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Tropical cyclones - Synoptic methods of forecasting

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सार — उष्णकटिबंधीय चक्रवात सबसे विनाशकारी प्राकृतिक आपदा है, जो जान तथा माल को क्षति पहुँचाती है। चक्रवात के साथ चलने वाली प्रबल पवन, भारी वर्षा और समुद्र में उठने वाली तरंगें ऐसी परिघटनाएँ हैं जो क्षति पहुँचाने के लिए उत्तरदायी हैं। आने वाले चक्रवातों के संबंध में समय पर चेतावनियाँ जारी करके चक्रवात से होने वाली जान-माल की क्षति में कुछ कमी की जा सकती है। चक्रवात के बनने, उसकी संरचना और गति का पूर्वानुमान प्रस्तुत करने के लिए उसके क्रमिक विकास तथा आगे बढ़ने की चाल को अच्छी तरह समझना चाहिए। इस लेख में चक्रवात के लक्षणों तथा उसकी संरचना से संबंधित साहित्य की समीक्षा करने का प्रयत्न किया गया है। चक्रवात के बनने और आगे बढ़ने के पूर्वानुमान से संबंधित सिनॉप्टिक विधियों की भी समीक्षा की गई। चक्रवात के क्यू. बी. ओ. और ई. एन. एस. ओ. (एन्सो) के साथ संबंधों पर उपलब्ध साहित्य के बारे में भी संक्षेप में यहाँ बताया गया है। प्रचालन पूर्वानुमानकर्ता के लिए उपयोगी कुछ पूर्वानुमान संबंधी नियमों का भी उल्लेख किया गया है।

ABSTRACT. The tropical cyclone is one of the most destructive natural disasters which is capable of causing loss of life and damage to the property. Strong winds, heavy rains and storm surges associated with the cyclones, are the phenomena which are responsible for causing the damage. The issue of warnings about the impending cyclones in time help to reduce the loss of lives that the cyclone causes. To forecast its formation, structure and movement, the processes involved in its evolution and subsequent movement, are to be understood well. In this article an attempt has been made to review the literature about the cyclone characteristics and its structure. Synoptic methods of forecasting its formation and movement are also reviewed. Existing literature on their association with QBO and ENSO is also summarised. Some forecasting rules that may be of help to an operational forecaster are mentioned.

Key words — Genesis parameter, Ekman pumping, Eye formation, Mesoscale convective system, Low level circulation centre, Outer core region.

1. Introduction

Tropical cyclones are intense low pressure systems in the atmosphere, which are conceived over warm tropical oceans, born among torrential thundershowers, and maintained by the convergence of moisture towards the central regions from far away. They are the most destructive of all natural disasters, capable of destructing many coastal cities and killing several thousand people. The major causes of damage are strong winds, storm surges and torrential rains associated with them. In fact, the available statistics the world over shows that the tropical cyclones are far ahead of any other disaster as killers, accounting for about 64% of the total lives lost. Individual tropical cyclones are capable of causing catastrophic losses of life. Though smaller in size than their counterparts in extratropical latitudes, the hurricanes are associated with violent winds near the centre and cause copious amounts of rainfall. The associated winds are often exceeding 200 kmph, rainfall exceeding 50 to 100 cm in a day, and worst of all very high storm tides often exceeding 7 metres cause disaster over the coastal areas wherever they strike. In extreme cases, a wind speed of 320 kmph gusting to 360 kmph, rainfall of 120 cm in 24

TABLE 1

Damage due to severe cyclonic storms in north Indian Ocean that affected the Indian coast during 1987-1996

Year	Dates	Landfall point	No. of lives lost	Damage (estimated)
1987	31 Oct-3 Nov	North of Nellore	78	18,120 houses damaged, 2.64 crores
1987	11-13 Nov	South of Machilipatnam	28	8000 houses damaged, 7 lakh acres of paddy crops affected
1988	23-30 Nov	Near Sagar Island	532	1,31,794 houses damaged, Rs. 137.77 crores
1989	23-27 May	40 km NE of Baleshwar	38	22400 houses damagd, Rs. 1.42 crores
1989	4-9 Nov	Near Kavali	55	1,49,000 houses damaged, crops in 62,380 hectres damaged
1990	5-10 May	Near Machilipatnam	969	6,59,000 houses damaged, Rs. 2,248 crores
1992	11-17 Nov	Near Tuticorin	294	Rs. 530 crores
1993	1-4 Nov	Near Karaikal	100	Rs. 700 crores
1994	29-31 Oct	Near Madras	304	Rs. 361 crores
1995	7-10 Nov	Near Tuni in AP	73	Rs. 1.5 crores
1996	18-20 June (Arabian Sea)	Near Diu in Gujarat	33	Rs. 6.84 crores

(Source : State Govt. reports)

hours and a storm surge of 13 to 14 metres have been recorded in association with tropical cyclones. Out of these, the most destructive phenomenon, which causes over 90% of the loss to life and property, is the storm surge. The storm surge is a rapid increase in sea level along the coast and is caused primarily by winds driving the water ashore. The devastating damage by the surge occurs if the storm crosses the coast at the time of high tide. Such was the case, when a cyclonic storm crossed Bangladesh coast in November 1970, when 3,00,000 people lost their lives. The damage that occurred during the past decade due to severe cyclonic storms in the north Indian Ocean is given in Table 1. The effects of high winds and storm surge are concentrated to within a few kilometers of the coast. The third important aspect of tropical cyclones is heavy rainfall which often affects areas hundreds of kilometers from the coast which may lead to flooding. The only positive consequence of a cyclone is that it provides rainfall essential over vast areas on the land when it crosses the coast.

Tropical cyclones are known by different names in different parts of the world. In the Atlantic and eastern Pacific they are called hurricanes, derived from the world Huracan (God of Evil), a name comes from an ancient tribe in central America. In the western Pacific they are known as "Typhoons" and in the Philippines they are called as "Bagious". In the north Indian Ocean they are called "Tropical Cyclones". The tropical cyclones are classified by the wind speed, estimated or observed with the system, as indicated below :

Name	*Wind speed*	
	(knots)	*(kmph)*
Low pressure	< 17	< 31
Depression	17-27	31-49
Deep depression	28-33	50-61
Cyclonic storm	34-47	62-88
Severe cyclonic storm	48-63	89-117
Severe cyclonic storm with core of hurricane winds	≥ 64	≥ 118

(a) *Geographical & seasonal distributions*

Each year about 80 tropical cyclones occur over the earth. Of these one half to two-thirds become hurricanes. About two thirds of all cyclones form in the northern hemisphere (NH). Tropical cyclones do not form in the south Atlantic and eastern south Pacific. They do not form within 4-5° of the equator and only a few form poleward of 22° N. About 65% of the cyclones form in the zone between 10° and 20° from the equator. The formation of tropical cyclones in the eastern and western hemisphere is in the ratio of 2:1. The frequency of formation is maximum during the summer to early fall with peak occurring during January to March in the southern hemisphere(SH) and July to September in the northern hemisphere, with the exception of the north Indian Ocean. The ratio of yearly northern to southern hemisphere cyclone frequency varies from 1.5 to 4.0.

The long time average of tropical cyclones in the north Indian Ocean is about 5.6 per year, which is the least in the world and is about 7% of the global total. Out of these 6 tropical cyclones, 2-3 intensify to the severe cyclonic storm stage.

