

Numerical prediction of tropical cyclones : A review of research at Andhra University

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सार – इस शोध पत्र में आंध्र विश्वविद्यालय में उष्णकटिबंधीय चक्रवातों के संख्यात्मक पूर्वानुमानों पर किए गए शोध अध्ययनों की समीक्षा प्रस्तुत की गई है। सरलीकृत एकसी सिमेट्रीक प्रिमिटिव समीकरण मॉडल का उपयोग करते हुए वर्ष 1983 में यह अनुसंधान अध्ययन शुरू किया गया था। अरकावा-शूबर्ट इमैनुएल, कैन-फ्रिट्च, ग्रेल और बेट्स मिल्लर की कपासी (क्यूम्युलस) प्राचलीकरण योजनाओं का चक्रवात तीव्रता के आरंभिक भंवर के विकास से जुड़े संवहन का अनुकरण करने के लिए परीक्षण किया गया है। प्राप्त परिणाम समुद्र से प्राप्त ऊर्जा और अनुकूल तापगतिकीय के तहत बड़े प्रवाह निर्माण, उर्ध्ववाह और अधोप्रवाह, संवहनीय समायोजन के आधार पर परिकल्पनाओं को मान्य सिद्ध करते हैं। इस मॉडल के परिणामों ने उच्च समुद्र सतह तापमानों (SST) पर उच्च तीव्रता वाले चक्रवातों को भी दिखाया और ये कम अक्षांशों पर उत्पन्न हुए थे।

बंगाल की खाड़ी में उष्णकटिबंधीय चक्रवातों के पूर्वानुमान के लिए 1995 से MM5 मेसोस्केल मॉडल का उपयोग किया जाता था। प्रयोगों ने दो तरफा बातचीत की रणनीति के साथ नेस्टेड डोमेन के फायदे दिखाए हैं। संवेदनशीलता प्रयोगों से पता चला है कि संवहन के लिए कैन-फ्रिट्च योजना का संयोजन, पी बी एल के लिए मेलोर-यमदा, योजना और गहन नमी के लिए मिश्रित चरण योजना तीव्रीकरण एवं गतिशीलता के संबंध में बेहतर अनुकरण दर्शाते हैं। गतिकीय विश्लेषण से पता चला है कि तनन (स्ट्रेचिंग) भ्रमिलता को बढ़ाने में हावी होती है जिससे सीस्क (CISK) परिकल्पना की पुष्टि होती है। चक्रवात के मार्ग के पूर्वानुमान में भ्रमिलता के क्षेत्रों की अनुकूलता की पहचान की गई है।

एक तुलनात्मक अध्ययन से पता चला है कि उष्णकटिबंधीय चक्रवातों का पूर्वानुमान करने में WRF मॉडल का कार्य निष्पादन MM5 मॉडल से बेहतर है। WRF मॉडल के साथ संवेदनशीलता प्रयोगों ने संवहन के लिए कैन-फ्रिट्च की प्राचलीकरण योजनाओं के संयोजन की पुनः पुष्टि की है, यहाँ की सीमा परत के लिए YSU योजना स्पष्ट माइक्रोफिजिक्स के लिए LIN और NOAH की भूमि सतह योजना ने तीव्रता एवं गति के बेहतर पूर्वानुमान दिए हैं। भ्रमिलता आरंभिकरण और आरंभिक परिस्थितियों में सुधार की दिशा में उपग्रह से प्राप्त डेटा को समाविष्ट करने की आवश्यकता को कई प्रयोगों के माध्यम से प्रदर्शित किया गया। एकल निर्धारणात्मक पूर्वानुमान की अपेक्षा एनसेम्बल पूर्वानुमान के फायदों का पता चला।

यह समीक्षा आंध्र विश्वविद्यालय में उष्णकटिबंधीय चक्रवातों की संख्यात्मक पूर्वानुमान पर लगातार चल रही शोध गतिविधि को दर्शाती है।

ABSTRACT. A review of research studies on the numerical prediction of tropical cyclones at Andhra University is presented. Research studies using simplified axi-symmetric primitive equation model had been initiated in 1983. The cumulus parameterization schemes of Arakawa-Schubert, Emanuel, Kain-Fritsch, Grell and Betts-Miller have been tested to simulate the convection associated with the development of an incipient vortex to cyclone intensity. Results validate the hypotheses based on mass flux formulation, updrafts and downdrafts, convective adjustment under favourable thermodynamic and energy support from ocean. Results with this model had also shown the higher intensity cyclones with higher Sea Surface Temperatures (SST) and originating at lower latitudes.

MM5 mesoscale model had been used since 1995 in the prediction of tropical cyclones over Bay of Bengal. Experiments have shown the advantages of nested domains with two-way interaction strategy. Sensitivity experiments depicted that the combination of Kain-Fritsch scheme for convection, Mellor-Yamada scheme for PBL and mixed phase scheme for explicit moisture better simulation in terms of intensification and movement. The need for compatibility

between horizontal and vertical resolutions had been emphasized. Dynamical analysis revealed that stretching dominates the vorticity enhancement confirming the CISK hypothesis. The applicability of interpreting potential vorticity fields in the prediction of cyclone track had been identified.

A comparison study revealed better performance of WRF model than MM5 model in the prediction of tropical cyclones. Sensitivity experiments with WRF model reconfirmed the combination of parameterization schemes of Kain-Fritsch for convection, YSU scheme for planetary boundary layer, LIN for explicit microphysics and NOAA land surface scheme yielded better prediction in terms of intensity and movement. The need for vortex initialization and assimilation of satellite data towards the improvement of initial conditions was demonstrated through several experiments. The advantages of ensemble prediction over single deterministic prediction had been ascertained.

This review illustrates the continued research activity on the numerical prediction of tropical cyclones at Andhra University.

Key words – Tropical cyclones, Axi-symmetric model, PSU/NCAR mesoscale model (MM5), WRF model.

1. Introduction

Tropical cyclones (TC) are known for their devastating nature all over the world. Tropical cyclones form over warm tropical oceans as a low pressure system, intensify into storm intensity and most of them cause enormous damage and destruction near the coastline at their landfall. About 80 tropical cyclones form globally every year, which have maximum sustained surface wind speeds exceeding 17 m/s and about 60% of these transform as very severe cyclone systems with wind speeds reaching higher than 33 m/s. These tropical cyclones are intense rotating vortices, with the relative vorticity having the values of the order of 10^{-3} s^{-1} which is about 100 times larger than its value at the formative stage and with the rotation rate to be 10 times larger than of earth. Indian subcontinent surrounded by the Arabian Sea and Bay of Bengal water bodies to the west and east experiences the TCs with an annual frequency of 5, of which 80% of them form over the Bay of Bengal. As per the reports of the India Meteorological Department, the Orissa “Super Cyclone” of 24-29 October, 1999 had an estimated central surface pressure of 912 hPa and wind speeds of 160 km/h and the estimated damages are of USD 4.45 million and deaths at 10,405.

Due to the importance of predicting the evolution of tropical cyclones in terms of intensification, track and landfall, researchers from all over the world attempted several observational, theoretical and prediction studies to understand the complex physical and dynamical processes, which have contributed to continued improvements in the prediction of TCs. Some of the earlier review articles and books (Anthes, 1982; Ooyama, 1982) describe the advancement of knowledge on tropical cyclones and also depict some outstanding problems that remain to be resolved.

Research on tropical cyclones were initially confined to observational and theoretical studies and later focussed on the application of numerical models of atmosphere. The pioneering observational studies of Gray (1968) have

provided favourable atmospheric conditions for the formation of tropical cyclones (cyclogenesis) as (i) low-level cyclonic vorticity (indicative of a low pressure conducive of development); (ii) a critical value of earth vorticity (Coriolis parameter at > 3 degrees latitude, which is necessary but not sufficient); (iii) lower vertical wind shear (that favours deep convection); (iv) potentially unstable atmosphere (indicated by the difference between the equivalent potential temperature between surface and 500 hPa levels, a value less than 10 K indicates conductivity to convection) and (v) higher sea surface temperature ($\sim > 26.5$ °C that provides energy supply from warm ocean to the atmosphere) and deeper ocean mixed layer (that helps development of cyclonic disturbance) and (vi) higher mid-tropospheric humidity ($\sim > 50$ that helps rising air parcel remain saturated despite environmental entrainment).

Tropical cyclones, thus, form over tropical warm oceans under favourable atmospheric conditions. These systems are dynamically intense vortices, manifesting as strong rotating atmospheric motion, embedded in the general atmospheric circulation flow. The vortex, in the first stage would be larger in horizontal extent and smaller in vertical extent and identified as a low pressure system. Under favourable atmospheric and ocean conditions, the system would get intensified slowly in the initial stages and faster as it develops. During the intensification of the vortex, the horizontal extent shrinks and the vertical extension increases following the gradient wind balance flow in correspondence with concentric near-circular isobaric pattern and increasing pressure gradient. While the genesis of a tropical cyclone is subject to the composite effect of Gray's dynamic parameters, the development is strongly controlled by the thermodynamics that favour development of deep convection due to cooperative interaction of the dynamical and thermodynamic processes suggesting a mechanism such as CISK (Conditional Instability of the Second Kind). This process should have support in the form of energy (latent heat and sensible heat) supply from the underlying warm ocean to the atmosphere during the

process of intensification of the cyclone vortex. Thus, an understanding of the tropical cyclone would mean an enunciation of the atmosphere on the synoptic scale (of few thousands of km), vortex scale (few hundreds of km) and convection scale (few hundred meters) and the energy transfer in the planetary boundary layer (few cm to meters). These features depict the complexity of the interaction of atmospheric processes of different scales that need to be assessed in the prediction of the tropical cyclones.

The use of atmospheric models for TC prediction had come into vogue after their success in short range weather predictions, but the problem of scale resolution had to be dealt with before they could be used for real time prediction of TCs. As the atmospheric models use primitive equations to estimate the time change of the wind, surface pressure, temperature and humidity and numerical methods to solve them, model resolution puts a constraint on the scale resolution. As known, horizontal resolution at “d” would effectively resolve all atmospheric processes with wavelengths higher than “5d” meaning that a grid resolution at 50 km would be able to resolve synoptic scale features. Although a higher resolution with $\sim < 10$ km is adopted with the use of nonhydrostatic dynamics, the unresolvable physical processes of moist convection, eddy diffusion, exchange of moisture, heat and momentum are to be included through the method of parameterization. The basic idea of parameterization is to derive the properties of the sub-grid scale processes in a parametric manner from the grid-scale values and to estimate the modification of the grid-scale variables due to sub-grid scale processes, retaining the sub-grid scale physical processes implicit in the formulation. Thus, the problem of the prediction of tropical cyclones using atmospheric models is twofold, *i.e.*, the solution of the nonlinear partial differential equation that describe the dynamics and representation of the physical processes through parameterization.

