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Tropical cyclone simulation with Emanuel's convection scheme

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सार — उष्णकटिबंधीय चक्रवात के विकास का अनुकरण करने के लिए इमानुएल द्वारा सुझायी गई नवीन संवहन प्राचलीकरण स्कीम का प्रयोग किया गया है। इस अध्ययन के लिए जो गणितीय निदर्श प्रयोग में लाया गया है वह एक 19 स्तरीय अक्ष-सममित आद्य समीकरण, जेड संयोजकता प्रणाली वाला जलस्थैतिक निदर्श है। 400 कि. मी. केन्द्रीय त्रिज्या में 20 कि.मी. के विभेदन पर तथा इसके उपरांत रेडियल दूरी में वृद्धि होने के साथ-साथ उर्ध्वाधर विस्तार शून्य से 18 कि.मी. तक और क्षैतिज विस्तार 3114 कि.मी. तक होता है।

9 मी./सेकण्ड की आरम्भिक तीव्रता वाले मूल रूप से संतुलित बवंडर की गति का इसमें अध्ययन किया गया है। यह बताया गया है कि आरम्भिक बवंडर के चक्रवात बनने और तीव्र चक्रवातीय तूफान में परिवर्तित होने के विकास क्रम को अनुरूपित करने में इमानुएल संवहन स्कीम सफल रही है। बवंडर के चक्रवात में परिवर्तित होने पर उसमें निम्न स्तर पर अधिकतम 70 मी./सेकण्ड वायुझोकों की गति के साथ न्यूनतम सतह दाब 930 हे.पा. पाया गया। बवंडर की परिपक्व अवस्था में वायु के अनुरूपी परिसंचरण लक्षण एक तीव्र चक्रवात की रचना के संकेत देते हैं।

दो भिन्न सुग्राहिता प्रयोग किए गए हैं। 0.5°K वाले चरणों में 300.5° से 302°K तक की एस.एस.टी. की विविधता पर किए गए कुछ प्रयोगों से पता चलता है कि एस. एस. टी. में वृद्धि के साथ मॉडल चक्रवात की तीव्रता में वृद्धि होती है। अक्षांश में विविधता के साथ किए गए कुछ अन्य प्रयोगों से पता चलता है कि निम्न अक्षांशों पर चक्रवातीय तूफान अधिक तीव्र होता है।

ABSTRACT. A new convection parameterization scheme proposed by Emanuel (1991) is used to simulate the evolution of tropical cyclone. The numerical model used for this study is a 19 level axi-symmetric primitive equation, hydrostatic model in a z co-ordinate system. The vertical domain ranges from 0 to 18 km and the horizontal domain ranges upto 3114 km with a resolution of 20 km in the central 400 km radius and with increasing radial distance thereafter.

The evolution of an initially balanced vortex with an initial strength of 9 m/sec is studied. It is shown that Emanuel's convection scheme is successful in simulating the development of the initial vortex into a mature, intense cyclonic storm. At the mature stage, a minimum surface pressure of 930 hPa is attained with the associated low level maximum tangential wind speed of 70 m/sec. The simulated circulation features at the mature stage show the formation of an intense cyclone.

Two different sensitivity experiments were performed. A set of experiments with the variation of sea surface temperature (SST) from 300.5° to 302° K in steps of 0.5° K have shown that the intensity of model cyclone increases with the increase of SST. Another set of experiments with variation of latitude has shown that the cyclonic storm is more intense at lower latitudes.

Key words — Tropical cyclones, Numerical models, Parameterization of convection

1. Introduction

Tropical cyclones are one of the most devastating natural disasters which recur annually. The intense devastating nature is the main reason for continuing scientific investigations to understand their mechanism. Scientific advances in satellite and computer technology have opened up new possibilities to probe cyclonic systems from space and to mathematically simulate the life cycle of cyclones. The tropical cyclones are known to originate over warm tropical oceans and intensify as they move over the oceans picking up the necessary energy and, finally, decay through landfall. Over the Indian region, the cyclonic storms mainly form over the Bay of Bengal and strike the east coast of India and the Bangladesh coast every year, causing great loss of life and damage to property. During the last three decades a number of modelling attempts have been made to simulate tropical cyclones using two dimensional axi-symmetric models and three dimensional asymmetric models.

Anthes (1982) gives a good review of different aspects of the tropical cyclones. It is clearly understood that supply of the necessary energy from the warm oceans and the release of latent heat in the convective elements, are the main physical mechanisms for the generation and maintenance of tropical cyclones. This co-operative mechanism between the large scale and convective scale circulations is termed as Conditional Instability of Second Kind (CISK), the concept of which has been the basis of many numerical models. A number of parameterization schemes—convective adjustment scheme, Kuo scheme, Betts scheme and Arakawa-Schubert scheme have been used by different scientists in their numerical models to study tropical cyclones.