The frequency of tropical cyclones in the Bay of Bengal is more than that in the Arabian Sea. About 35% of the initial disturbances reach tropical cyclone strength, while 45% of these cyclones reach the severe tropical cyclone stage. The seasonal variation has a bimodal distribution with the primary peak in November and a secondary peak in May. During the monsoon season, these disturbances form in the north Bay and generally move westwards. Since the time available for these systems over the ocean is not large enough, before encountering the Indian land mass, they do not attain the structure of tropical cyclone. This is the basic reason why tropical cyclones do not form in the north Indian Ocean during June to September. Another reason for their failure to attain cyclone stage is the prevalence of high vertical wind shear over north Bay of Bengal during monsoon season.

2. Life cycle of a tropical storm

The average life period of storms and depressions in the north Indian Ocean is about 4-5 days in the post monsoon months. Storms of hurricane intensity, have an average life period of 2-4 days in the north Indian Ocean, as against the world average of 6 days. The entire life period of tropical cyclones is divided into four stages. They are (*i*) Formative; (*ii*) Immature; (*iii*) Mature and (*iv*) Decaying Stage.

2.1. *Factors favourable for cyclogenesis*

Based on observational evidence of large number of storms in the Pacific and Atlantic, Gray (1968) identified the following environmental factors favourable for cyclogenesis.

(a) *Low level relative vorticity*

A strong correlation exists between the location of tropical storms and large values of low level vorticity. According to McBride (1974) the low level vorticity in developing cloud clusters is twice that in non-developing disturbances. In a developing tropical disturbance, the effect of intense convection is to generate a convergent low level wind field as air flows in towards convection. This convergence produces an increase of relative vorticity. Surface friction in the presence of low-level vorticity produces upward motion in regions of positive vorticity and sinking motion, where the relative vorticity is negative. Therefore, the regions of low level positive vorticity are associated with enhanced upward motion, cumulus convection and release of latent heat. The increased heating leads to increase in horizontal convergence which in turn increases the relative vorticity.

(b) *Coriolis parameter*

Since the Coriolis parameter is very small near the equator, tropical storms do not form in that region. This parameter is combined with the first one by Frank (1977) into absolute vorticity.

(c) *Weak vertical wind-shear of horizontal winds*

This factor is related with the interaction of a disturbance with the larger scale tropical circulation. Low vertical wind shear is essential for a disturbance to develop as the latent heat generated during the convective processes is not advected away from the circulation field. Moreover, during the formative stage, if the disturbance comes under the divergent portion of an upper air trough and when the low level convergent region is superimposed by the upper level divergence associated with the trough, it gets accumulated. The surface low tends to deepen and as a result, the surface pressure would fall, convection is enhanced by large scale lifting and the low level convergence is increased. The disturbance tends to spin up. On the other hand, if the disturbance comes under the upper level convergence field, it would weaken and dissipate ultimately.

(d) *Sea surface temperature (SST) & depth of warm water*

The threshold value of the sea surface temperature, below which tropical cyclones do not form, is 26.5°C.

Since cooler temperatures prevail in the southeast Pacific and south Atlantic, no cyclones form in these regions. Recent estimates by Frank (1977) from the composited radiosonde data, indicated the magnitude of the sea to air flow of sensible plus latent heat in the average typhoon in about $62\text{X}10^6\ \text{Jm}^{-2}\ \text{d}^{-1}$ (712.21 $\text{Watts/m}^2/\text{d}^1$) in the inner 80 km. This large surface energy requirement inhibits the formation of tropical cyclones over land. Due to the above requirement of energy, the cyclones can weaken when they cross the track of a previous cyclone which has produced a lower sea surface temperature due to upwelling and evaporation.

(e) *Degree of convective instability as given by* $\partial\theta_e/\partial p$

The vertical gradient of equivalent potential temperature $\partial\theta_e/\partial p$ represents the degree of convective instability. Since deep cumulus convection is essential for mature tropical cyclones, it would appear that strong convective instability (large $\partial\theta_e/\partial p$) would be associated with tropical cyclogenesis. Since the tropical atmosphere is conditionally unstable in both winter and summer and daily variations in $\partial\theta_e/\partial p$ being small, it appears that the variation in magnitude of surface θ_e is the only measure cyclogenesis. Since convection is typically associated with a substantial decrease of θ_e between the boundary layer-and the middle troposphere, the optimum θ_e gradients between surface and 500 hPa appear to be between 15 to 20°K according to Gray (1968).

(f) *Large value of relative humidity in the lower and middle troposphere*

This is an important parameter for tropical cyclone formation. Regions with low relative humidity in the middle troposphere are unfavourable for cyclogenesis for two reasons. Firstly, the convective clouds which originate in the boundary layer are eroded by entrainment of dry air as they rise through middle troposphere.

Secondly, much of the mass convergence takes place in tropical cyclones, above the boundary layer, dry middle level air means less total moisture convergence in a column and less latent heat release. Though this parameter is important for tropical cyclogenesis, this does not differ significantly in convective systems which intensify into tropical cyclones and those which do not (McBride 1979).

2.2. *Gray's parameter 'P'*

By taking these six parameters, Gray designed a parameter '*P*' known as genesis parameter which is represented by

$$P = f(\xi_r + 5)\ [1/(S_z + 3)]\ E(\partial\theta_e/\partial p + 5)\ \ [(\text{RH-}40)/30]$$

where, ξ_r is the relative vorticity, f is the Coriolis parameter, S_z is the vertical wind shear between 900 and 200 hPa, E is the ocean energy measured in terms of excess of sea surface temperature over 26°C and expressed as $E = {}^{0}\!\int \rho\, c(T-26)\, dz$ or when temperature is 26°C. Where ρ is the density of sea water, c its specific heat, T is the surface temperature, θ_e is the equivalent potential temperature and RH is the mean relative humidity between 500 and 700 hPa.

The threshold value of P for Pacific cyclones is $305.6\ \text{X}\ 10^{-4}\ [\text{Watts/m}^2/\text{d}]^{\circ}\text{K/m}$, while that in the case of the Arabian Sea cyclone on 18 June 1979 was obtained as $318.1\ \text{X}\ 10^{-4}\ [\text{Watts/m}^2/\text{d}]^{\circ}\text{K/m}$ (Mandal *et al.* 1981). However, to obtain an average value of P for the cyclones of north Indian Ocean, a large number of cases need to be studied, but due to the non-availability of upper air observations over the oceans it is not possible to do so.

The product of first three parameters is defined by Gray as dynamic potential for cyclone development, as they are the functions of horizontal dynamics while the product of the last three is defined as thermodynamic potential.

The thermodynamic potential varies slowly with time in the cyclone season, while the dynamic potential can change dramatically through synoptic activity (Gray 1975). Hence, cyclone formation takes place during periods when the dynamic potential exceeds its climatological mean.

2.3. *Synoptic scale features favourable for cyclone formation*

(*i*) Tropical cyclones form from pre-existing disturbances containing abundant deep convection.

(*ii*) The pre-existing disturbance should acquire warm core through the troposphere.

(*iii*) Prior to the formation, the lower tropospheric vorticity increases over an horizontal area of 1000-2000 km.