Attempts are being made continuously to better the prediction of tropical cyclones through improving the parameterization schemes and the data assimilation methods towards generating augmented initial state of the model atmosphere. Researchers at the Department of Meteorology and Oceanography, Andhra University had initiated research on the simulation and prediction of tropical cyclones in 1983, firstly using axi-symmetric models to understand and assess the behaviour of the various cumulus parameterization schemes in the evolution of tropical cyclones and later using 3-dimensional hydrostatic and non-hydrostatic models in the prediction of tropical cyclones over North Indian Ocean.

This paper presents a review of the research work done on numerical modelling of tropical cyclones at

Andhra University, describing the salient results achieved since 1983 till date that have significantly contributed to the advancement of tropical cyclone prediction in India.

2. Models

2.1. Axi-symmetric model

The axi-symmetric primitive equation model, with the governing equations written in cylindrical coordinates of r , θ and z are:

Equation for radial wind V_r

$$\frac{\partial V_r}{\partial t} = -V_r \frac{\partial V_r}{\partial r} - w \frac{\partial V_r}{\partial z} + \left(f + \frac{V_\theta}{r} \right) V_\theta - \theta \frac{\partial \phi}{\partial r} + K \left(\nabla_1^2 - \frac{1}{r^2} \right) V_r + \frac{1}{\rho} \frac{\partial \tau_r}{\partial z}$$

Equation for tangential wind V_θ

$$\frac{\partial V_\theta}{\partial t} = -V_r \frac{\partial V_\theta}{\partial r} - w \frac{\partial V_\theta}{\partial z} - \left(f + \frac{V_\theta}{r} \right) V_r + K \left(\nabla_1^2 - \frac{1}{r^2} \right) V_\theta + \frac{1}{\rho} \frac{\partial \tau_\theta}{\partial z}$$

Equation for the potential temperature θ

$$\frac{\partial \theta}{\partial t} = -V_r \frac{\partial \theta}{\partial r} - w \frac{\partial \theta}{\partial z} + \frac{1}{\rho \phi} \left(M_c \frac{\partial s}{\partial z} + D(s_c - s - Ll_c) \right) + \frac{L}{\phi} C + K \nabla_1^2 \theta$$

Equation for the mixing ratio of water vapor q

$$\frac{\partial q}{\partial t} = -V_r \frac{\partial q}{\partial r} - w \frac{\partial q}{\partial z} + \frac{1}{\rho} \left(M_c \frac{\partial q}{\partial z} + D(q_c - q + l_c) \right) - C + K_q \nabla_1^2 q$$

Equation for continuity of mass

$$\frac{\partial}{\partial z} \rho w = -\frac{1}{r} \frac{\partial}{\partial r} \rho r V_r$$

Hydrostatic equation

$$\frac{\partial \phi}{\partial z} = -\frac{g}{\theta}$$

where,

$$\phi = C_p \left(\frac{P}{P_0} \right)^{R/C_p}$$

The stresses τ_r and τ_θ are taken as

$$\tau_r = \rho \mathcal{G} \frac{\partial V_r}{\partial z}$$

$$\tau_\theta = \rho \mathcal{G} \frac{\partial V_\theta}{\partial z}$$

and at the surface

$$\tau_{rs} = \rho_s C_D |V_s| \mathcal{G}_s$$

$$\tau_{\theta s} = \rho_s C_D |V_s| \mathcal{G}_{\theta s}$$

where, suffix s denotes surface values, \mathcal{G} and C_D denote the vertical eddy viscosity coefficient and the drag coefficient, respectively.

The mixed layer equations are written as

$$\frac{\partial s_M}{\partial t} = -V_r \frac{\partial s_M}{\partial r} + K_H \nabla_1^2 s_M + F_s$$

$$\frac{\partial q_M}{\partial t} = -V_r \frac{\partial q_M}{\partial r} + K_H \nabla_1^2 q_M + F_q$$

At the lateral boundaries, the imposed conditions are

$$V_r = V_\theta = 0 \text{ at } r = 0 \text{ and } r = r_{\max}$$

$$\partial\phi/\partial r = \partial\theta/\partial r = \partial q/\partial r = 0 \text{ at } r = 0 \text{ and } r = r_{\max}$$

where, r_{\max} is the radius of the outer periphery of the computational domain.

The coefficients used are defined as:

$$K = K_\theta = K_q = K_H = 10^3 \text{ m}^2 \text{ s}^{-1} \text{ and } \mathcal{G} = 10 \text{ m}^2 \text{ s}^{-1}$$

2.2. PSU/NCAR mesoscale model (MM5)

NCAR MM5, is a primitive equation model, developed by Pennsylvania State University (PSU)/ National Center for Atmospheric Research (NCAR). The model with its first version produced in 1970s had been updated several times to fix bugs, conform to new technologies and to be run on different types of

computers and software and also applicable to parallel processing for faster computations. The last updated version MM5 model had the capabilities of multiple-nesting; non-hydrostatic dynamics that facilitates the choice of fine-grid horizontal and vertical resolutions; multi-tasking capability on shared- and distributed-memory machines; four-dimensional data assimilation; and several parameterization options for many physical processes. The model has a terrain following vertical σ -coordinate, staggered horizontal grid with corresponding terrain- topographical information to realistically simulate mesoscale atmospheric circulations. This model has versatility to choose the domain region of interest; horizontal resolution; interacting nested domains and with various options to choose parameterization schemes for convection, planetary boundary layer (PBL), explicit moisture; radiation and soil processes. A detailed description of the NCAR MM5 is given by Grell *et al.* (1994).

2.3. Advanced research WRF (ARW) model

The advanced research WRF (ARW) modeling system is one of two cores of the Weather Research and Forecasting WRF) modelling system developed jointly by National Center for Atmospheric Research (NCAR) and the National Centers for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA). This modelling system is supposed to be the next-generation mesoscale numerical weather prediction system, developed to overcome the deficiencies of the MM5 modeling system (such as non-conservative nonhydrostatic dynamics, low-order numerics leading to less accurate solutions for finer scales and lack of applicability of software attributes such as portability, parallelism, extensibility, software layers and application programming interfaces) and intended to be useful for atmospheric research and operational forecasting. As such, the model would be applicable to a wide range of meteorological systems with scales ranging from tens of meters to thousands of kilometers.

This model system has versatility to choose the domain region of interest; horizontal resolution; interactive nested domains and with various options to choose parameterization schemes for convection, planetary boundary layer (PBL), explicit moisture; radiation and soil processes. ARW is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on parallel computing platforms and a detailed description was provided by Skamarock *et al.* (2008). The model consists of fully compressible non-hydrostatic equations and the prognostic variables include the three-dimensional wind, perturbation quantities of pressure, potential temperature, geopotential,

surface pressure, turbulent kinetic energy and scalars (water vapor mixing ratio, cloud water etc). The model equations are formulated using mass-based terrain following coordinate system and solved in Arakawa-C grid using Runge-Kutta third order time integration techniques. The model has several options for spatial discretization, diffusion, nesting and lateral boundary conditions. ARW modelling system supports horizontal nesting that allows a resolution to be focused over a region of interest by introducing an additional grid (or grids) into the simulation with the choice of one-way and two-way nesting procedures.

3. Description of research studies

Research studies on tropical studies at Andhra University had focused on the understanding the role of physical processes such as cumulus convection, cloud microphysics and planetary boundary layer on the evolution of tropical cyclones over North Indian Ocean. Earlier studies were aimed at the design and application of simple axi-symmetric models towards perceiving the importance of parameterization of cumulus convection and assessing its role in the evolution of tropical cyclones. Subsequent studies were to use nonhydrostatic models with high resolution in the simulation of tropical cyclone intensification and movement for further use in real time prediction. Several research studies have been taken up, firstly with the MM5 model and later with ARW model for assessment of their use in tropical cyclone prediction. The studies have brought forth many interesting and important results that have impacted real time prediction of tropical cyclones in India. The following is a brief description of the research illustrating the salient results.

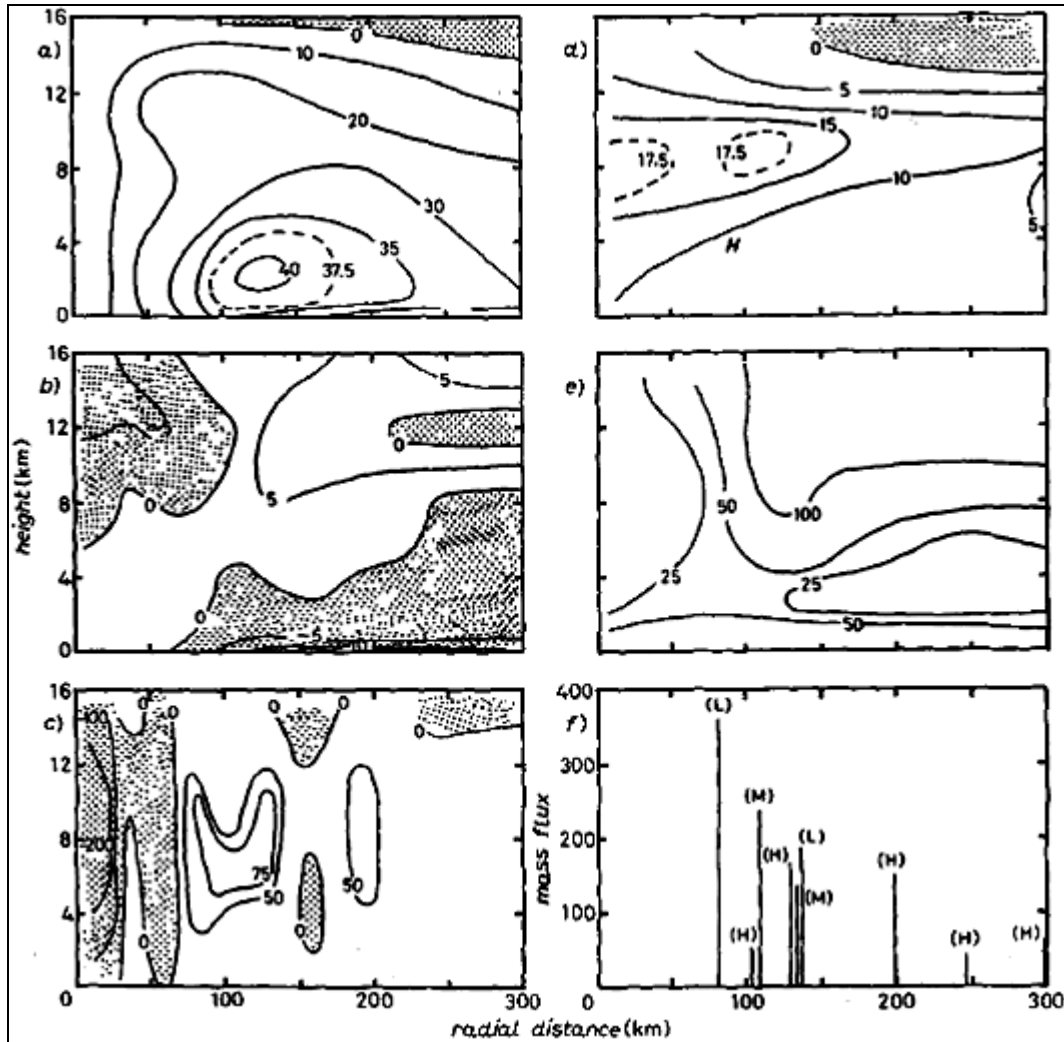
3.1. Application of axi-symmetric models