Emanuel (1991) proposed a scheme of cumulus convection for use in large-scale and meso-scale models. This scheme has been used by Brown and Bretherton (1994) to study tropical wave instabilities, but so far it was not implemented in tropical cyclone modelling studies. In the present study an attempt has been made to study the evolution of a vortex into a cyclone system using an axi-symmetric primitive equation model with the inclusion of Emanuel's scheme. In section 2 the basic details of the axi-symmetric model, data, initial vortex and Emanuel's convection scheme are described. The results from the control simulation and sensitivity experiments are presented in sections 3 and 4. The important conclusions are summarised in section 5.

2. Model

An axi-symmetric primitive equation model is designed for use in this study. This model is basically similar to the one used by Bhaskar Rao (1987) and differs only in the treatment of the Planetary Boundary Layer (PBL). The basic equations are written in a cylindrical z co-ordinate system which are as follows :

Equation for radial wind, V_r :

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

Equation for tangential wind, V_θ :

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

Thermodynamic energy equation :

$$\frac{\partial \theta}{\partial t} = -V_r \frac{\partial \theta}{\partial r} - w \frac{\partial \theta}{\partial z} + \frac{L}{\bar{\phi}} C + K_\theta \nabla_1^2 \theta + (\nabla \theta)_c \tag{3}$$

Equation for the mixing ratio of water vapour q :

$$\frac{\partial q}{\partial t} = -V_r \frac{\partial q}{\partial r} - w \frac{\partial q}{\partial z} - C + K_q \nabla_1^2 q + (\nabla_q)_c \tag{4}$$

Equation for continuity of mass :

$$\frac{\partial}{\partial z} \bar{\rho} w = -\frac{1}{r} \frac{\partial}{\partial r} \bar{\rho} r V_r \tag{5}$$

Hydrostatic equation :

$$\frac{\partial \phi}{\partial z} = -\frac{g}{\theta} \tag{6}$$

where, V_r is the radial wind component; V_θ is the tangential wind component; w is the vertical velocity; θ is the potential temperature, q is the mixing ratio of water vapour, p is the pressure and P_0 is taken as 1000 hPa; ρ is the density of air, f is the Coriolis parameter; g is the acceleration due to gravity; K is the horizontal eddy viscosity coefficient; K_θ is the horizontal eddy thermal diffusivity; K_q is the horizontal eddy moisture diffusivity; R is the gas constant for air; L is the latent heat of condensation, C_p is the specific heat of air at constant pressure, τ_r is the radial component of vertical shear stress; τ_θ is the tangential component of vertical shear stress; C is the large-scale condensation per unit time and unit mass and

$$\phi = C_p \left(\frac{P}{P_0} \right)^{\frac{R}{C_P}} \tag{7}$$

and

$$\nabla_1^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} \tag{8}$$

Overbars denote functions of height alone and the last terms $(\nabla q)_c$ and $(\nabla \theta)_c$ in Eqns. (3) and (4) represent the effects of convection.

For computational accuracy, ϕ and θ fields are divided into a basic and perturbation parts,

$$\phi(r, z, t) = \overline{\phi}\,(z) + \phi'\,(r, z, t)$$

and

$$\theta(r, z, t) = \overline{\theta}\,(z) + \theta'\,(r, z, t) \tag{9}$$

from which hydrostatic Eqn. (6) is written as,

$$\frac{\partial \overline{\phi}}{\partial z} = -\frac{g}{\overline{\theta}} \tag{10}$$

and

$$\frac{\partial \phi}{\partial z} = \left(\frac{g}{\overline{\theta}} \right) \left[\frac{\theta'}{\overline{\theta}} - \left(\frac{\theta'}{\overline{\theta}} \right)^2 \right] \tag{11}$$

The stresses τ_r and τ_θ are taken as follows:

$$\tau_r = \overline{\rho}\, I \frac{\partial V_r}{\partial z}, \quad \tau_\theta = \overline{\rho}\, I \frac{\partial V_\theta}{\partial z} \tag{12}$$

and at the surface,

$$\tau_{rS} = \rho_S C_D \,|\, V_S \,|\, I_{rS}, \quad \tau_{\theta S} = \rho_S C_D \,|\, V_S \,|\, I_{\theta S} \tag{13}$$

where I is the vertical eddy viscosity coefficient; C_D is the drag coefficient and subscript s denotes the surface values.