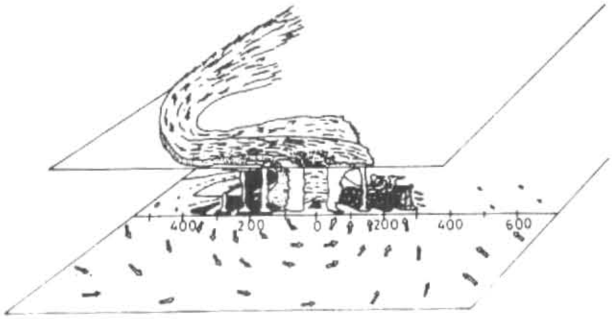


Fig. 1. Schematic three-dimensional view of hurricane (Stormfury 1970)

(*iv*) The vertical wind shear of the horizontal wind (*U*- component) should be low in the environment on a large scale.

(*v*) Formation often occurs in conjunction with an interaction between the incipient disturbance and an upper tropospheric trough.

(*vi*) Existence of low level wind surges that propagate inward to the centre of the incipient disturbance.

(*vii*) Appearance of curved banding features in the deep convection of the incipient disturbance is an indication of the cyclone development.

Though the above conditions are, in general, required for the formation of tropical cyclone, all cloud clusters do not develop into cyclones. The developing systems differ from the non- developing ones in the following respects:

(a) The warm area at 300 hPa and the low-level height anomaly are much more pronounced in the developing system.

(b) Existence of low level wind maximum.

(c) The developing system has an upper level anticyclone while the non-developing does not have it.

(d) Low level easterlies to the north of the system should persist.

(e) Warmer atmosphere over a large horizontal scale about 8° radius in all directions.

(f) Large positive zonal shear poleward and negative zonal shear equatorward and southerly shear to the west and northerly shear to the east. The scale of this shear pattern is over a 10° lat. radius circle.

3. Formative stage

In this stage one or more of the following developments take place :

(*i*) Unusual falls of pressure in and around the centre of deepening easterly wave.

(*ii*) Asymmetric strengthening of wind and appearance of gale force in one sector but not of hurricane force.

(*iii*) On ITCZ large elliptical or circular wind circulation develops.

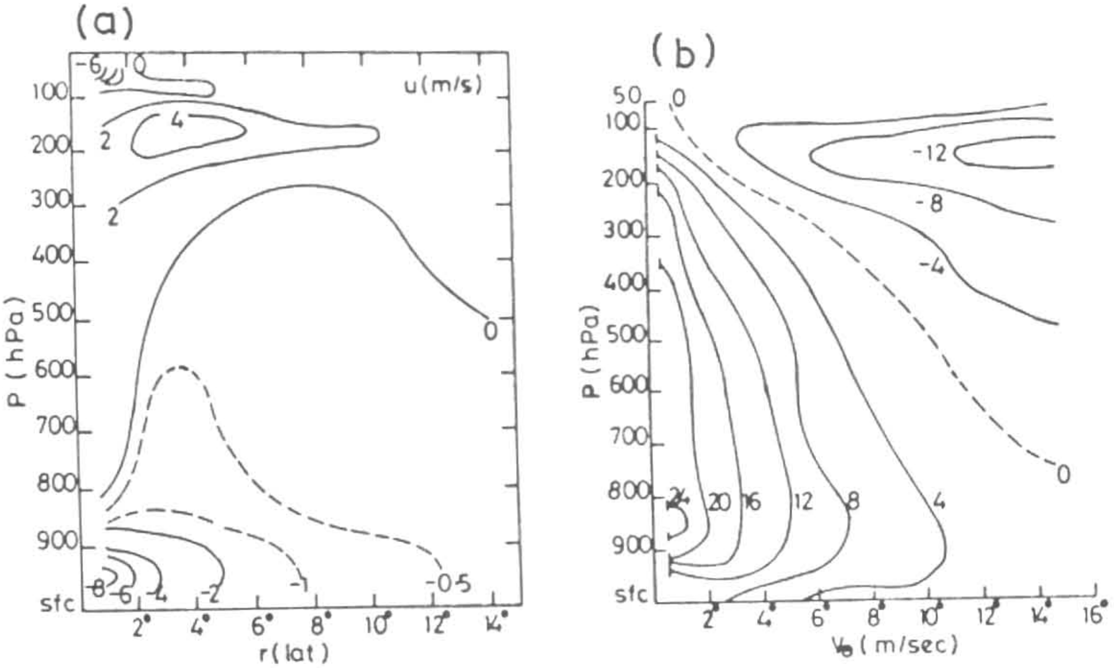
(*iv*) Satellite pictures show isolation of marked cloud mass from other nearby cloud areas.

4. Immature stage

In this stage the wind increases to hurricane force, usually at a distance of about 50 km from the cyclone centre and pressure fall increases. Intensification may be slow taking as much as 3 days or it may be an explosive occurrence in a few hours. The cloud and rain pattern changes from disorganized squalls to narrow organized bands spiralling inward.

5. Mature stage

During the mature stage the central wind speed need not increase and pressure need not fall. But the circulation expands and in moving storms, hurricane winds may extend several hundreds of kilometers from the centre to the right of the direction of motion (in NH). A well-formed inner ring of maximum winds encircles the "eye", where pressure stops falling, wind is light, rainfall ceases and clouds disappear. Even in this stage, the hurricane may undergo wide fluctuations



Figs.2(a&b). Vertical cross section of radial winds (ms^{-1}) for (a) western Atlantic composite hurricane (Gray 1979) and (b) the Pacific composite typhoon (Frank 1977)

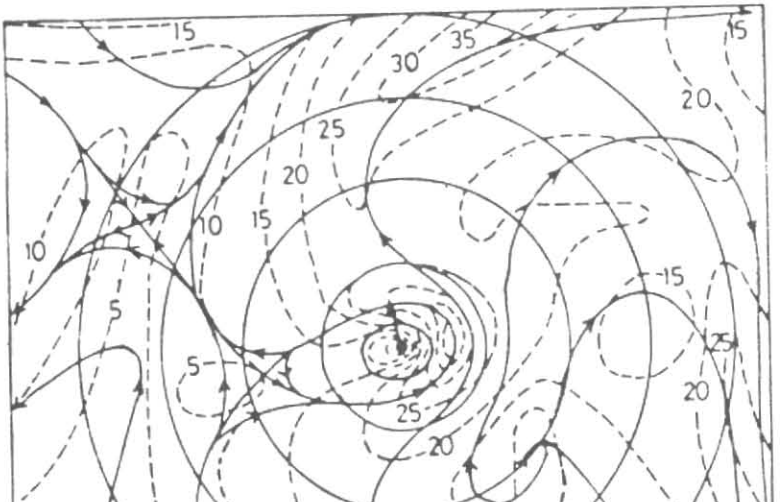


Fig. 3. Upper level (200 hPa) streamlines and isotachs (ms^{-1}) for hurricane Camille (1969) (Black and Anthes 1971)