Observational and theoretical studies have indicated that the development of a tropical cyclone is driven by the release of latent heat due to formation of deep convection following the concept of CISK mechanism, *i.e.*, cooperative interaction of cumulus scale and synoptic scale cyclone circulations. Since numerical weather prediction models are constrained by grid resolution that forbids the resolution of sub-grid scale physical processes, they are to be expressed through parameterization. In the case of tropical cyclone, the properties of cumulus convection are to be derived from grid scale variables and the influence of cumulus convection on the grid scale circulation is to be parameterized. As such, different parameterization schemes of cumulus convection had been developed based on different hypothesis, such as cloud mass flux formulation, convective adjustment, cloud updrafts and downdrafts apart from using simple empirical relations. Since the tropical cyclone evolution is known to

be strongly related to inherent cumulus convection, each of the parameterization schemes is to be tested through idealized experiments. As the fully formulated 3-dimensional atmospheric models include complex interactions of all the physical processes of convection, boundary layer, cloud microphysics, surface physics etc, difficulties arise to make precise assessment of any of the parameterization schemes individually due to the problem of delineating cause and effect from the model predicted variables. So, axi-symmetric models to simulate tropical cyclones have been designed and used with the sole purpose of understanding and assessing different physical processes such as cumulus parameterization schemes.

Research studies to understand the role of different parameterization schemes of cumulus convection using an axi-symmetric model had been initiated at Andhra University in 1983. An axi-symmetric primitive equation model with the formulation of dynamical equations in cylindrical coordinate system had been designed, the details of which are given in Section 2. This model had the flexibility to the choice of number of vertical levels, horizontal resolution, incorporation of different types of cumulus parameterization schemes all of which facilitating the simulation of evolution of a pre-included vortex of reasonable strength. Several studies of tropical cyclone evolution had been carried out with the parameterization schemes of Arakawa-Schubert, Emanuel, Grell and Betts-Miller and the results of which are briefly presented as follows.

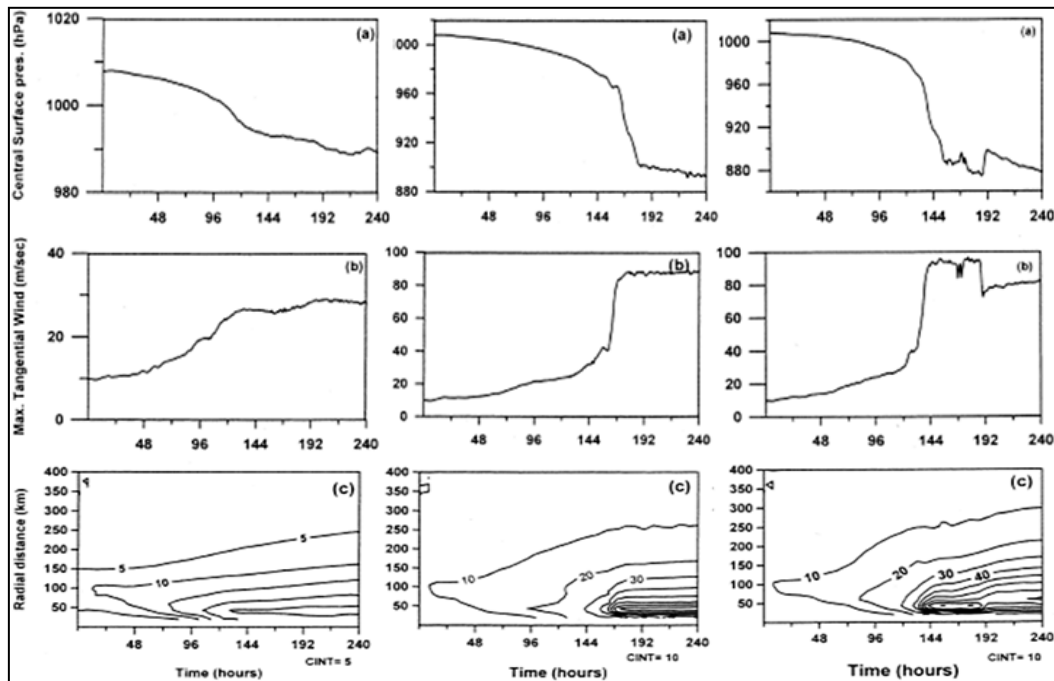
The first study (Bhaskar Rao, 1987) was to simulate the evolution of tropical cyclone from a predefined initial vortex using 6-level axi-symmetric model with Arakawa-Schubert (AS) cumulus parameterization scheme (Arakawa and Schubert, 1974). AS scheme was included in a discrete form, with three cloud types all having the cloud base at the top of the mixed layer, but with cloud tops at different model levels. This scheme has the basic assumption that the horizontal extent of the cloud is very small as compared to the area of the grid element and hypothesizes that the energy transfer from the mixed layer to the free atmosphere and moist convective instability of large scale atmosphere contributes to convection formation and the formation of convection stabilizes the atmosphere hindering the cloud formation. Convection is assumed as an updraft rising from the cloud base entraining environment air from the sides and detraining completely only at the cloud top level. The clouds are assumed to modify the environment only through compensating cumulus-induced subsidence (warming) and detraining saturated air and liquid water at the cloud-top level which contributes to moistening and cooling. Presence and level of each cloud-top and the strength of mass flux in each cloud is determined by solving the



Figs. 1(a-f). Radius-height distributions of (a) tangential wind (m/s); (b) radial wind (m/s); (c) vertical velocity (cm/s); (d) potential temperature deviation from the initial field (K); (e) relative humidity (%); (f) cloud base mass flux (gm-2s-1). Negative fields are dotted denoting (a) anticyclonic motion (b) inward motion (c) downward motion and (d) cooling; all at mature stage of the cyclone

energy equations that would yield mass flux at the cloud base for each cloud. The thermodynamic profile of the vertical temperature and humidity profiles were taken from the mean tropical sounding and the potential temperature was perturbed with an increase of 0.42 K at 10 km level and the humidity was taken as constant in the horizontal. This perturbation leads to an initial vortex with surface pressure at the centre to be 1008.5 and slowly increasing to 1010 hPa at 221 km and with the tangential wind having maximum of 8 m/s at 128 km at 0 and 1 km heights reducing upward and away from the centre. The initial saturated moist static energy of the mixed layer was fixed at 84.5 cal/gm, which exceeds the saturated moist static energy value at 12 km level allows the formation of deep clouds. With this set up, model integration up to 120 hours had shown the simulation of the deepening and

mature stages as evinced by the cyclone scale circulations at these two stages. The simulation clearly brought out the development of the initial vortex into a strong cyclone with the features of warm core, increase of tangential winds and establishment of radial-vertical circulations that completely agree with observed features of a tropical cyclone [Figs. 1(a-f)]. The most important result of this study is the simulation of all the three types of clouds, *i.e.*, with the formation of deep convective clouds in the deepening stage together with presence of low clouds in the mature stage, all of which validate the hypothesis of AS cumulus parameterization scheme. This is one of the earliest studies which had emphasized the cooperative interaction of the cumulus and synoptic scale circulations as hypothesized in AS scheme.



Figs. 2(a-c). Time variations of (a) central surface pressure (hPa); (b) maximum tangential wind (m/s); (c) time-radius section of tangential wind (m/s); all with $f = 5 \times 10^{-5} \text{ s}^{-1}$. Left panel correspond to experiment with SST = 300 K; middle panel correspond to experiment with SST = 301 K; and right panel correspond to experiment with SST = 302 K

Using the same axi-symmetric model with the AS scheme as of the earlier study, simulation studies have been made with different sea surface temperatures (SST) to understand the evolution of convection and the intensification (Bhaskar Rao and Ramakrishna, 1994). Four experiments were performed with SST values taken as 298, 299, 300 and 301 K had brought out interesting results. The model produced intensification of the initial vortex had shown that minimum SST is needed to trigger the deep convection, as SST at 298 K did not show deepening of the vortex and that deep convection could be triggered when the SST is above 299 K confirming that warm ocean is one important condition for cyclogenesis. Higher SSTs had shown higher intensities till ~ 300 K above which final intensity does not change, but intensification would occur more rapidly.

Sensitivity to mixed layer formulation was studied using the same axi-symmetric model (Bhaskar Rao *et al.*, 1996). Energy in the form of dry static energy and moist static energy in the mixed layer is known to be important as the sensible and latent heat transfer from the ocean to atmosphere occurs through the mixed layer. Two simulation experiments were performed, one with the moist static energy in the mixed layer to be constant at 83.7 cal/gm (value at the initial time) and another varying with time. The evolution of cyclone was reported to be more realistic with time varying mixed layer energy, with

the attained central surface pressure to be lower and the surface maximum winds and with the occurrence of deep convection earlier. This study emphasizes the need to formulate the mixed layer formulation to include realistic transfer of the energy from ocean to the atmosphere.