2.1. *Boundary conditions*

To determine pressure field through mass continuity equation, vertical velocity w is taken as zero $Z = 0$ and $Z = Z_{\max}$, *i.e.*, at the bottom and top of the model atmosphere. At the lateral boundaries, we have

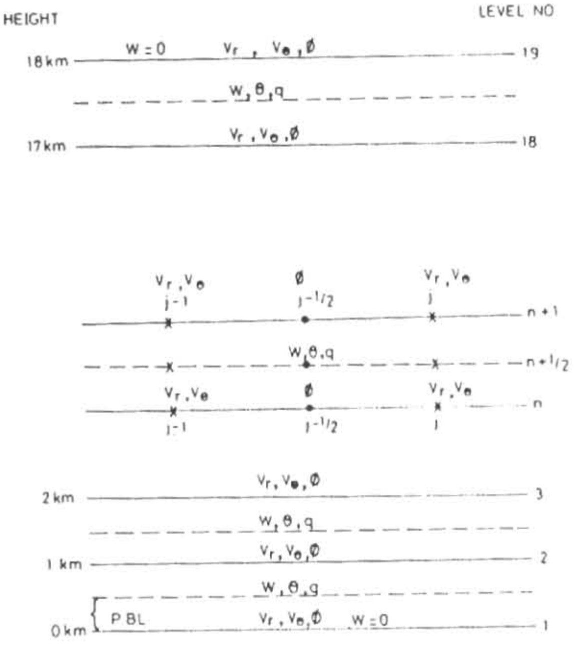


Fig. 1. Structure of the model

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

$$\frac{\partial \phi}{\partial r} = \frac{\partial \theta}{\partial r} = \frac{\partial q}{\partial r} = 0 \quad \text{at } r = 0 \text{ and } r = r_{\max} \tag{14}$$

$r_{\max}$ is the radius of outer periphery of the computational domain which is taken as 3114 km in this model. The surface fluxes are calculated using the PBL formulation following Deardorff (1972). The coefficients used are defined as follows:

$$K = K_\theta = K_q = 10^3\, m^2 \sec^{-1}$$

$$I = 10 \text{m}^2 \sec^{-1}$$

$$C_D = (1.10 + 0.04\,|\,V\,|) * 10^{-3} \;\; (V \text{ in m sec}^{-1}) \tag{15}$$

$$f = 5 * 10^{-5} \sec^{-1}$$

During the model integration, large-scale condensation is assumed to occur when the water vapour mixing ratio exceeds the saturation value and the temperature and mixing ratio values are adjusted for saturation and all the condensate is assumed to fall directly to the ground.

2.2. *Finite difference scheme*

The vertical structure of the model is given in Fig. 1. The atmosphere is divided into 18 layers, each layer

TABLE 1

Position of grid points

Index	Radius (km)	Index	Radius (km)
1	20	20	400
2	40	21	422
3	60	22	446
4	80	23	472
5	100	24	502
6	120	25	537
7	140	26	579
8	160	27	630
9	180	28	669
10	200	29	764
11	220	30	855
12	240	31	969
13	260	32	1111
14	280	33	1289
15	300	34	1511
16	320	35	1789
17	340	36	2136
18	360	37	2571
19	380	38	3114

bound by integer levels and represented by half integer. V_r, V_θ and ϕ are defined at integer levels whereas w, θ and q are defined at half integer levels. The depth of the planetary layer is assumed to be constant with a value of 500 meters. The computational domain in the horizontal is divided into 38 concentric rings with varying grid distance same as used by Rosenthal (1978) and is given in Table 1. The six variables are placed in a staggered grid horizontally with V_r and V_θ defined at integer points r_j (j = 1, 2, ...38) denoted by crosses while w, θ, q and ϕ are placed at half integer points, *i.e.*, $r_{j-1/2}$ (j = 1, 2, ...38) denoted by thick dots (Fig. 1). Upstream finite differencing is used for space differentiation. Time staggering is used for time derivatives with θ, q and ϕ being defined at $T \Delta T$ time interval while V_r, V_θ and w are defined at intermediate points as $(T + 1/2)\ \Delta T$. A time step ΔT of 60 sec is used to avoid computational instability.

TABLE 2

List of input parameters used in version 2.03 of the Emanuel cumulus parameterization scheme

Parameter	Value	Description
PBCRIT	200 hPa	Critical cloud depth beneath which precipitation efficiency is assumed to be zero
PTCRIT	850 hPa	Cloud depth above which precipitation efficiency is assumed to be unity
PPMIN	700 hPa	Minimum pressure from which convecting parcels are assumed to originate
SIGD	0.04	Fractional area covered by unsaturated downdraft
SIGS	0.15	Fraction of precipitation falling outside of cloud
ALPHA	1.00	Used in controlling the approach to quasi-equilibrium
BETA	0.98	Used in controlling the approach to quasi-equilibrium
DTCRIT	– 2.0° K	Critical buoyancy used to adjust the approach to quasi-equilibrium (< 0)

2.3. *Emanuel convection scheme*

Emanuel (1991, 1993) proposed a scheme of cumulus convection for meso-scale and large-scale models. This scheme has been formulated following the episodic mixing model of Raymond and Blyth (1986) differing only in the assumption that precipitation may form and re-evaporate partially in unsaturated downdrafts. Emanuel's scheme uses the representation of the collective effects of an ensemble of about 100 metre-scale drafts and differs from other schemes which consider ensembles of clouds. The updrafts are assumed to ascend from the subcloud layer to each level between the cloud base and the cloud top. It is assumed that a specified fraction of the amount of condensed water is converted to precipitation. The remaining cloud air is allowed to mix with the undisturbed environment forming a spectrum of mixtures. Then each mixture ascends or descends to a new level of neutral buoyancy, where the liquid water potential temperature is equal to that of the environment.

