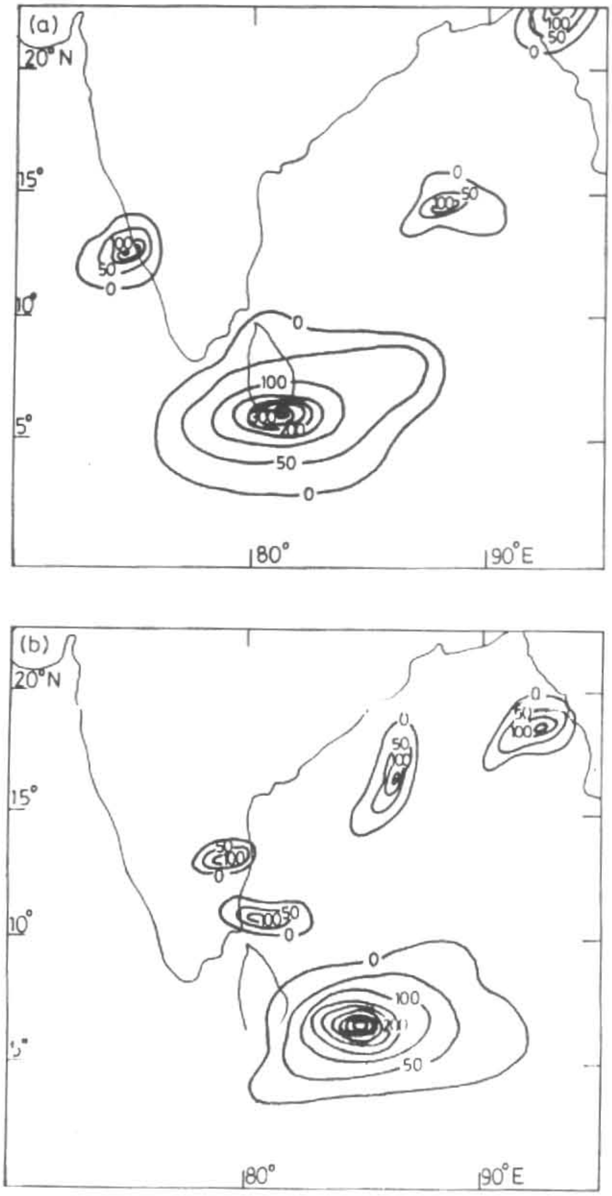


Figs.7(a & b). E-W vertical cross-section of temperature anomaly along 12°N latitude valid for 00 UTC of 7 November 1995; (a)Analysis and (b) 72 hr forecast

tive vorticity and Coriolis parameters can be combined into the absolute vorticity.

Although the above conditions exist over large portions of the tropical oceans for extended periods of time, genesis of cyclones remains a relatively infrequent occurrence. Gray (1975) hypothesized that the cyclones develop only during periods when these conditions are perturbed to values above their regional climatological means. Attempts to apply these criteria to daily forecasting of cyclogenesis have met with little success. McBride (1981) and McBride and Zehr (1981) performed a series of composite and case studies of cyclones in the North Atlantic and north Pacific. Their results indicate that while the thermodynamic conditions necessary for tropical cyclogenesis are commonly satisfied, the formation usually does not occur until a pre-existing convective disturbance moves into a large-scale region with above-average cyclonic vorticity at low-level and anticyclonic vorticity at upper levels. Genesis usually occurs along the line of zero vertical wind shear between regions with stronger shears with opposite signs on either side. Zehr (1992) studied individual cases of cyclogenesis in the Northwest Pacific to differentiate between pre-tropical storms and non-developing disturbances. Five different types of analysed variables were chosen for the purpose. These are : 850 hPa relative vorticity and divergence; 200 hPa relative vorticity and divergence; and; 200- 850 hPa vertical wind shear vector. Noticing the significance of some of these parameters in the initiation of cyclogenesis, he combined three of these five factors to define a quantity known as 'Genesis Parameter' which is given by:

$$GP = (850\ VOR^*).(850\ -DIV^*).(S)$$



Figs.8(a & b). Distribution of Genesis Parameter (10^{-12} sec^{-2}) valid for 00 UTC of 7 November 1995; (a) Analysis and (b) 72 hr forecast