After the successful experiments of evaluating the AS cumulus parameterization scheme in the simulation of tropical cyclones, the parameterization scheme of Emanuel was also evaluated using the same axi-symmetric model. The Emanuel scheme (Emanuel, 1991) assumes ensembles of updrafts and downdrafts in contrast to assumption of clouds in other schemes. The updrafts are assumed to be on the scale of ~ 100 meters rising from the sub-cloud layer to reach each of the model layers between the cloud base and top. At each level, a fraction of the condensed water is converted to precipitation and the remaining air is mixed with the undisturbed environment air forming a spectrum of mixtures and each of which reaches its level of neutral buoyancy, *i.e.*, the level at which the parcel liquid water potential temperature of the parcel equals to that of the environment. Downdrafts are assumed to form due to evaporation from falling precipitation and only one downdraft could exist at a grid point. The closure is to estimate the sub-cloud layer mass flux of each updraft considering parcel precipitation efficiency, fraction of precipitation falling through unsaturated environment and fractional area of the

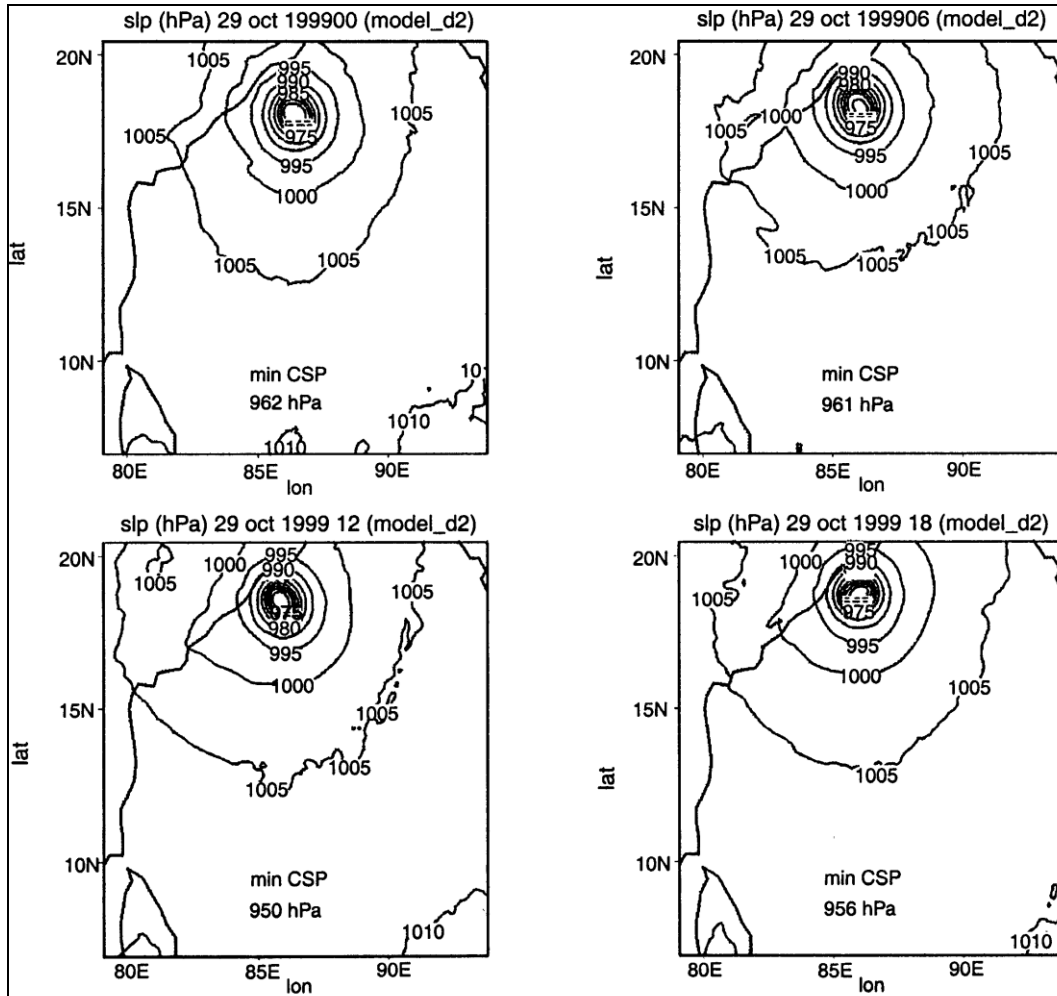
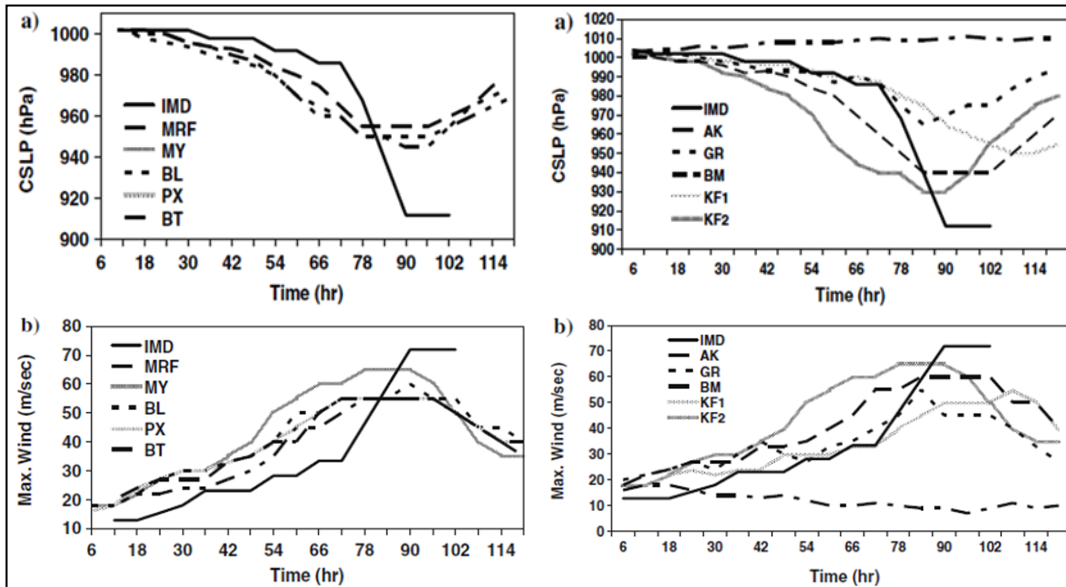


Fig. 3. MM5 model simulated central surface pressure (hPa) of the Orissa super cyclone at four different times on 29th October, 1999

precipitating downdraft. A study of the evolution of a vortex with initial strength of 9 m/s using the axisymmetric model with Emanuel scheme has been made to assess the performance of the Emanuel scheme (Bhaskar Rao, 1997). The results have shown the development of an intense cyclone with a maximum wind of 70 m/s and minimum sea level pressure of 930 hPa, with the structures at different stages as similar to observations. Further sensitivity experiments indicated increase of intensity to increase of SST and intensification is more rapid at lower latitudes. This study authenticates the hypothesis of Emanuel scheme considering ensembles of updrafts and downdrafts as useful for the simulation of deep convection systems such as tropical cyclones.

Another study was made with the axisymmetric model modified to have 10 vertical levels that permits 7-cloud types to occur simultaneously in the AS scheme and formulation of planetary boundary layer following

Deardorff (1972) that supports more realistic energy exchange from the ocean. Evolution of the vortex with an initial strength of 10 m/s at 120 km radius and with the initial thermodynamic profile of November at Port Blair (92.4° E, 11.4° N) in Bay of Bengal for 240-hours was studied (Bhaskar Rao and Ashok, 1999). The results have shown a steady evolution of the vortex, attaining cyclone intensity of 17 m/s around 78 hours and a maximum of 87 m/s at 210 hours and the lowest surface pressure of 890 hPa. The evolution clearly depicted a pre-deepening stage up to 156 hours, deepening stage of 30-hours during 156-186 hours followed by mature stage. The structure of the cyclone at mature stage illustrate the simulation of the central eye region, warm core, strong cyclonic circulation in the central 300 km with low-level inflow; strong vertical motion at the eye wall and outflow aloft and with deep convection coinciding with the radius of maximum wind all portraying the features of a tropical cyclone.



Figs. 4(a&b). Model simulated time variations of (a) central surface pressure (hPa) and (b) maximum tangential wind (m/s). Left panel correspond to experiments with different PBL schemes. Right panel correspond to experiments with different convection scheme

Further sensitivity experiments were performed with the same model set up to assess the role of origin latitude in terms of “Coriolis parameter” and the sea surface temperature (SST) (Bhaskar Rao and Ashok, 2001). The experiments with the value of “Coriolis parameter” at three latitudes of 15, 20 and 25 N had shown that vortex originating at lower latitudes develop faster than at higher latitudes and also that low latitude storms are more concentric conforming with the intensity [Figs. 2(a-c)]. Sensitivity experiments with SST varying from 299K to 302 K have brought out an important result that the vortex did not intensify with SST at 299 K whereas it would attain cyclone strength with SST at 300 K confirming that SST plays an important role in the intensification through energy supply from the ocean. Further, increase of SST produced stronger cyclone with increase of maximum winds as 80 (90) m/s with SST as 301 (302) K and also larger storm size with higher SST. These studies have refined the earlier results validating the mass flux hypothesis by Arakawa-Schubert in the formation of cumulus convection and confirming the CISK hypothesis in the evolution of tropical cyclones. Many of these studies using simplified axi-symmetric models had been found to be useful in the application of different cumulus parameterization schemes with 3-dimensional models that are more relevant for real time weather prediction as also of tropical cyclones.

3.2. Experiments with MM5 model

After the occurrence of the Orissa Super Cyclone (OSC), referred to by the IMD as the most intense

cyclonic storm occurred over Bay of Bengal since the false point cyclone of 1885 with an estimated Central Sea-level pressure of 912 hPa and associated maximum wind of 140 knots, almost all research groups in India attempted to simulate this cyclone to understand the dynamical and thermo dynamical reasons for the reported intensity and to assess the predictability of such intense tropical cyclones using numerical models. Since the availability of MM5 model (described in Section 2) through the public domain in 1990s and due to its versatile applicability, most of the researchers started using MM5 model for weather prediction research and so also for tropical cyclone studies. Research on tropical cyclones at Andhra University had utilised the MM5 model accordingly and the results from different simulation studies are presented here.

Gandikota and Bhaskara Rao (2003) performed numerical prediction experiments of “Tropical cyclone Earl” of 1998 over Atlantic Ocean and “Orissa Super Cyclone” of 1999 over Bay of Bengal using MM5 model with two-way interactive nested 4-domains and 2-domains respectively. Apart from the prediction of evolution of both the TC systems in general in terms of intensification and movement similar to the observations, the MM5 model had predicted, importantly, the genesis of meso-cyclones as evinced by the confluence of streamlines at 925 hPa level in the “Earl” cyclone and the structure of the cyclone at different stages including the spiralling rain-bands in the “Orissa Super Cyclone” (Fig. 3), all of which authenticate the usefulness of MM5 modelling system.