It is assumed that at the most one downdraft is present at each grid point at any time step which

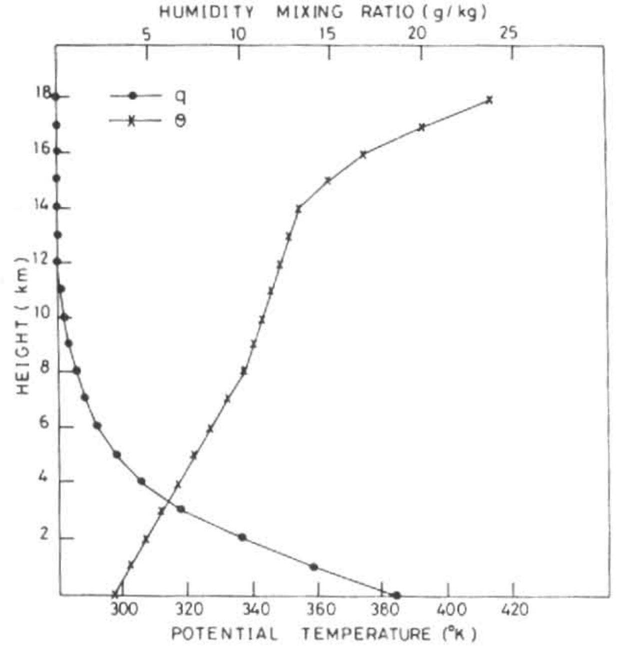


Fig. 2. Vertical distribution of undisturbed potential temperature (°K) and humidity mixing ratio (g/kg)

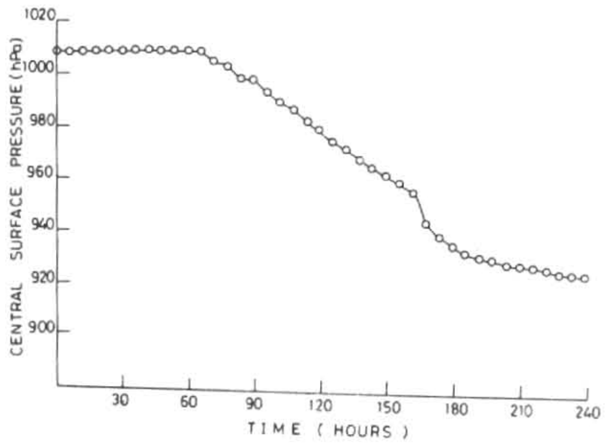


Fig. 3. Time variation of central surface pressure (hPa)

results from the evaporation of precipitation by updrafts at any level. Finally, the subcloud mass flux of each updraft is computed from the environmental forcing using a "soft quasi-equilibrium" scheme. These computations require the specifications of the closure parameters; (*i*) parcel precipitation efficiencies, (*ii*) fraction of precipitation falling through the unsaturated environment and (*iii*) fractional area covered by precipitating downdrafts.

In the present study Emanuel's convection scheme (Version 2.03 provided by Emanuel) has been used. The default parameters used in the convection scheme are given in Table 2.

2.4. *Initial field*

The initial vertical distribution of potential temperature θ and relative humidity q are taken from the mean climate data at Port Blair (11.4°N, 92.4° E) representing the month of November as given by the India Meteorological Department (IMD). This is chosen to represent the mean atmospheric sounding for the Bay of Bengal region for the month during which the cyclone frequency is maximum. The vertical distributions of undisturbed potential temperature and humidity mixing ratio are shown in Fig. 2.

The initial condition used in the study is designed to have a weak balanced vortex in the wind field. This is obtained by introducing a perturbation in the basic potential temperature field using the equation

$$\theta'(r,z) = 0.2\left\{\cos\left(\frac{\pi}{r_0}\right)r + 1\right\}\sin\left\{\frac{\pi}{z_T}z\right\}$$

$$\text{for } r < r_0 \ \ (200 \text{ km}) \qquad (16)$$

The initial pressure field is obtained using a hydrostatic equation and then the wind field from the gradient wind equation. The weak balanced vortex obtained is found to have a maximum tangential wind of 9.0m/sec at 128 km at 0 and 1 km levels. The tangential wind is about 5 m/sec between 60 and 160 km and vanishes beyond 200 km. The initial surface pressure is 1010 hPa beyond 220 km and gradually reduces to 1008.5 hPa at 10 km radius. The potential temperature distribution is largest with an increase of about 0.5° K at 10 km level. The initial relative humidity values are assumed to be uniform horizontally. For the model integration the Sea Surface Temperature (SST) is kept constant over the entire model region.