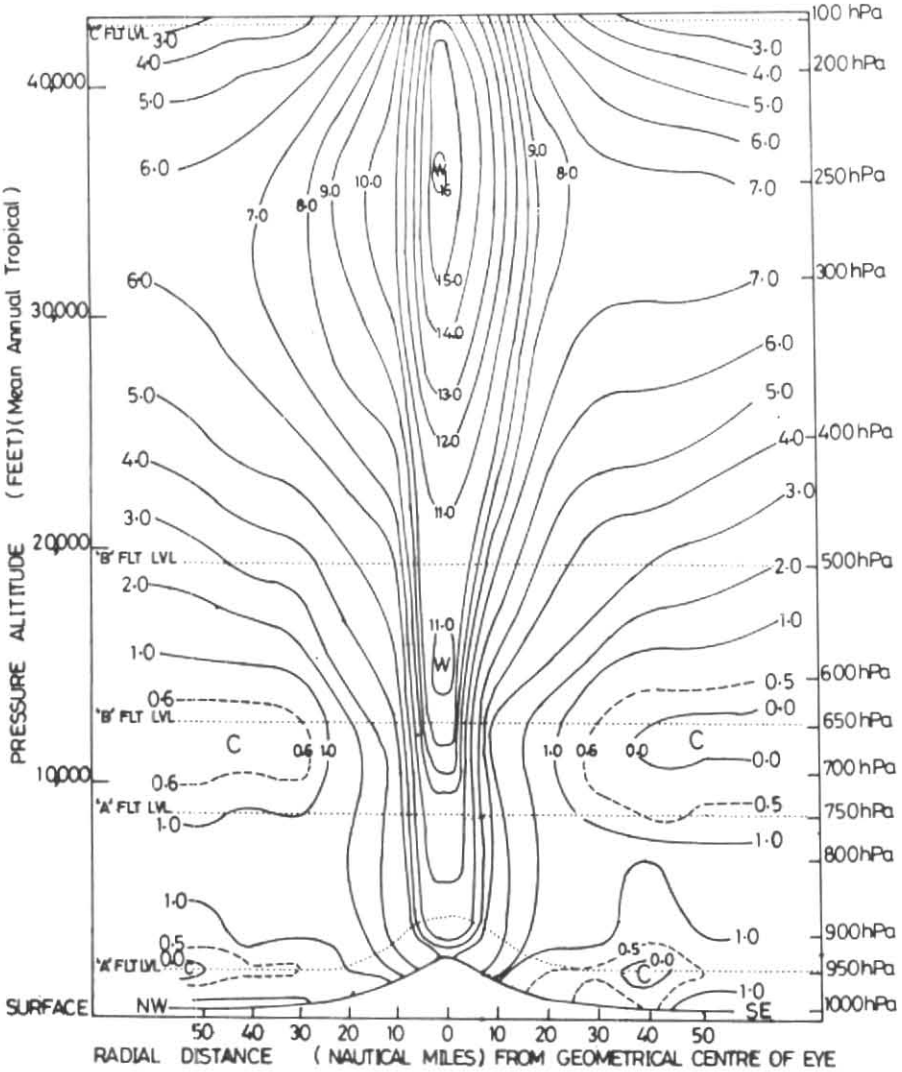


Fig. 4. Vertical cross sections of temperature anomaly for hurricane Inez on 28 September 1996 (Hawkins and Imbembo 1976)

in its intensity; pressure in the centre may increase or decrease by as much as 60 hPa in a day. The structure of a mature cyclone is shown in the Fig. 1.

In the lower levels the wind spirals cyclonically inward towards the low pressure increasing in speed nearer to the centre. At large distances from the centre the low level winds are divergent and the associated subsidence produces low relative humidities and clear skies. At a distance of about 400 km from the centre the inflowing air becomes convergent, the mean vertical motion is upward resulting in cumulus convection. The intensity and the tops of convection depend on the thermodynamic stability of the middle and upper troposphere and the rate of low level moisture convergence. Deep convection produces dense cirrus overcast at the tropopause.

The convective clouds align themselves in bands that spiral around into the storm. Due to the strong radial pressure gradient, the air is pulled closer to the storm centre and by the law of conservation of angular momentum its radial velocity increases. With the increase of radial and tangential wind speeds, low level moisture convergence also increases and so does the rainfall.

At a certain distance which varies from 10 to 100 km the inflowing air suddenly turns upward in a ring of intense convection surrounding the centre. This ring or wall of convection is called an "eye wall" and it is here that the strongest wind speeds and heaviest precipitation occur, sometimes of the order of 50 cm day^{-1}.

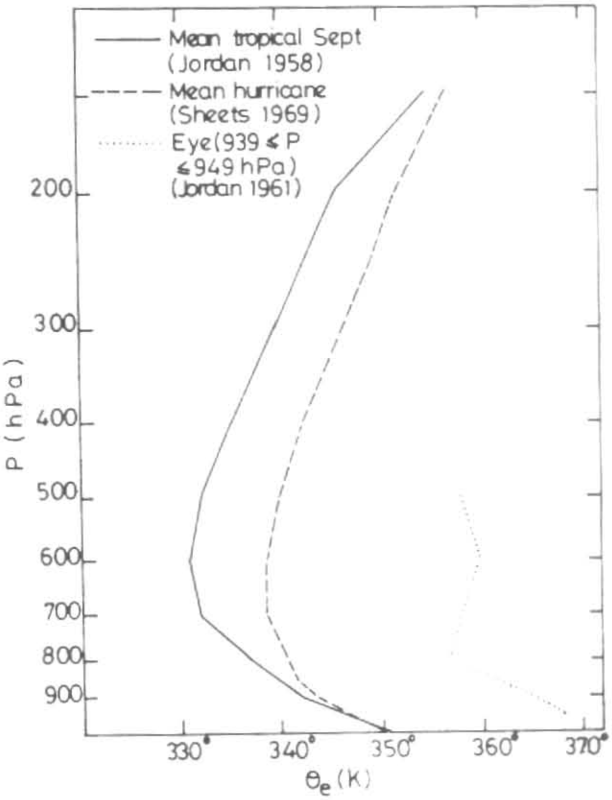


Fig. 5. Vertical profiles of equivalent potential temperature for mean tropical September sounding, mean hurricane within 100 n mi of centre, and mean eye of storms with 939 < p_{min} < 949 hPa

Inside this radius, the winds and precipitation decrease rapidly. Shallow cumulus clouds or clear skies may prevail. This region is called the "eye" of the storm which is easily recognized in satellite or radar pictures unless the cirrus canopy covers it.

When the air rising in the eye wall encounters the strongly stable air in the stratosphere, it turns outward and flows away from the storm centre. The cyclonic rotation rapidly decreases and the air acquires anticyclonic rotation (outflow), typically at a radius of about 300 km.

The distribution of wind, pressure and temperature in a typical mature hurricane is given below:

(a) *Wind distribution*

Fig. 2(a) gives the distribution of radial wind in a hurricane. Near the surface, due to the retarding effect of the surface friction, the component towards the lower pressure at the storm centre increases (–ve values indicate inflow towards the centre). The strongest inflow occurs at an elevation of 500 m, although weak inflow occurs upto 3 km or more. Above this height the flow gradually reverses its direction, being stronger at about 200 hPa. In Fig. 2 (b) the tangential wind component is shown. Though the radial wind component is significant component below 1 km, the tangential component dominates through most of the troposphere. It varies very little with height.

From the above wind distribution, a cyclone can be divided into three layers, vertically as follows:

(*i*) The lowest layer from the surface upto 3 km is called the inflow layer, where the radial component is significant and the flow is towards the cyclone centre.