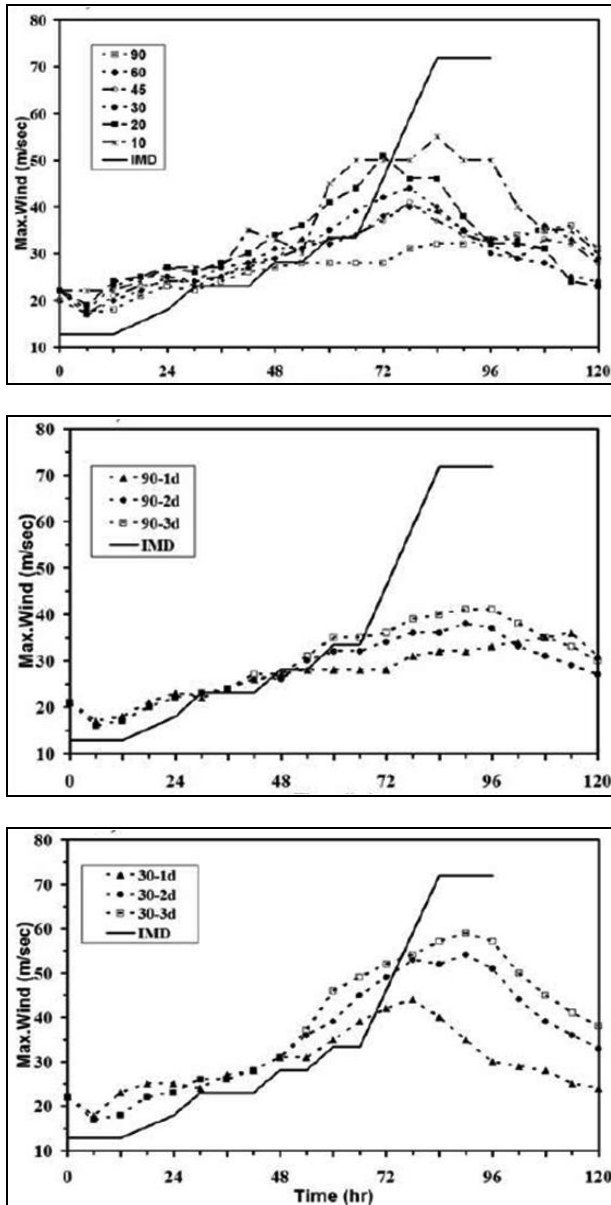


Fig. 5. Time variation of MM5 Model simulated maximum tangential wind (m/s) at 925 hPa level from different experiments: Top panel shows results from experiments with single domain and different resolutions; middle panel shows results for 90-km domain with single domain (1D), two domains (2D) and three domains (3D) experiments

A number of simulation studies to assess the sensitivity of the prediction of the evolution of OSC to the parameterization of cumulus convection, cloud microphysics (explicit moisture) and planetary boundary layer were performed (Bhaskar Rao and Prasad, 2006 & 2007). Several experiments with different combinations of the three important physical processes revealed some interesting results: that the PBL processes are important for cyclone intensification and the convection processes

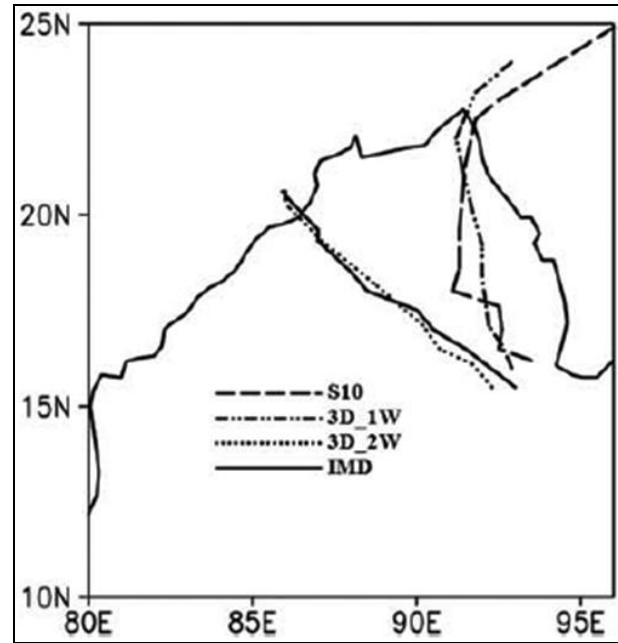
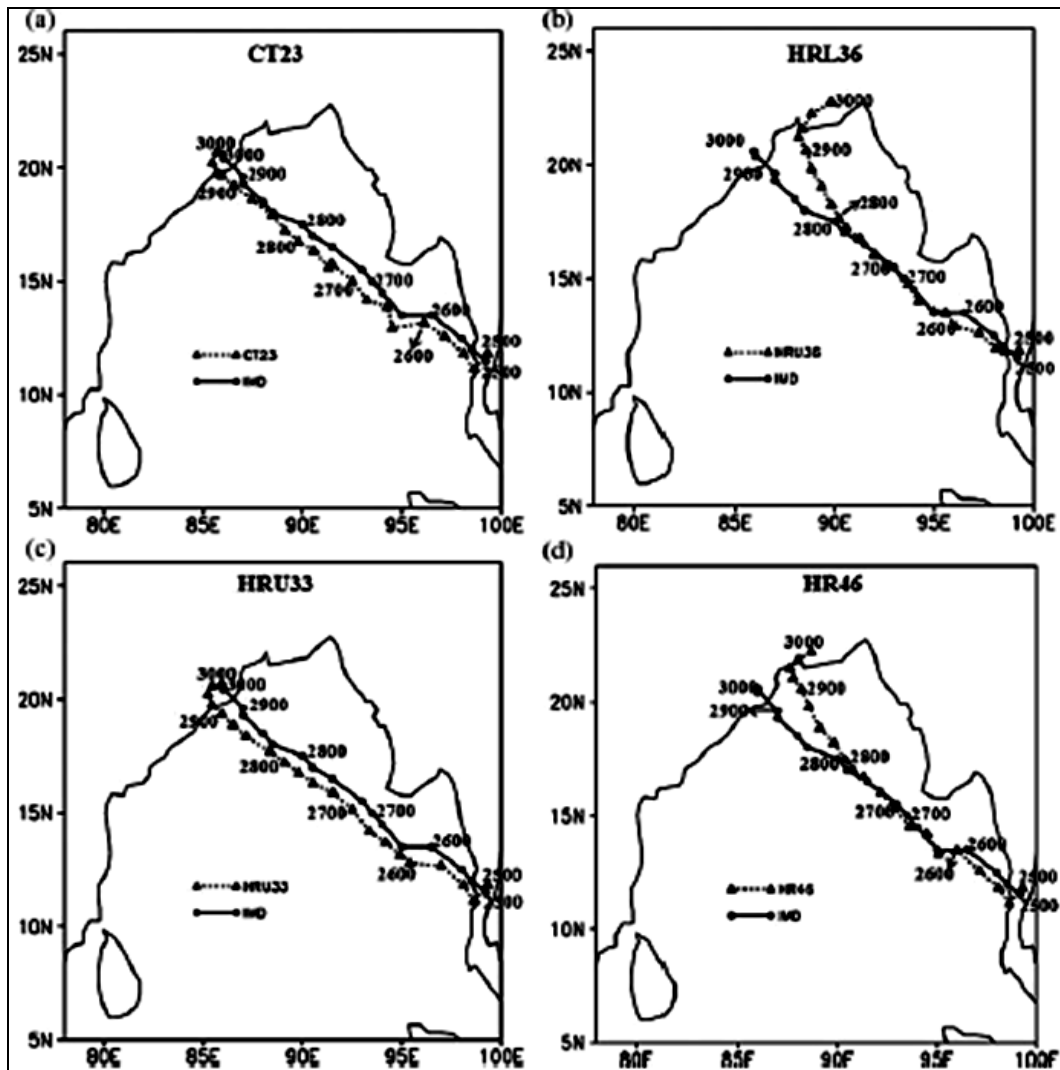


Fig. 6. MM5 Model simulated track from the experiments with single domain with 10 km resolution (S10), 3-domains with one-way nesting (3D_1W), and 3-domains with 2-way interaction (3D_2W) for the simulations of the Orissa super cyclone (1999)

contribute to track movement while explicit moisture processes modulate the track or movement [Figs. 4(a&b)]. Further, their results concluded that the combination of KF2 (Kain-Fritsch) scheme for convection, Mellor-Yamada scheme for PBL and mixed phase scheme for explicit moisture produces the best prediction in terms of track and intensity.

Since MM5 model facilitates the adoption of nested domains and considering the need to investigate the implications of one-way and two-way interaction approaches in numerical weather prediction, Bhaskar Rao *et al.* (2009) made detailed study of the prediction of OSC using the MM5 model for evaluation of the nesting domains strategy. Results from several model simulations with six different domain resolutions (varying from 10 to 90 km) revealed that the model predicts higher intensity and lesser time period of deepening with increase of resolution, which is expected as higher resolution helps to resolve finer scales especially the horizontal convergence and vertical velocity distributions and that the model resolution does not impact the track prediction. Further, simulations of the intensification and movement of the OSC were made with one, two and three nested domains and with the options of both the one-way and two-way nesting approaches. All experiments with the one-way nested approach with 3-domains had produced track movement similar to the 1-domain experiments. In



Figs. 7(a-d). MM5 Model simulated track of the Orissa Super Cyclone from the four experiments with different vertical resolutions: (a) 23-levels (CT23); (b) 36-levels with high resolution below 500 hPa (HRL36); (c) 33-levels with high resolution above 500 hPa (HRU36); and (d) 46-levels with high resolution throughout ((HR46)

contrast, experiments with two-way interaction in both the 2- and 3-nested domains show better track prediction bringing out the advantage of two-way nesting approach (Fig. 5). Further the authors demonstrated the modification of the flow through lateral boundaries in the two-way interaction as the reason for better prediction through making several experiments with domain size variations (Fig. 6). Further, these authors have confirmed that the improved prediction is due to two-way interaction only by performing several sensitivity experiments with different combinations of parameterizations of cumulus convection, cloud microphysics and planetary boundary layer. These results were identified as notable, which clearly brought out the need to adopt two-way interaction approach with nested domains as of all the earlier studies which had been using single domain with high resolution.

The performance of KF2 (Kain-Fritsch) cumulus convection scheme in the prediction of tropical cyclones through was evaluated through a case study of Orissa Super Cyclone (Sathi Devi *et al.*, 2006). MM5 model, with two-way interacting 3 nested domains and the innermost domain resolution at 10 km, was used to simulate the evolution of the cyclone system for 5-days. The model produced the gradual intensification as indicated by the sea level pressure distribution during the first 2 to 3 days and then rapid intensification for about 24 hours as of the observations. The distributions of wind, vorticity and vertical velocity and the shrinking of the vortex through the deepening and mature stages and the rainfall at the landfall were well simulated. However, the rate of rapid intensification could not be predicted accurately which led to underestimation of the attainment of both the sea level

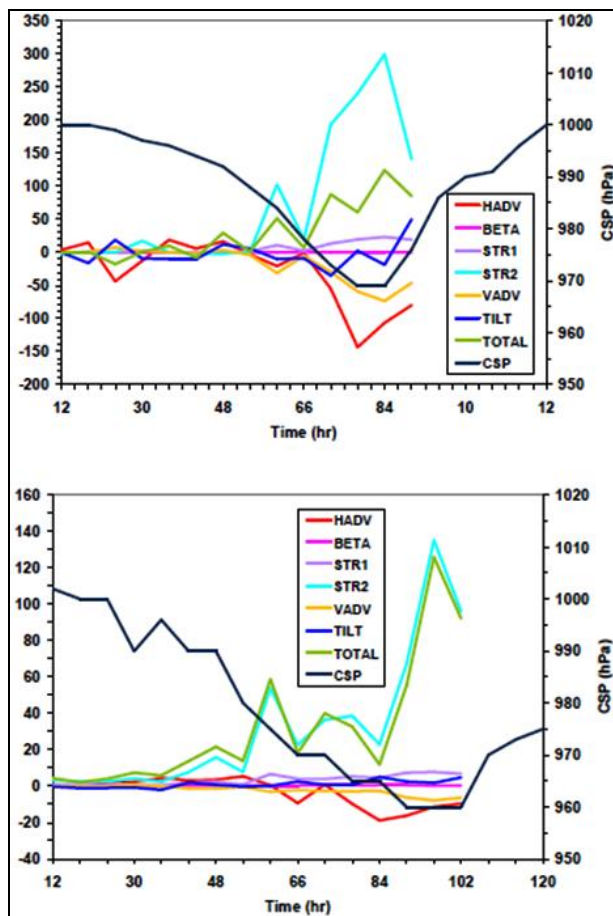


Fig. 8. Time variation of MM5 Model simulated central surface pressure (hPa) along with magnitudes of different terms in the vorticity tendency equation computed at 850 hPa level as shown for the 30 km domain of the 1-domain experiment (top) and 90 km domain of the 3-domain experiment (bottom)

pressure and maximum winds at mature stage by 20-30%. This study had shown the performance of KF2 scheme to simulate deep convection and so the sudden deepening of the cyclone and the underestimation of the observed intensity was attributed to constraints of model resolution.