3. Control simulation

In the control simulation experiment the model incorporating the Emanuel's convection scheme as described in the previous two sections is integrated for 240 hours keeping the SST value at 301° K and other parameters fixed as given in section 2. The results obtained from the control simulation are described as follows.

The time variation of the Central Surface Pressure (CSP) is shown in Fig. 3. The CSP remained constant upto about 60 hr and then decreased gradually up to 150 hr and then steeply up to 180 hr, reaching a minimum of 930 hPa at 240 hr. The associated time variation of the Maximum Tangential Wind (MTW)

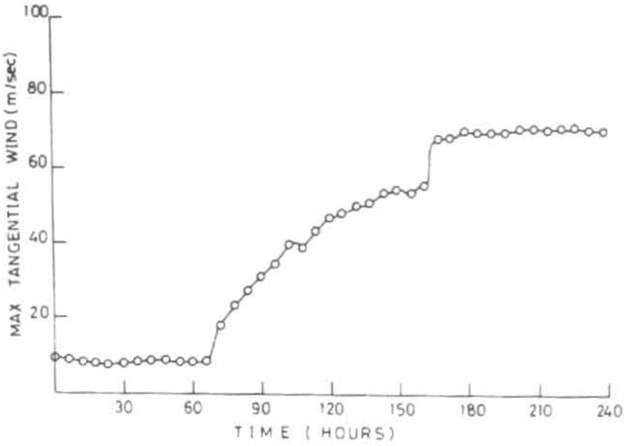


Fig. 4. Time variation of maximum tangential wind (m/sec)

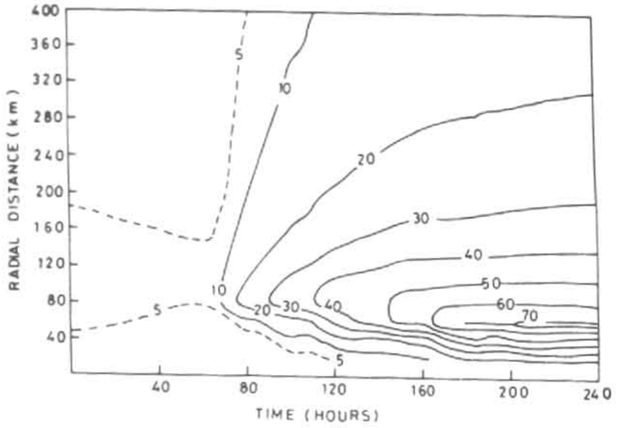
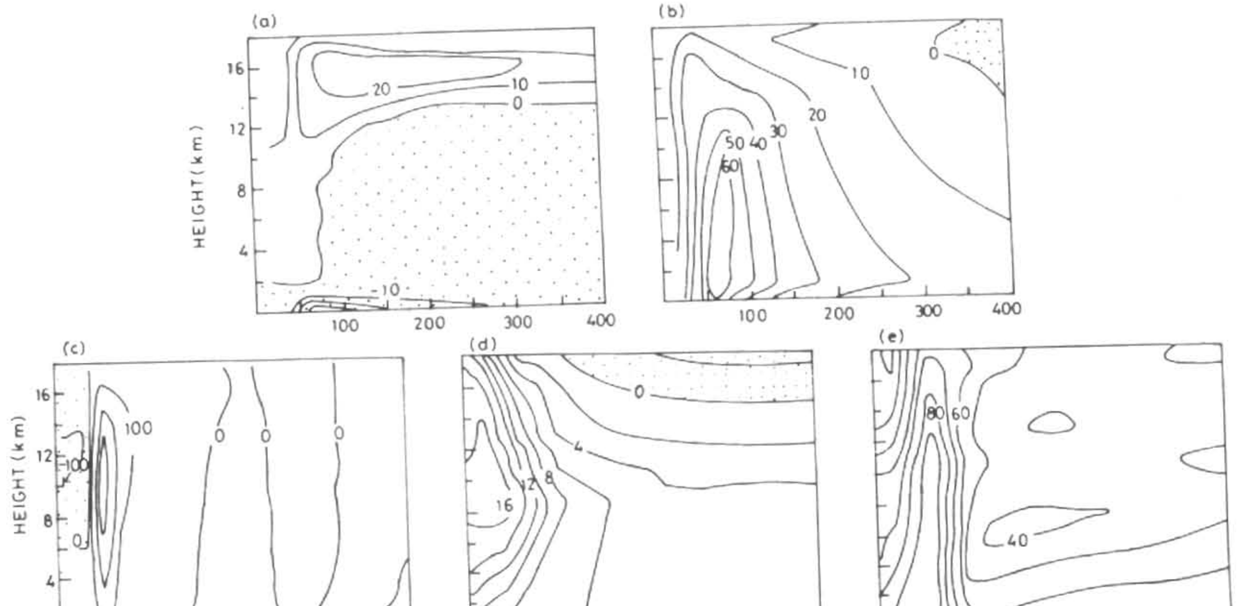