(*ii*) The layer between 3 and 7.6 km is called the middle layer. The flow is mostly tangential with no radial component.

(*iii*) The layer between 7.6 km and the top of the storm is called the outflow layer where the wind is anticyclonic. Pronounced outflow is seen around 200 hPa. In this layer the radial component has a significant value but it is now outward (Fig. 3).

The vertical cross section of wind speed for hurricane Inez indicated the two significant features: (a) slow increase of wind speed as the centre is approached from outside and (b) a rapid decrease inside the radius of maximum wind, a regime of weak vertical wind shear between 900 and 400 hPa.

(b) *Pressure and temperature distribution*

A reliable sign of an approaching hurricane is the fall of pressure, slowly at first, then more rapidly as the eye approaches. Sea level pressure varies from a mean value of 1013 hPa in the environment to below 900 hPa in extreme cases.

The lowest ever recorded pressure is 870 hPa in typhoon 'Tip' in 1979. The sea level pressure varies exponentially with the radius out to a distance of 10 times of radius of maximum wind. The greatest pressure gradient occurs between the eye and about twice the radius of maximum wind.

The vertical cross section of temperature anomaly in the case of hurricane Inez is given in Fig. 4. Most of the hurricanes exhibit similar features. The interesting feature is the concentrated core of warm air with temperatures 15°K above the mean tropical values. The greatest anomaly occurs at 250 hPa and a strong

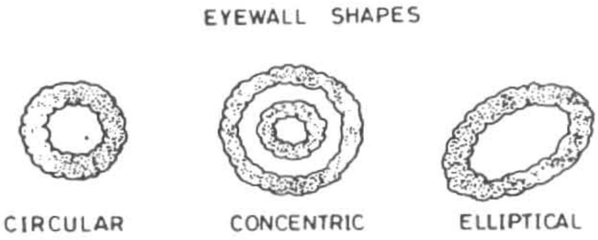


Fig. 6. Schematic depiction of three types of eye-walls observed: circular, concentric and elliptical

radial gradient exists across the eye-wall.

Presence of cooler air, in the region of precipitation, between 30 and 60 nautical miles, in the layer from the surface to 600 hPa can be seen. The static stability of the hurricane and its environment can be obtained by plotting the vertical profiles of equivalent potential temperature as shown in Fig. 5.

(c) *Eye formation*

In most of the mature hurricanes, eye formation takes place where the weather is absent and subsidence is observed. Any theory provided to explain the formation of the eye in a hurricane must be able to explain the phenomenon of why the maximum upward motion occurs at some distance from the centre of the storm rather than at the centre and the reason for the occurrence of the subsidence with the eye. Though a number of theories are formulated, no single theory is able to explain both the phenomena. However, modelling and synoptic studies have provided some insight into the problem.

The frictional forces in the boundary layer cause the flow to deviate from the gradient balance, which while inducing the vertical motion at the boundary layer, produces inflow towards the lower pressure. The horizontal divergence of this radial flow induces either upward or downward motion depending on the radial variation of the tangential flow. This is called "Ekman pumping". According to Eliassen (1971), for a circular vortex of solid rotation Ekman pumping becomes inefficient near the axis of rotation. Thus the maximum upward motion at the top of the boundary layer occurs at some distance outward from the centre. Though the intensity of the vertical velocity thus produced, is affected by the release of latent heat, it can reasonably be assumed that boundary-layer processes play an important role in determining the horizontal position of the maximum upward motion (surrounding the eye) in the hurricane, the occurrence of the subsidence is not explained by this argument.

Different theories and observations lead to the following conceptual model of eye formation. As a tropical storm intensifies, the air rises in vigorous thunderstorms and tends to spread out horizontally near the tropopause. As air spreads out aloft, a positive perturbation pressure at high levels is produced, which accelerates downward motion next to the convection. With the inducement of subsidence air warms up by compression and warm "eye" is generated.

Weatherford (1987) investigated 101 cyclones over the Pacific during the period 1980-84 and his findings about the "eye" of the storms are summarised below:

(*i*) Basically three shapes of "eye" walls are observed. They are: (a) circular, (b) concentric and (c) elliptical as shown in Fig. 6.

(*ii*) The size of the "eye" varied from 7 to 220 km in diameter for the typhoons and the averaged value is 42 km. The measurement of the diameter may be classified into 4 groups as : (a) small eyes (0-28km), (b) medium eyes (28-55 km), (c) large eyes, (> 55 km) and (d) cyclones exhibiting no eye. Medium "eyes" are the most common. It is also noticed that the intensity of the cyclone does not determine the size of the eye.

(*iii*) The eye contracts while the cyclone intensifies and expands at the time of filling up of the system. Small scale fluctuations can occur. There is a period of time, common to the most intense cyclones in which the eye reaches a minimum size and remains locked even though the central pressure continues to fall.

(*iv*) The initial eye was often elliptical and became more circular with intensity. Large changes in the elliptical size are typical. Elliptical eyes changed in diameter on an average over every 12 hours as opposed to circular eyes which expand or contract on an average 2 km/12 hr. Elliptical eyes generally appeared in the early stages or late filling stages of the cyclone. Elliptical eyes are rarely found in intense stages.

(*v*) The eye in a cyclone normally develops when the pressure falls to 980 hPa. If the eye develops at an early stage (985 hPa), the cyclone deepens rapidly and the eye generally is small. In the case of rapid deepening the pressure decreases typically by 42 hPa/day. Cyclones forming an eye at higher pressures than the average, fall into the early class while those whose eyes form after the average pressure fall into the late class. Cyclones which develop an early eye are normally located farther southeast than the others. Maximum wind speeds were the same but their outer core strength (OCS-area weighted tangential wind) were less. Cyclones forming early eye had significantly greater inflow inside 150 km from the centre. The ease with which a cyclone can import momentum through the outer core (1-2.5° radius from the centre) and near the centre is vital to its further capacity to intensify. It is for this reason, that the cyclones forming early eye deepen rapidly before, the OCS strengthens so that the transport of momentum into the inner core takes place without any hindrance.

(*vi*) As the cyclone intensifies, the eye becomes smaller and circular and once it obtains its maximum intensity it usually exhibits the smallest eye and reaches a minimum value. Further intensification may occur, but the eye does not contract. If at this stage, the pressure falls lower than 945 hPa, concentric eyes form, though it is a rare phenomenon. Whenever concentric eyes are seen, they form on an average 3 days after the initial eye is sighted. Concentric eyes are observed to last only a fraction of a day. The diameter for the concentric eyes are typically 20 km for the inner eye and 55 km for the outer eye.

(*vii*) During the filling stage, the eye wall generally expands until it is so diffuse that it can no longer be recognised as an eye. The faster the filling rate the quicker the eye disappears.

(*viii*) The temperature inside the eye is indirectly an indication of the force of vertical motions in the eye wall convection which in turn induces subsidence warming in the center. The stronger the eye wall convection, the warmer one would expect the eye temperature to be. The eye temperature not only increases with lower central pressure but also with the shape and structure of the eye. The temperature inside the concentric eye is cooler for the same intensity than either a circular or an elliptical eye. The possible reason is that due to the subsidence associated with the development of the outer wall, the inner eye wall vanishes by evaporation. This evaporative cooling would cause a lowering of temperature. The eye temperature is not only strictly a function of its intensity and character but also intensity change. Maximum temperature was found to occur at the time of intensification and not at its maximum intensity, which corresponds to a steady state, nor while filling.