Another important problem in the application of numerical weather prediction models is the choice of vertical resolution as most of the studies were concerned with horizontal resolution alone that would resolve the desired weather system (such as tropical cyclone) that is to be predicted. In fact, some studies have clearly indicated the need for compatibility between the chosen horizontal and vertical resolutions and that lack of consistency lead to generation of noise affecting predictability. Considering this important issue of NWP, a study on the sensitivity to vertical resolution in the prediction of Orissa Super Cyclone had been made using MM5 model (Bhaskar Rao *et al.*, 2010). Four different vertical

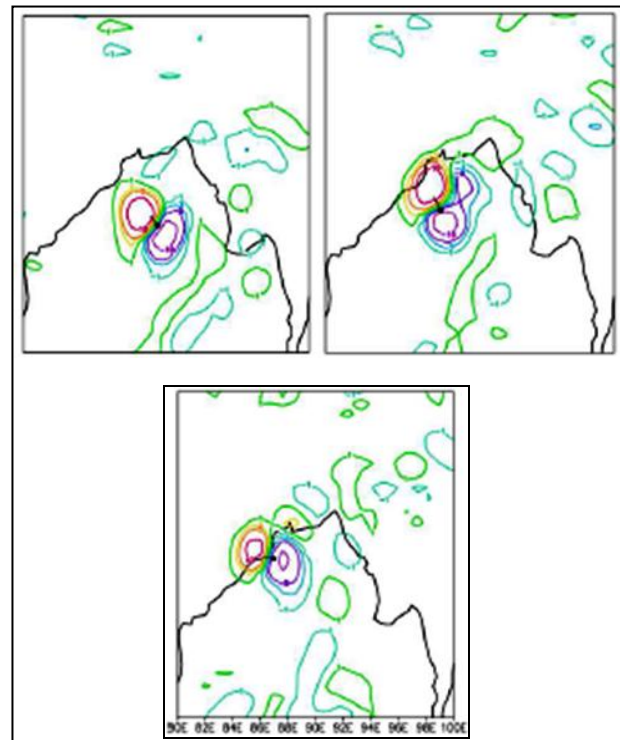


Fig. 9. MM5 Model simulated potential vorticity tendency ($\times 10^{-11}$) field at 500 hPa level for the 30-km domain of the experiment with 3-domains at the times of: 0000 UTC of 28 October, 1999 (top left); 1200 UTC of 28 October, 1999 (top right); 0000 UTC of 29 October, 1999 (bottom)

resolutions were chosen with 23, 33, 46 and 46 vertical σ -levels, considering 23-levels as a general choice adopted by several researchers and the other three resolutions based on a suggested relation between the vertical and horizontal resolutions through the ratio of Coriolis parameter to buoyancy frequency and with 33 vertical levels to have high resolution in the upper troposphere; 36 vertical levels to have high resolution in the lower troposphere and 46 vertical levels to have increased vertical resolution throughout the troposphere as relative to the experiment with 23-levels. The results had brought forth important result that increased vertical resolution in the lower troposphere produces efficient intensification and better structure in terms of eye and eyewall; increased vertical resolution at lower levels improved the prediction of vertical shear of horizontal wind; and experiments with high resolution in the lower troposphere and high resolution throughout the troposphere simulated better track up to 72 hours [Figs. 7(a-d)]. This research investigation is unique as no other studies related to this topic had been attempted for the North Indian Ocean tropical cyclones.

Dynamical analysis of the model output from a prediction experiment of the Orissa Super Cyclone using MM5 model was made to understand which of the

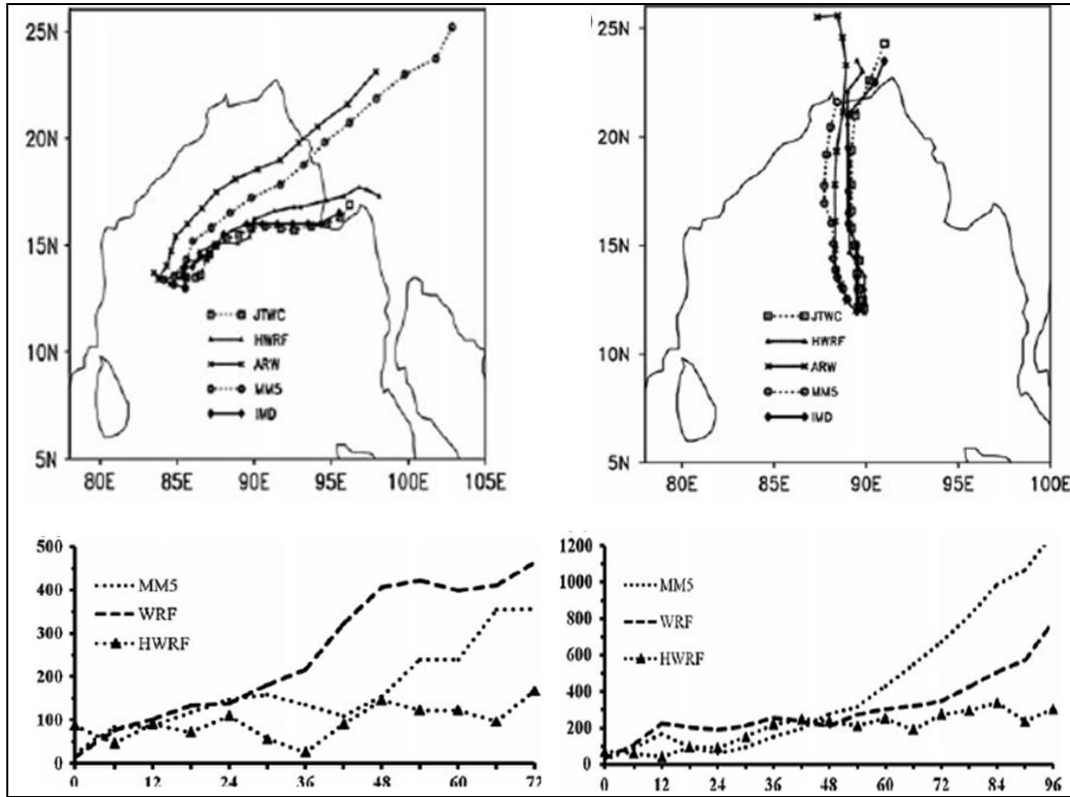


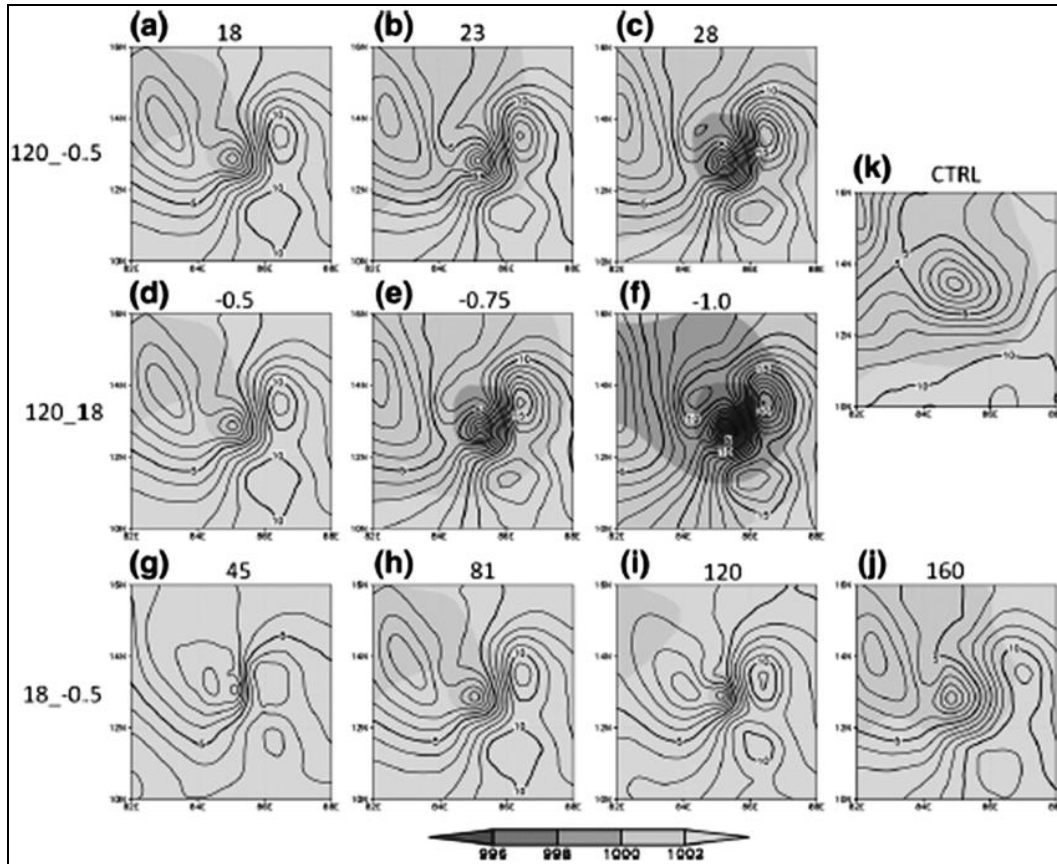
Fig. 10. Model simulated tracks and track errors from the experiments with MM5, WRF and HWRP models. Top panel shows tracks along with JTWC. Bottom panel shows track errors (km). Left panel shows results for SIDR cyclone. Right panel shows results for NARGIS cyclone

dynamical and thermodynamic processes contribute to the evolution of tropical cyclones at different stages (Dasari and Bhaskar Rao, 2014). Analysis of the time variation of relative vorticity at 850 hPa clearly brought out the dominance of the stretching term contribution in the deepening stage, which implies the role of deep convection in the intensification of the cyclone (Fig. 8). Analysis of the time evolution of potential vorticity at 500 hPa level, which denotes the level of steering flow, have indicated a distinct dipole structure with positive and negative values located adjacently with respect to the centre of the cyclonic system at the surface. Experiments with single domain and nested domains have similar dipole structure with the gradient from negative centre to positive centre through the zero line coincident with the movement of the cyclone (Fig. 9). This study had brought out an important and potential tool in the form of “potential vorticity” that could be used for the prediction of the movement of tropical cyclones. Further the study emphasizes the need for dynamical analysis to understand the intensification and movement of the tropical cyclones in addition to the routine of application of models for cyclone prediction.