Where,

850 VOR* = 850 hPa relative vorticity (850 VOR), if 850 VOR> 0

850 VOR* = 0, if 850 VOR < 0

Similarly, 850-DIV* = 850 hPa convergence (850-DIV), if 850-DIV >0

850-DIV* = 0, if 850-DIV < 0 (*i.e.*, divergence at 850 hPa)

$$S = \text{Shear Coefficient} = \frac{25.0\ \text{m/s} - (200\text{–}850\ \text{SHEAR})}{20.0\ \text{m/s}}$$

for 5.0 m/s < (200-850 SHEAR)<25.0 m/s

if (200-850 SHEAR) < 5.0 m/s, S = 1.0

if (200-850 SHEAR) > 25.0 m/s, S = 0.0

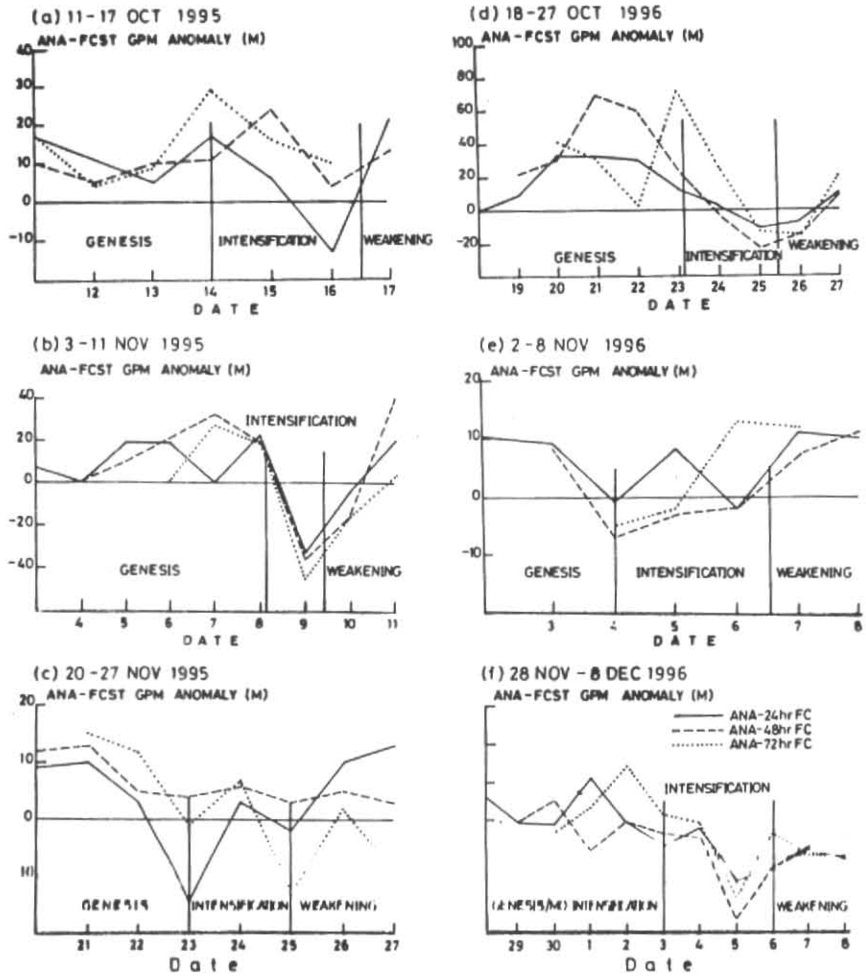
Thus, the genesis parameter (GP) is the product of the convergence and relative vorticity at 850 hPa which is linearly weighted according to the 200-850 hPa wind shear speeds between 5 and 25 m/s. Wind shears greater than 25 m/s reduce the value of GP to zero. The GP is expressed in units of $10^{-12}s^{-2}$.

Figs.8(a & b) are the GP distributions in the analysis and 72 hr forecast valid for 00 UTC of 7 November 1995. An area of highest GP of the order of 400 x $10^{-12}s^{-2}$ can be seen in the region south of Srilanka in the analysis. A comparison with the location of cyclonic circulation in the 850 hPa analysis shows that the highest GP values lies southwest of the position of cyclonic circulation. The possible explanation for the discrepancy may be evident from Fig.3(a) which shows that strong northerlies are converging towards the lower latitude westerlies in the analysis giving rise to strong convergence and high relative vorticity as discussed earlier. There are two more areas with high GP values of 150 x $10^{-12}s^{-2}$, one over the central parts of the Bay of Bengal and other over Karnataka coast. Fig.8(b) depicts GP distribution in the 72 hr forecast valid for 7 November 1995. The highest magnitude of GP of more than 400 x $10^{-12}s^{-2}$ lies over southwest Bay of Bengal. This area of high GP also lies south of predicted cyclonic circulation. As the north sector of the predicted circulation appears to have strong winds converging towards coast, there are four relatively smaller areas with high GP values of the order of 100 to 150 x $10^{-12}s^{-2}$ over Tamilnadu, west central and northeast Bay of Bengal. This is also consistent with the wind, vorticity and convergence fields discussed in previous paragraphs.