(d) *Moisture and precipitation distribution*

The distribution of absolute and relative humidity in a hurricane is determined by the structure of temperature and vertical motion.

(*i*) Specific humidity is maximum at the surface and decreases rapidly with elevation.

(*ii*) Since the distribution of relative humidity depends over the vertical motion field. The relative humidity exceeds 70% throughout the troposphere inside a radius of 400 km where the mean vertical motion is upward.

(*iii*) Convective clouds cover upto 50% of the area near the centre of the storm. Beyond a radius of 100 km, the active updrafts cover only a small percentage of the area. In this area, dense cirrus overcast occurs. If the subsidence is strong enough and extends to lower levels, a clear area is seen or there may be patches of high and low clouds.

(*iv*) With the availability of an unlimited source of water vapour from the warm oceans, the rainfall rates are maximum in the regions where the horizontal convergence of wind is strong. Strong rainfall rates occur in the eye wall region. The rainfall rates decrease rapidly away from the centre. In immature storms, the rainfall distribution about the centre is not symmetric, heaviest rainfall usually occurs around the right semicircle (in the direction of storm motion). The distribution of rainfall around the storm depends on its direction and speed of motion and the local effects such as topography and orientation of the coast. There is diurnal variation also in the precipitation associated with the storm when it is in mid ocean. Maximum occurs between 1000-1200 hr local time while minimum occurs at 1800 hr LT.

(e) *Rain bands*

The major convective clouds in tropical cyclone have a spirally banded structure as shown by radar and satellite observations. The bands converge toward the centre in a wall of clouds surrounding the "eye". The individual cells in the bands tend to move with the mean wind in the layer, while the band as a whole moves slower than the mean wind. Vertical heat transport and conversion of potential to kinetic energy occurs mainly in the rain bands. Satellite pictures show that the cloud mass is more amorphous in the weaker disturbances and it gets organised as the intensity of the system increases. The bands become very well defined in a severe cyclonic storm.

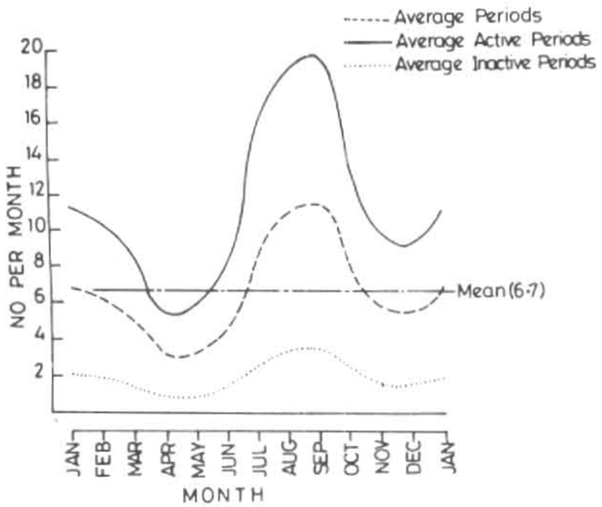


Fig. 7. Annual variation in global tropical cyclone formation, togetherwith the average numbers forming during active and inactive periods. The data used were all named tropical cyclones for the period 1978-1985. (After M. Gray 1993)

Precipitation can be quite heavy in the bands. In regions of heavy precipitation, the temperature may decrease slightly, but on the whole there is little difference across the bands. A possible source of the spiral bands is an instability of the boundary layer flow which is associated with the variation in mean wind direction with height.

5. Decaying stage

The tropical storms begin to lose their intensity when they move out of the environment of warm moist tropical air, or move over land or move under an unfavourable large scale flow aloft. Sometimes they may recurve towards northeast when they come under the influence of an upper air westerly trough due to which they may travel to the regions where ocean temperatures are cooler. When the storm enters the land, it rapidly weakens as the central pressure is filled up at a rate of about 2 hPa/hr. This weakens the radial pressure gradient, and the radius of maximum wind expands outward. The factors that are responsible to weaken the system after entry over the land are : (a) dramatic reduction in evaporation, (b) due to cooler surface temperatures as the land is cooler than ocean and (c) surface friction.

Tropical cyclones in north Indian Ocean generally weaken only after entering the land. Since the sea surface temperatures are above 27°C in the post-monsoon season, cyclone's weakening over oceans due to cooler surface temperatures does not arise. Some of them, in these areas decay over the oceans by entering into the strong vertical wind shear zone generally prevailing in the northern parts of north Indian Ocean.

6. Role of mesoscale convective systems in tropical cyclones

Moist convection in the atmosphere displays a tendency for organisation into mesoscale convective systems. Large convectively active regions contain a variety of mesoscale organisations, in which small systems tend to merge into larger and longer lived systems thus enhancing the rainfall activity. Studies by Ritchie *et al.* (1993) indicate that these systems are present in all stages of a tropical cyclone, besides enhancing the rainfall activity they influence the tropical cyclone motion as well. The authors, while presenting the case studies, explained the meandering motion of the tropical cyclone SARAH over west Pacific in the month of September, 1991, due to its interaction with a convective cluster which developed north of the system.

The interaction between the tropical cyclone and a mesoscale system is similar to that between two cyclones in close proximity, which is commonly known as the "Fujiwara effect". Fujiwara (1923) demonstrated that the relative motion of two adjacent cyclonic vortices was composed of cyclonic orbit around their centroid, coupled with a mutual attraction. The rate of orbit increase as they spiral inward towards one another and eventually the two vortices coalesce into one vortex located at the centroid. However, most interacting cyclones deviate considerably from this idealised model.

Most pairs of cyclones are initially located too far apart to manifest a mutual cyclonic orbit. They approach steadily toward the centroid, often in a centroid relative anticyclonic rotation. The interacting tropical cyclones rarely orbit along a smooth inward spiralling path as shown in the figure. But their separation distance may generally decrease, in some cases they remain equidistant, while in other cases they orbit anticyclonically.

Coalescence of two tropical cyclones into a single cyclone located at the centroid has not been observed. But merger typically occurs when one member of the interacting pair decays and looses its identity as it nears the centre of its companion. The other possibility is that, the two cyclones may escape which may occur as abruptly as the merger. They may move straight outwards in an anticyclonic orbit.

Ritchie *et al.* (1992) presented an interesting case of the interaction between three cyclones (Odessa, Ruby & Pat) over the western Pacific in August 1985. Initially the interaction was between Odessa & Ruby. As the Storm Odessa approached Pat a sharp bifurcation occurred in which Pat & Odessa began to interact while Ruby escaped and commenced an anticyclonic orbit.

7. Clustering of tropical cyclones in time

Cyclones tend to cluster in time and space. Sometimes 5-15 cyclones are observed over the globe within 1-2 weeks separated by 2-3 week periods, when there is very little cyclone activity. This clustering in time is noticed in both the hemispheres. The annual variation in global tropical cyclone formation is shown in Fig.7. The obvious 30-40 day cycle in tropical cyclone activity implies that there may be some connection with the Madden-Julian Oscillation (MJO), especially the cyclone activity shown in the diagram is primarily confined to tropical cyclone activity a latitudes between 20°N to 20°S. This observation provides a qualitative indication of the potential degree of activity over the next few weeks and this statistics, collected over a long period of time, can be used to develop objective forecasting techniques.