3.3. Experiments with ARW model

WRF model, first version released in 2000, is undoubtedly the most popular atmospheric model with registered users of ~36,000 across 162 countries. The use of WRF-ARW model for research on tropical cyclones at Andhra University had been initiated during early 2000s, first by making comparison of simulations with both the MM5 and ARW models to assess their relative performance.

An evaluation study of the performance of MM5 and ARW models in the prediction of tropical cyclones was made through a case study of “SIDR” cyclone over Bay of Bengal with life cycle during 11-16 November, 2007 (Bhaskar Rao *et al.*, 2009). This cyclone system had a typical life cycle, with rapid intensification in the early stages from a low pressure to severe cyclone storm, remained with same strength for nearly 30 hours and then sudden intensification into a very severe cyclone storm and attainment of super cyclone stage within a short period of 12 hours. The cyclone system had peculiar movement, moving northward during the period of intensification, static during non-intensification and



Figs. 11(a-k). Model simulated spatial distributions of sea level pressure (hPa) (shaded) along with 10-m level wind speed (m/s). Top panel represents experiments with different MW (m/s) with fixed values of RMW=120 km and $\alpha=-0.5$; Middle panel correspond to different values of α and fixed values of RMW=120 km and MW=18 m/s; bottom panel corresponds to different values of RMW and fixed values of MW=18 m/s and $\alpha=-0.5$

moving northeast during final intensification period. Both the MM5 and ARW models were designed to have two-way interacting nested domains with 9 km resolution for the innermost domain and integrated with the same initial conditions. Model predictions were made with four initial conditions taken at different stages of the cyclone development. The results had shown that although both the MM5 and ARW models could predict the general intensification and movement, the ARW model predicted better, with higher intensity than MM5 model. However, MM5 model predicted the track better with initial conditions in early stages of development, while ARW model predicted better with model integration during the later period of intensification.

Another study comparing the performance of the MM5, WRF-ARW (Advanced Research Weather Research and Forecasting) and HWRF (Hurricane WRF) models in the prediction of tropical cyclones was made through case studies of “NARGIS” cyclone of 2007 and “SIDR” cyclone of 2008 (Bhaskar Rao and Vijay, 2012). The results have shown better predictions with HWRF

model due to inherent vortex initialization and movable nesting. Between the MM5 and WRF-ARW models, ARW model had shown better track prediction but with overestimation of intensity (Fig. 10). This study had brought out the importance of vortex initialization as the initial conditions derived from global analysis may not truly represent the characteristics of the incipient vortex in terms of both the location and intensity.

The performance of the high-resolution ARW model in the prediction of tropical cyclones over Bay of Bengal was evaluated through case studies of 21 cyclone systems (Srinivas *et al.*, 2012). Sensitivity experiments with respect to the parameterizations of cumulus convection, planetary boundary layer, explicit moisture and land surface have indicated that the combination of Kain-Fritsch (KF) convection, Yonsei University (YSU) planetary boundary layer (PBL), LIN explicit microphysics and NOAH land surface schemes had produced the best simulations of intensity and track. The model was noted to overestimate the intensity and the track predictions were the best for northward moving

cyclones followed by northwestward, westward and northeastward tracking cyclones.

To emphasize the need for vortex initialization in the prediction of tropical cyclones, ARW model was used to make predictions by adopting the “bogus vortex” module of the modelling system. The model was designed to have two-way interacting 3 nested domains and 36 experiments with variations of the maximum wind (MW), radius of maximum wind (RMW) and a scaling factor. To understand the implications of vortex initialization and model spin-up, several experiments were performed to simulate the evolution of “NARGIS” cyclone over Bay of Bengal during 27 April-3 May, 2008 (Srinivas and Bhaskar Rao, 2014). The results have demonstrated realistic representation of initial structure and location of cyclone vortex due to vortex initialization and have shown large disparities between the experiments with and without vortex initialization [Figs. 11(a-k)]. Without vortex initialization, the initial vortex had deficiencies in the form of lower MW, larger RMW and lower vertical extent of cyclonic circulation which were corrected with vortex initialization. Vortex initialization reduced the initial position errors by 50 % which also lead to reduction of track errors than other predictions of the same cyclone. This study also investigated the evolution of cyclone vortex during model spin-up in the cold start runs. This research is important as the state of vortex at the end of spin-up should be closer to the observations than at the initial time. The sensitivity to spin-up had brought out an important result that the vortex initialized to have the same intensity in terms of maximum wind and radius of maximum wind would lead to higher intensification during the spin-up period and so the initial vortex is to be designed to have lower intensity by 20% would produce the vortex as similar to the observations at the end of spin-up period. This is an important result that the vortex initialization is to be affected by taking slightly reduced (20%) values of maximum wind and not as of the observations.

The errors in numerical weather prediction are known to occur due to inaccuracies in initial conditions, approximations in numerical integration methods and parameterization of physical processes. The concept of ensemble prediction methodology had evolved from the important finding of better forecasts arising from aggregating different model predictions (treated as an ensemble) than of the individual predictions. Further, ensemble predictions had the advantage of translation of model outputs as probabilistic for better understanding the value of the forecast. There are several methods of generating the ensembles, e.g., with variations in initial conditions or physical parameterizations or numerical models or a combination of these variations. A

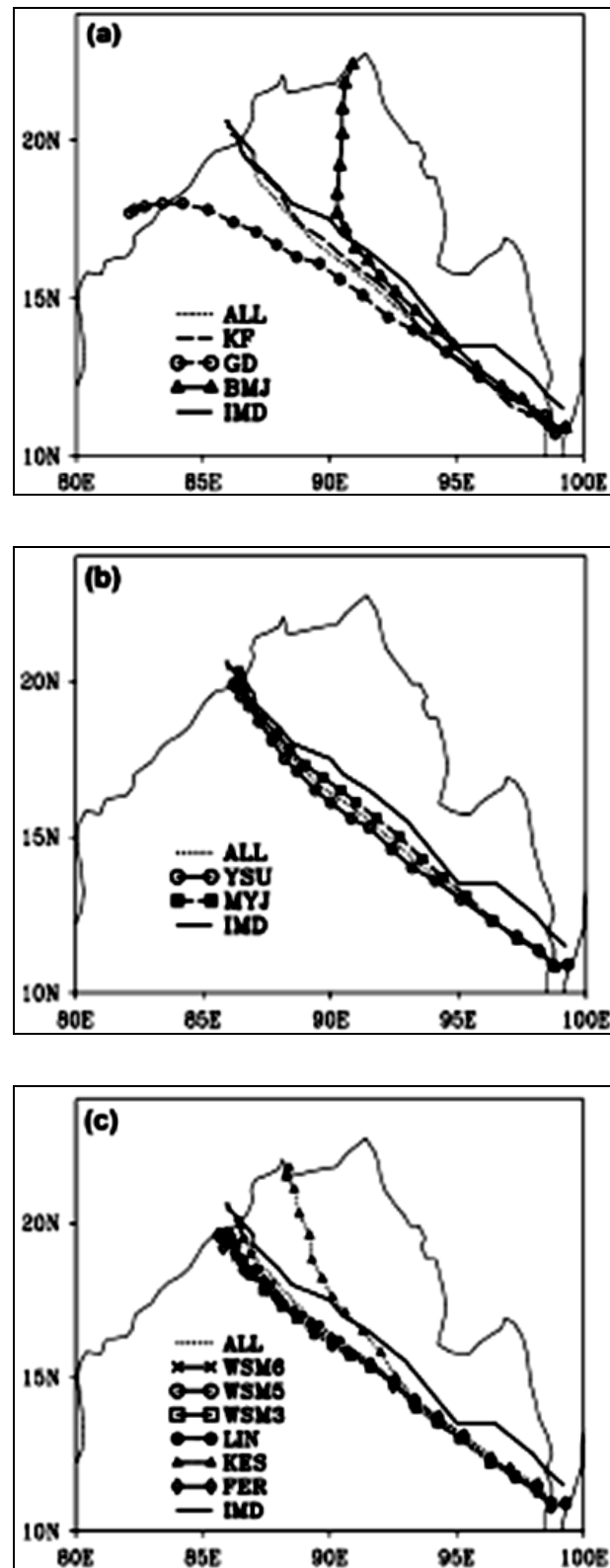
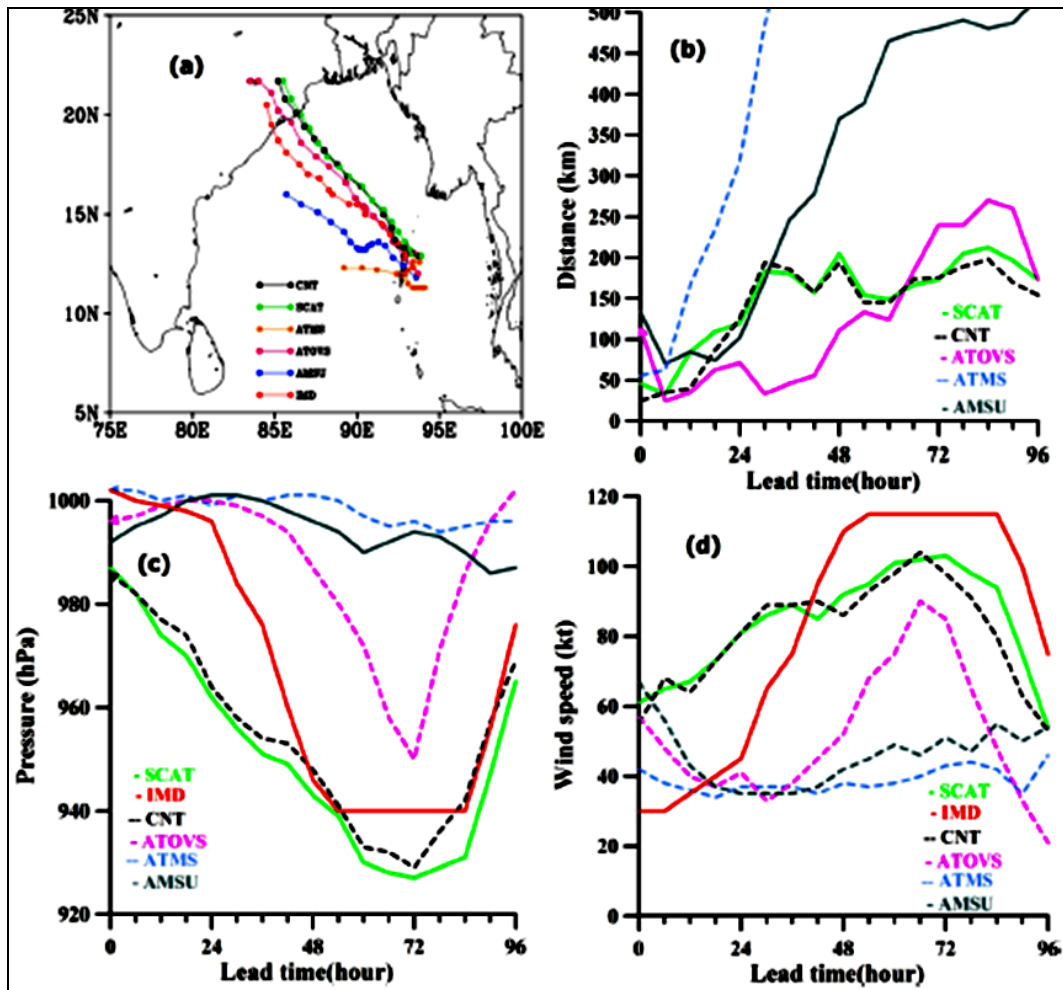