Fig. 5. Time-radius section of tangential wind at 1 km level



Figs. 6(a-e) Height - radius distributions at mature stage (186 hr) of (a) radial wind (m/sec), (b) tangential wind (m/sec), (c) vertical velocity (cm/sec), (d) potential temperature deviation from the initial field and (e) relative humidity (%). (Negative areas are shaded)

at 1 km level (Fig. 4) shows no variation upto 60 hr, then increases gradually until 150 hr and steeply upto 180 hr reaching a maximum of 70 m/sec which remained invariant after 180 hr. This shows the deepening of the initial vortex from 60 to 150 hr and attainment of the mature stage at 180 hr. The increase in the MTW shows a steady deepening of the pressure gradient.

The time-radius section of V_θ at 1 km level is shown in Fig. 5. It is observed that the tangential wind V_θ reaches cyclone intensity after 80 hr and

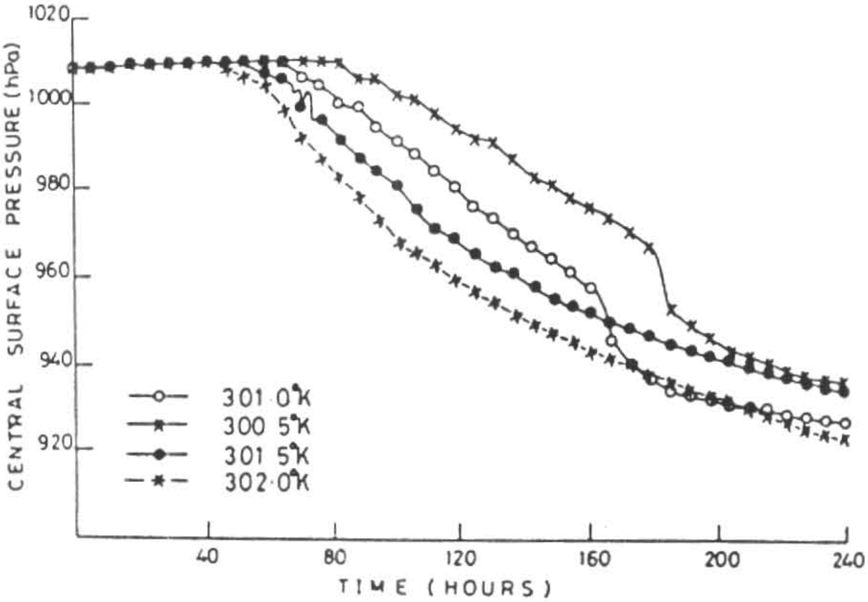


Fig. 7. Time variation of the central surface pressure (hPa) for different SST values

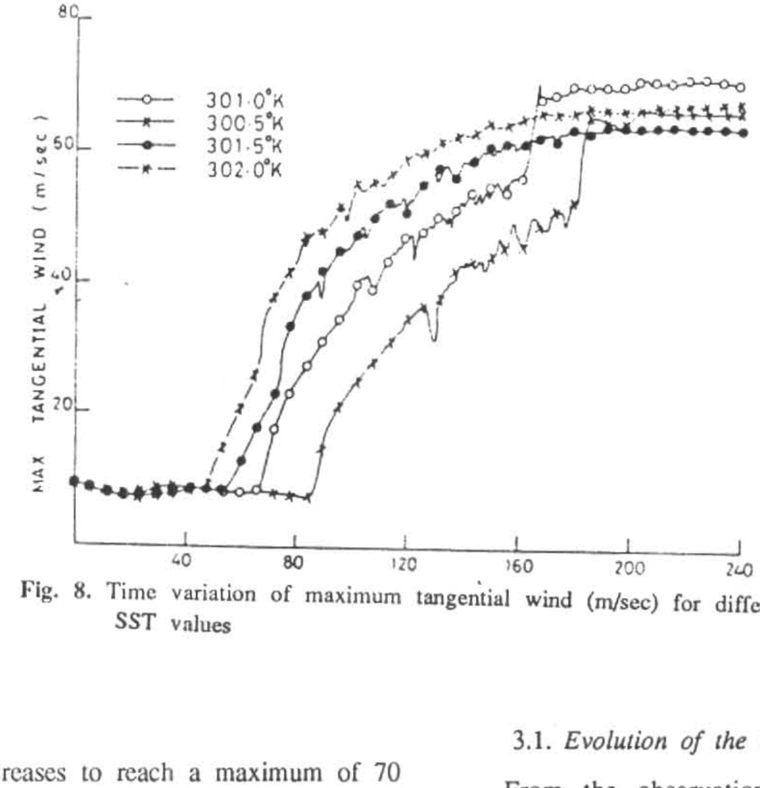


Fig. 8. Time variation of maximum tangential wind (m/sec) for different SST values