8. Tropical cyclones in relation to ENSO

Recent studies have brought out relationships between the El-Niño, Southern Oscillation (ENSO) and tropical cyclone activity in each ocean basin. Their relationships, however, vary from basin to basin. In view of the differences in the prevailing upper tropospheric wind flow patterns and surface meteorological features over different parts of the tropical ocean where the cyclones form, such differences are not unexpected.

TABLE 2

Recommended seasonal tropical cyclone activity forecasts by region during a moderate or strong El Niño event or a moderate or strong anti-El Niño event

Cyclone Basin	El Niño years		Anti-El Niño years	
	Frequency	Intensity	Frequency	Intensity
North Atlantic Basin	Large Decrease	Small Decrease	Small Increase	Small Increase
Eastern North Pacific Basin	Slight Increase	Increase	Slight Increase	Decrease
Western North Pacific Basin:				
Eastern Part;	Increase	No Change	Decrease	No Change
Western Part.	Decrease	No Change	Increase	No Change
North Indian Ocean	No Change	No Change	No Change	No Change
South Indian Ocean	No Change	No Change	No Change	No Change
Australian Region:				
Western	Slight Decrease	No Change	Slight Increase	No Change
Central and East	Decrease	Slight Decrease	Increase	Slight Increase
South and Central Pacific (> 160°E)	Increase	Increase	Decrease	Slight Decrease

(Source: TCP 31; WMO Publication)

The ENSO modulation of tropical cyclone frequency and intensity is strongest in the north Atlantic basin. Comparing the activity between El-Niño years and non El-Niño years it is observed that : (*i*) there is a substantial reduction in cyclone numbers, particularly in low latitudes, (*ii*) a 60% reduction in the number of hurricane days and (*iii*) overall reduction in system intensity, during El-Niño years. Contrary to this variation, over eastern north Pacific, the increased frequency of hurricane force systems was noticed during El-Niño years. In the central & western Pacific regions, though there is not much change in cyclone activity during the ENSO cycles, but the primary centres of tropical cyclone activity shifts eastward during El-Niño years. A similar trend is noticed in the south Pacific also. According to Chan (1985) the frequency of tropical cyclones in the north Pacific between 140-160°E is increased during El-Niño years. South China Sea activity follows an inverse relationship, experiencing decreased activity in El-Niño years and increased activity in anti El-Niño years. ENSO related variations of seasonal tropical cyclone frequency is not noticed in both north and south Indian ocean.

There are notable differences in the physical causes of ENSO- induced variations of tropical cyclone activity between the Australian and north Atlantic regions. During El-Niño years, development of anomalously strong westerly winds and increase in the vertical wind shear is noticed in the north Atlantic (Gray 1992) which is attributed to the reduction in the cyclone development in that region. On the other hand, cool sea surface temperature anomalies and associated high barometric pressure accompany El-Niño events and are associated with the diminished frequency of Australian Coral Sea area cyclones. (Gray 1992). These relationships are also helpful in making seasonal forecasting of tropical cyclone activity. The observations are summarised in the Table 2.

9. Forecasts

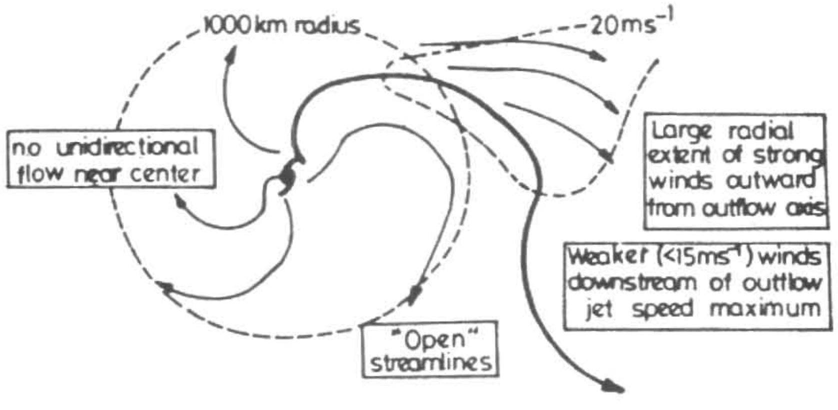
Tropical cyclone forecasting involves the forecasting of different aspects of the cyclones, such as, the forecasting of structure, intensity, movement, and, finally the storm surges that occur at the time of storm crossing the coast. Cyclone structure forecasting has received considerably less attention than that of the motion forecasting. This is also a more difficult problem since the dynamics is more highly non-linear and occurs over smaller scales under conditions that make them very difficult to observe. Due to this, the forecasting techniques are, therefore, highly empirical.

Prediction of tropical cyclone structure involves the analysis of the present conditions and the estimation of changes in the future. To infer the size and intensity of a developing cyclone over the ocean, where the conventional observations are absent, one has to resort to estimation of the structure from frequent satellite imageries. Changes in the structure of the cyclone can be inferred from the short term indications from satellite cloud signatures. Unless the forecaster has enough experience in interpreting the satellite imageries, the changes in the cloud imageries, may not be correctly interpreted. These changes may be mistaken to be the diurnal changes and may be ignored. Even when the changes are noted, they may be given different degree of importance by different forecasters. Hence, the accuracy of such inferences depends on the experience of the forecaster and to that extent, they are subjective.

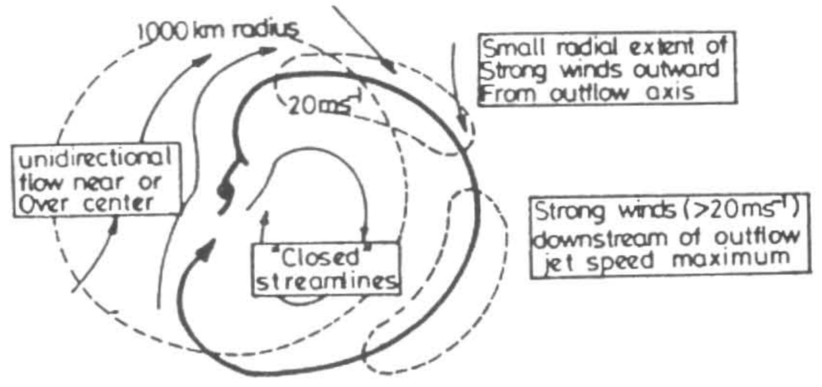
Tropical convective systems, especially those at sea, undergo large diurnal variations because of differences in the short wave and longwave radiation budgets of clear and cloudy regions (Mc Bride and Gray 1980), though the tropical cyclone structure changes show little diurnal preference. It is for this reason that caution should be used while interpreting satellite cloudiness during the formation stage of the cyclone. The diurnal variability of satellite-observed cloudiness has been described for the north Indian Ocean for monsoon season (Rao and Rao 1993). The convective activity (Cloud Top Temperatures $< 235^{\circ}$ K) is a maximum over north Indian Ocean between 13 to 18 hr local time, while the minimum occurs between 21 to 00 hr local time in the month of July. The diurnal cycle over north Indian Ocean is different from that over west north Pacific, where the maximum occurs between 21-00 hr local time, and the minimum is between 15 to 18 hr local time. These diurnal variations are to be kept in mind while interpreting the satellite pictures for the estimation of its intensity.