Genesis parameter has been computed for other cases of tropical cyclones. The detailed analysis of GP in different cases shows that though individual dynamical parameters used in the computation of GP might be inconsistent with the qualitative analysis of cyclonic circulations discussed in section 3.1, GP distributions appear to be more consistent and are matching closely with the position and intensity of these circulation in the analysis and forecast fields.

3.3. *Systematic errors of T-80 model predictions of mass field in the genesis. Intensification and weakening stages of the tropical cyclones*

As discussed in section 3.1, the predicted vortices in the cyclogenesis stage were in general stronger and more intense compared to analysed ones. It clearly follows from this discussion that there appears to be a systematic bias in the model prediction. The aim of this section is to evaluate this bias quantitatively in the three important stages of the vortices, *viz.*, genesis, intensification and dissipation/weakening in order to accomplish the task, the difference of minimum geopotential heights associated with the vortex in the analysis and forecasts valid for the dates of analysis were obtained in each of the cases. These are plotted against



Figs. 9(a - f). Systematic errors of prediction of mass field (ANA- FCST) in different stages of development of six tropical storms considered for study: (a) 11-17 Oct 1995, (b) 3-11 November 1995, (c) 20-27 November 1995, (d) 18-27 October 1996, (e) 2-8 November 1996 and (f) 28 November-8 December 1996

respective dates of analysis and shown in Figs. 9(a - f). Each of these plots are divided into three parts, *viz.*, genesis, intensification and weakening stages depending on the observed intensity changes in each case.

Fig.9(a) is one such plot for the Arabian Sea cyclone of 14-17 October 1995. It may be seen that throughout the genesis stage till 14 October 1995 (before the system becomes a depression), the Analysis-Forecast (ANA-FC) geopotential heights were positive indicating weaker cyclonic circulation in the analysis compared to forecasts. However, at the beginning of intensification stage on 14 October, though the ANA-FC remained positive, yet the values began to fall. By 16 October, all the three values, *viz.*, ANA-24 hr FC, ANA-48 hr FC and ANA-72 hr FC show lowest magnitude. While ANA-24 hr FC shows a negative value on this day, the others remained positive. Subsequently as the storm weakens, these values show sharp increase, especially ANA-24 hr FC which shows a steep rise from -12 m on 16 October to 20 m on 17 October. These results clearly indicate that during intensification process, the analysed vortex grows more intense and stronger compared to predicted vortices. On the other hand, during weakening process of the vortex, the predicted vortices are found to be more intense compared to analysed one. This is an interesting result which exhibits model bias for more intense vortex in the prediction during genesis and weakening stages but less intense during intensification of the vortex.

Similar results are obtained for other cases with minor deviations. For example, in the case of severe cyclonic storm of 7-10 November 1995, the ANA-FC values were positive throughout the genesis stage till 8 November but became excessively negative (-35 to -50 m) during its intensification [Fig.9(b)]. On the other hand, in the case of the storm of 21-26 November 1995, the ANA-FC values were very high (upto 70 m) before the intensification process. During intensification, these have fallen rapidly to negative values of -10 to -25 m [Fig.9(c)]. Similar results were observed for the storm of 28 November-6 December 1996 [Fig.9(f)].

4. Conclusions

Following general conclusions may be drawn from the analysis and discussion presented above:

(*i*) The T-80 model has the capability to not only capture the initial vortex in the analysis, but also to predict its genesis about 72 hr in advance in all the cases considered in this study. In general, at the cyclogenesis stage the predicted circulations are more intense and stronger as compared to analysis both in terms of wind and mass fields. The fact that the Bay of Bengal and the Arabian Sea are nearly data void regions with almost negligible upper air soundings and meagre surface data coverage, these results assume considerable importance for the operational cyclone forecasters and numerical modelling.

(*ii*) The quantitative estimates of certain dynamical and thermodynamical parameters favourable for cyclogenesis also confirm the conclusions drawn from the qualitative analysis of cyclogenesis predictions of the model in terms of visible appearance of cyclonic circulation. The analysis of genesis parameter which is a combination of several dynamical parameters, also confirms these results.

(*iii*) On examining the model systematic errors of prediction it is inferred that the model has a clear bias for predicting more intense vortex during genesis and weakening stages. On the other hand it predicts relatively less intense vortex during intensification process.

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