then gradually increases to reach a maximum of 70 m/sec at 180 hr. The cyclone intensity tangential winds initially were confined to the central 60-100 km region at 80 hr which then extends to a region of 20 to 250 km region as the system intensifies. The maximum V_θ moves inward in the beginning and moves outward during the deepening stage.

3.1. *Evolution of the vortex*

From the observations noted in the previous paragraph it is clear that the attainment of mature stage of the cyclonic vortex is at about 180 hr. The structure of the circulation at 180 hr corresponding to the mature stage is presented in Fig. 6. It is observed that the tangential wind reached a maximum of 65 m/sec.

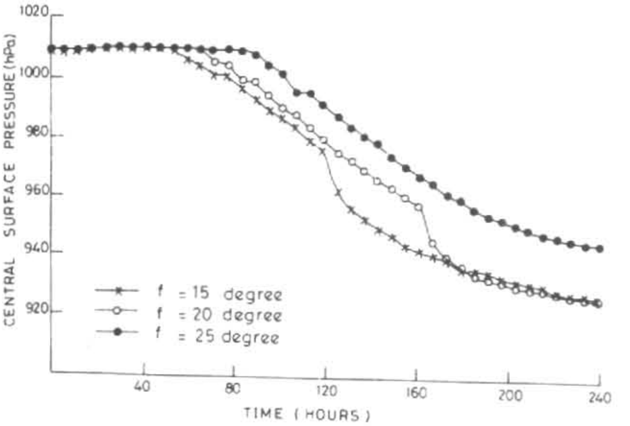


Fig. 9. Time variation of the central surface pressure (hPa) for different latitudes

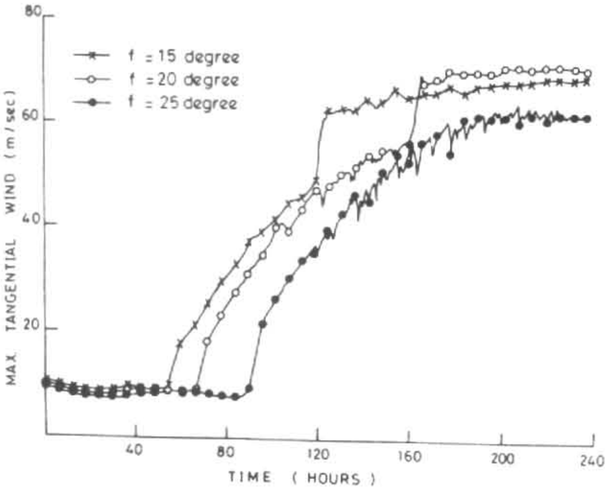


Fig. 10. Time variation of maximum tangential wind (m/sec) for different latitudes

The height - radius section of radial wind (Fig. 6a) shows strong inflow at the lower levels with a maximum of 20 m/sec below 2 km in the central region of 40-200 km radius, and an outflow at the upper levels. The tangential wind field (Fig. 6b) shows cyclone intensity winds in the central region of 20-250 km at the lower levels, which decrease to about 20-100 km region at 16 km. This indicates a strong and vigorous cyclonic circulation extending to the whole of the troposphere at the central core region of 200 km radius. A central maximum of 65 m/sec is obtained at 60 km radius between 1-3 km. The vertical wind field (Fig. 6c) shows strong ascending motion in the 40-60 km radius with a maximum of 300 cm/sec at 10 km level. Descending motion is observed at the central core within a radius of 30 km. This indicates the presence of convection in the region of ascending motion and subsidence at the centre it demonstrates the formation of an 'eye' at the centre. The temperature field (Fig. 6d) shows warming of the atmosphere in the central 150 km radius with maximum warming occurring at 10-12 km. A cold region is clearly observed in the lower stratosphere above 16 km. The relative humidity field (Fig. 6e) shows dry region in a narrow column within 30 km radius which corresponds to the region of subsidence. Deep moist region with relative humidity exceeding 90% is observed throughout the troposphere in the 40-70 km radius which corresponds with the region of active convection and the outflow region.