Fig. 12(a-c). Ensemble mean and IMD tracks at 6-hour interval for the experiments with (a) cumulus convection based ensembles; (b) PBL based ensembles and (c) cloud microphysics based ensembles



Figs. 13(a-d). Model simulated (a) track positions; (b) vector track errors; (c) time variation of central surface pressure (hPa); and (d) time variation of maximum wind (m/s) for different sensitivity experiments of data assimilation along with IMD reported values

study of multi-physics based ensemble has been made using the ARW model with two-way interacting nested two domains with 90-30 km resolution to predict Orissa Super Cyclone of October, 1999 for 120-hours (Venkata and Srinivas, 2014). Orissa Super Cyclone was chosen as it was the most intense tropical cyclone over Bay of Bengal in recent times and that several predictions of this cyclone were made by researchers the results of which would be useful for comparing the ensemble prediction. A 36-member ensemble was generated with the combinations of the parameterizations of 3 cumulus convection schemes, 2 PBL schemes and 6 cloud microphysics schemes. An evaluation of the ensemble prediction brought out important findings that the spread increased equitably on both sides with time illustrating the potentiality of the ensemble method as the 36-member ensemble prediction had the vector track errors and landfall errors consistently less than most of the individual

members. Further 12-member ensemble with KF cumulus convection scheme, 18-member ensemble with MYJ PBL scheme had the least of track errors than other corresponding ensembles. The 6-member ensemble with cloud microphysics had also yielded better prediction than individual members but not as good as of the cumulus convection and PBL ensemble predictions [Figs. 12(a-c)]. This is the only ensemble prediction study based on multi-physics attempted for the predictions of tropical cyclones over the North Indian Ocean which emphasizes the advantages of the multi-physics ensemble prediction of tropical cyclones.

In numerical weather prediction, precise specification of initial conditions is important, as short range weather prediction is essentially an initial value problem. Since atmospheric models use a grid domain, observations available at indiscrete locations have to be

collocated to derive optimised description of the initial state. Thus data assimilation is important for model generated weather predictions and so objective methods had been developed from simple polynomial estimation of 1950s to optimum interpolation of 1990s to variational assimilation methods (2DVAR and 4DVAR) of the present time. For the prediction of tropical cyclones, prescription of initial state had severe limitations due to paucity of observations over oceans and the availability of satellite data in recent years and possibilities of its assimilation have considerably improved the generation of accurate initial conditions. Although assimilation of satellite data have shown improvements in tropical cyclone prediction, considering the need to evaluate the impact of new satellite data, a numerical prediction study of “Phailin” cyclone using ARW model was made with and without assimilation of satellite data (Dodla *et al.*, 2016). Numerical experiments were made without and with the assimilation of scatterometer winds and radiances from ATOVS and ATMS. The results of the assessment, in terms of the movement and intensification of cyclone, had shown that ATOVS data assimilation experiment yielded the best prediction with least track errors less than 100 km up to 60 hours and simulating the pre-deepening and deepening periods accurately. In contrast, experiments without assimilation and assimilation of only Scatterometer winds had track errors of 150-200 km and with gradual deepening from the beginning itself instead of observed sudden deepening [Figs. 13(a-d)].

In recent years, atmospheric temperature and humidity profiles are being retrieved through a new technique, *i.e.*, Global Position System (GPS) Radio Occultation (RO). National Center for Environmental Predictions (NCEP) Global Data Assimilation System (GDAS) operationally assimilates the RO data globally and total daily atmospheric soundings of ~2,000 as a part of NCEP GFS (Global Forecast System). Since very few studies had been attempted to assess the impact of GPSRO data on short range weather prediction that includes tropical cyclones, Srinivas *et al.* (2016) had made an assessment of the impact of GPSRO temperature and humidity profiles in the evolution of two tropical cyclones, Chapala and Megh that occurred over Arabian Sea in 2015 using ARW modelling system that includes 3DVAR assimilation module.

The results had clearly shown that assimilation of GPSRO data has substantially modified the initial conditions, to have stronger vortex in the case of “Chapala” and weaker vortex in “Megh” cyclone along with improved humidity distribution leading to improved prediction. The results from experiments with assimilation had simulated proper intensification of “Megh” cyclone that could not be obtained in the experiment without

GPSRO data assimilation and a stronger “Chapala” cyclone closer to observations. Thus predictions of both the cyclones had clearly brought out the usefulness of GPSRO data assimilation in the prediction of tropical cyclones by improvement of the initial temperature and humidity distributions.

4. Summary

A review of the research studies on “numerical prediction of tropical cyclones, carried out at the Department of Meteorology, Andhra University is presented. Research studies using an axi-symmetric primitive equation model, designed and modified to include cumulus parameterization scheme, had been initiated in 1983. The evolution of a pre-designed vortex due to cooperative interaction of cumulus and synoptic scale circulations was the motivation for the use of this simple modelling strategy. The model is expected to respond to initial thermodynamic structure of the environment supposing the existence of conditional instability, energy transfer from the ocean to the free atmosphere through mixed layer and then the initiated convection and the environment interacting with each other leading to the intensification of the initial vortex. The cumulus parameterization schemes of Arakawa-Schubert, Emanuel, Kain-Fritsch, Betts-Miller and Grell were assessed for the development of tropical cyclones over North Indian Ocean. The model was found to be suitable with the adopted dynamics through primitive equation formulation and the salient results are summarised as follows:

Model simulations, with all of the cumulus parameterization schemes, had shown the intensification of an initial vortex to a mature cyclone with the features such as warm core, increase of tangential winds and establishment of radial-vertical circulations along with the formation of deep convective clouds in the mature stage.

The model experiments has shown sensitivity to sea surface temperature, clearly establishing a threshold SST of ~26.5 °C above which only the vortex had intensified and that higher SST would lead to higher intensity and faster intensification.

Sensitivity experiments have shown that cyclones would have higher intensity and also rapid evolution when the formation is at lower latitude.

Although the simplified 2-dimensional model formulations had limitation of not having applicability in real time predictions, they have been found useful to understand the role of different cumulus parameterization

schemes and to make an assessment of the final attainable intensity in terms of initial thermodynamics and SST.

Research on tropical cyclones using mesoscale models have started in 1995 with NCAR-MM5 model. Several simulation studies of the Orissa Super Cyclone (1999) were made considering it a challenge for the modellers to yield the observed high intensity with surface pressure of 912 hPa and winds of 160 km/hour.

Sensitivity experiments had shown that the combination of Kain-Fritsch scheme for convection, Mellor-Yamada scheme for PBL and mixed phase scheme for explicit moisture produced the best simulation in terms of track and intensity.

Since the MM5 model had the capability of using nested domains and their interactions as one-way and two-way, several experiments with a single domain and different resolutions ranging from 10 to 90 km and nested 2- and 3-domains with different resolutions and also with one-way and two-way interaction approaches, the results had brought out clearly the advantages of using two-way interacting nested domains especially to improve track prediction. These experiments had confirmed that higher resolution would yield higher intensity.

Simulation studies with different vertical resolutions had shown the need for compatibility between horizontal and vertical resolutions conforming with the ratio of Coriolis parameter to buoyancy frequency. Sensitivity experiments have shown that better resolution in the lower troposphere yielded realistic intensification as evinced by the simulated structure in terms of eye and eyewall and vertical shear of horizontal wind.

A study of the dynamical analysis of the model simulated output had shown that stretching term plays the dominant role in the deepening stage emphasizing that the cooperative interaction between cumulus and synoptic scale circulations are essential for cyclone development.

Further, the results have shown that the “potential vorticity” distribution at 500 hPa level would be useful for track prediction in terms of the direction of its gradient from negative centre towards positive centre.

ARW model, which replaced the MM5 model in 2000, had been used since 2005 for all the tropical cyclone studies. A comparison study of the performance of MM5 and ARW models through case studies of different cyclones had shown that ARW model yields better prediction in terms of both intensification and movement.

Sensitivity experiments have shown that the combination of the parameterization schemes of Kain-

Fritsch for convection, YSU scheme for planetary boundary layer, LIN for explicit microphysics and NOAA land surface scheme had produced the best prediction in terms of intensity and movement.

Another study had brought out the need for vortex initialization as the initial conditions derived from coarse resolution global or regional analysis may not be truly representative of the incipient vortex. Simulation experiments have shown improvements in both the intensity and track with vortex initialization.

Since ensemble predictions provide probabilistic predictions in contrast to single deterministic forecast and the prediction errors are likely to arise from errors in initial conditions, approximations in physics parameterizations and the model variations, multi-physics ensemble predictions have clearly shown the advantages of ensemble predictions.

Improvements in the initial conditions are possible through assimilation from different sources, especially from satellites as they have been providing different types of atmospheric data. Numerical experiments were made without and with the assimilation of scatterometer winds and radiances from ATOVS and ATMS and the results had shown that ATOVS data assimilation experiment yielded the best prediction with least track errors and simulated the pre-deepening and deepening periods accurately whereas assimilation of only Scatterometer winds had higher track errors and with gradual deepening from initial time.

Numerical experiments of two cyclones with assimilation of GPSRO data had shown substantial modification of the initial conditions, to have stronger vortex in the case of “Chapala” and weaker vortex in “Megh” cyclone and improved humidity distribution leading to weaker intensification of “Megh” cyclone (as compared to without assimilation) and a stronger “Chapala” cyclone closer to observations.

Research studies at Andhra University focused on the prediction of tropical cyclones of North Indian Ocean and many significant results applicable to real time prediction had been obtained. The research is continuing with focus on the contemporary problems and currently addressing the impacts of satellite and Doppler Weather Radar data assimilation and ensemble predictions.

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