The above described features of the circulation at the mature stage of the evolution of the vortex clearly demonstrate the development of the weak initial vortex into an intense cyclonic storm. The inflow and outflow features observed in the radial wind field, which correspond to the vertical motion alongwith the maximum of the tangential wind and the moist and dry regions noted in the relative humidity field and the intense warm core clearly show all the features of a cyclonic system. Distinct formation of 'eye' at the narrow central core region is a significant feature of the simulated cyclone. Simulation of all these features indicate that the numerical model and the Emanuel convection scheme described in section 2 produce the features of the evolution of a vortex into a mature cyclone.

4. Sensitivity experiments

As the model could successfully simulate the features of the tropical cyclone, two types of sensitivity experiments were made. One set of experiments is performed with the variation of SST values fixed at 300.5°, 301.0°, 301.5° and 302°K. The time variations of the CSP and the MTW corresponding to the four experiments with different SST values are shown in Figs. 7 and 8. The time variation of the CSP (Fig. 7) shows that with the increase of SST the deepening is more rapid during 80-160 hr. The time taken for the deepening is about 180 hr with SST at 300.5°K while it is about 160 hr in the other experiments. The CSP decrease from 1010 hPa is about 40, 55, 60 and 70 hPa at SST values of 301°, 301.5° and 302°K respectively. The features at the mature stage are similar in all the four experiments and are not presented here.

The time variation of MTW shows (Fig. 8) rapid increase with increase of SST during the deepening stage which corresponds to the variation of the CSP noted above. The MTW attained at the mature stage is nearly same in all the four experiments. However it is observed that the MTW attained in the experiment with SST at 301°K reached the highest when compared with the other three experiments by about 5 m/sec. This shows that the pressure gradient at the centre in the experiment with SST equal to 301°K is slightly more than the other experiments. This may be due to the behaviour of the convection scheme and is to be further examined.

Another set of experiments has been performed with the variation of latitude. This has been done by changing the value of '*f*' to be at 15°, 20° and 25° latitude. The time variation of CSP shows (Fig. 9) that the deepening is more rapid at lower latitudes. The pressure decrease during the deepening stage from 80-160 hr is about 40, 55 and 70 hPa for *f* at 25°, 20° and 15° latitude respectively. The minimum CSP attained is lower by about 20 hPa in the experiments with 15° and 20° latitude compared with experiments with 25° latitude. This agrees well with the observations. The time variation of MTW (Fig. 10) shows rapid increase of the MTW during the deepening stage which corresponds with the variation of CSP noted above. The MTW attained is nearly the same in the experiments with *f* at 15° and 20° latitude while in the experiment with 25° latitude the MTW is less by about 10 m/sec.

The above described sensitivity experiments with the variation of SST and with latitude show differences in the intensity of the simulated cyclone which agree with the observations and simulation results of other workers. (Bhaskar Rao and Ramakrishna 1994, Baik *et al.* 1990a, b).

5. Summary and conclusions

In this paper the evolution of an initially balanced weak vortex has been studied using the recently proposed Emanuel's convection scheme in a numerical model. The numerical model is an axi-symmetric, primitive equation, hydrostatic, finite difference model with a vertical resolution of 1 km from 0 to 18 km. A horizontal domain upto 3114 km is used with a resolution of 20 km upto 400 km radius and increasing radial distance beyond 400 km. The convection parameterization scheme is based on episodic mixing concept and assuming 100 m scale vertical drafts.

The result of a control simulation has shown that the convection scheme is successful to simulate the development, intensification and mature stages of a tropical cyclone from a weak vortex. Starting from a vortex with an initial tangential wind of 9 m/sec and central surface pressure of 1008 hPa, the simulated cyclone reached a CSP of 930 hPa and attained a MTW of 70 m/sec. The circulation features of the mature stage showed a clear inflow and outflow regions associated with intense cyclonic winds; strong ascending motion in the region of active convection; descending motion in a narrow central core region and a strong warm core and the formation of an 'eye' at the centre. All these features clearly demonstrate the successful simulation of an intense cyclonic storm.

Two sets of sensitivity experiments have been performed in relation to variation in SST and latitude. The model sensitivity experiments clearly indicated the strong dependence of cyclone intensification on SST. The rate of intensification is rapid when the SST increased from 300.5° to 301° K while it is small when SST varied from 301° to 302° K. Sensitivity experiments with the variation of latitude have shown that at lower latitudes of 15° the intensification is more rapid than at higher latitudes of 20° and 25°.

The purpose of this study was to investigate the use of Emanuel's new convection scheme to simulate the developmet of a tropical cyclone. This scheme is found to be successful in simulating all the observational features of a tropical cyclone and the heating and moisture profiles are found to be realistic. The convection scheme presently uses some parameters, which are to be defined, that have a control on the development of convection. Sensitivity studies in relation to these parameters are under progress.

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