10. Formation of tropical cyclones

Dvorak's (1984) technique is the widely used method to monitor tropical cyclone formation, using satellite data. This analysis togetherwith conventional observations and analysis, should be used to infer the various stages of tropical cyclone formation. According to Gray (1992), for a disturbance to develop into the tropical storm stage, it is not only necessary that the disturbance exists in an environment of .weak tropospheric vertical wind shear with low level tangential winds of the order of 2-3 m/s at radii of 3°-6° around developing systems, but the occurrence also of low level asymmerical wind surge on one side of the tropical disturbance. These wind surges can trigger intense heavy convection to break out within 3-6 hr or to intensify an existing one. The wind surges bring about the required inward horizontal eddy fluxes of the tangential momentum and mass convergence needed for the development of Mesoscale Convective Clusters (MCC). The disturbances which develop into a tropical storm always have small mesoscale vortices known as "Low Level Circulation Centres (LLCC)" of about 1° diameter. They function as foci for general development of tropical cyclones and help to create low level vorticity values which are 3-5 times more than earth's vorticity. These vortices will go undetected in conventional observations, unless there is a dense network of observations.



INTENSIFYING



NON - INTENSIFYING

Fig. 8. Summary of outflow and ventilation differences between intensifying and non-intensifying Atlantic hurricanes. Note the flow over the centre of the non-intensifying system. (After Merrill 1988)

Deep convection that develops within these small areas of LLCC regions can cause a high efficiency of warming (Schubert and Hack 1982) which promotes a rapid drop of surface pressure and a much faster development of the system that would otherwise be possible from broader scale considerations. The wind surges help establish the MCCs from which LLCCs develop, which subsequently may cause strong and concentrated asymmetrical inflow to penetrate to near the centre of an LLCC where vorticity is already high. Despite favourable synoptic conditions, if the triggering wind surge action is missing or it does not penetrate to the location of LLCC centre, the tropical cyclone development does not take place.

Tropical cyclone formation takes place in two stages. In the first stage, due to wind surge, vigorous MCC system and LLCC's develop. During the stage pressure fall is very little. Once formed, this small scale vorticity maximum can be maintained for several days. It often takes 1-3 days for the environment to force another wind surge to penetrate (stage 2) and cause deep convection to erupt over a small region where the vorticity has already been concentrated. Many times this never occurs and the development does not proceed. When once the second stage occurs, the cyclone development takes place and the system then becomes largely self-sustained. In view of the importance of the low level wind surges as triggering mechanism in the formaion of tropical cyclone, Conditional Instability of the Second Kind (CISK) argument appears to have little relevance to the tropical cyclone formation process. This may have relevance at the inner core of the already developed structure. Since the development of LLCC's can be inferred from the development of deep convection, satellite pictures play an important role in monitoring the cyclone formation.

11. Forecasting formation of cyclones

The cases where formation can be adequately forecast are much less common. Many times, though the enviornmental conditions do not appear adverse, an apparently vigorous disturbance fails to develop. Therefore, forecasting is a watchful waiting. However, attempts can be made to infer the development by carefully assessing the synoptic conditions and satellite cloud signatures. The cloud top temperature changes (relative to the diurnal cycle) in the deep convection in the area of an existing circulation needs be observed. Further trends can be inferred from the tendency of the area covered by cloud tops colder than about –65°C, within 250 km radius of the disturbance centre in a 24 hr period can give a better clue. If the area increases, formation is favoured. Low vertical wind shear of horizontally averaged winds in a ring of 500-1000 km around the disturbance also favours the formation. If both these conditions are fulfilled, simultaneously, the probability of the formation of the cyclone increase to a large extent. Climatology can help estimate the probability that a given disturbance will progress to tropical cyclone stage, particularly where large scale synoptic information is scarce. Preparation of checklists as illustrated by Merrill (1993) can be of help in forecasting the formation of tropical cyclones.

12. Tropical cyclone intensity

The intensity change of a tropical cyclone is defined as the alteration of either the maximum wind velocity or the minimum sea level pressure. The processes which maintain and spin up the tangential winds of the cyclone's inner core (0-1° radius) and those of the outer core (1-2.5° radius) are different. Weatherford and Gray (1988) have shown that the inner core (0-1 radius) and outer core (1-2.5 radius) tangential winds of intense tropical cyclones do not vary in unison. This means that decrease or increase in one does not necessarily imply similar changes in the other. A decrease of the inner core maximum winds as a cyclone begins to weaken later in its life cycle is typically accompanied by an increase in the outer core winds. By way of contrast, in a rapidly intensifying cyclone, when the winds in inner core increase, those in the outer core have little simultaneous change.

The inner core pressure gradient of a tropical cyclone is directly proportional to the square of the tangentinal wind speed and inversely proportional to its radius. Due to large increase in the centrifugal term (V_r^2/r) at inner radius, very large inner core pressure gradients are established. Large increase in tangential wind acceleration occurs even with moderate transverse circulations, due to the strong inner core pressure gradients. As a result, a ring of strong winds (Radius of Maximum Winds) develop close to the centre and the RMW is frequently observed to decrease with time. A rapid wind acceleration is possible first inside the RMW where vorticity and convergence are highest. Then it can occur just out side the RMW where the vorticity is substantially low. However, the decrease in RMW with time cannot continue indefinitely. When the RMW becomes sufficiently small, the eyewall cloud is no longer able to process all of the frictionally induced mass convergence, entering from larger radii. It, therefore, becomes necessary for a new or a double eye wall cloud to develop at a larger radius as shown in Fig. 8. This outer eye wall causes the inner eye wall cloud to weaken and then disappear (Willoghby *et al*. 1982). All these processes can occur independent of the outer radius wind strength. For the maintenance of the strong inner-core wind velocities, it is essential that the weak troposphere wind shear should persist. This condition is essential for maintaining a favourable vertical alignment of the lower and upper tropospheric levels inner-core circulations. The net flow across the cyclone's inner-core at upper levels must be nearly identical to that at lower levels for cyclone intensification to occur (Gray 1968). The ambient upper tropospheric wind associated with intense (or intensifying) hurricanes typically has little net directional flow across the centre (i.e., ventilation) in comparison with non-intensifying or weakening cyclones (Merrill 1988).

13. Movement of the tropical cyclones

Though a wide variety of tracks of tropical cyclones can be found in the belt between 20°N-20°S, they move westward and poleward from the place of their origin. The details of the methods used in an operational mode to predict the movement of tropical cyclones are described below:

(i) Persistence and climatology

These methods are based on the assumption that the integrated effects of all forces, which have steered the tropical cyclone during some past period will continue to be effective during some future period. The persistence forecast is the linear extrapolation over the next 12 hours of the smoothed path of the storm during the past 12 to 24 hr. This is simple method.The temporal and spatial repetetiveness of the cyclone tracks produced by the synoptic pattern in steering the cyclones is helpful in making prediction based on climatology.

(ii) Steering

This method is based on the assumption that the storm is steered by the basic current in which it is embedded. Opinions are strongly divided in choosing the levels which steer the cyclonic storm. Chan & Gray (1982) presented a comprehensive study of the relationship between the movement of tropical cycones and the large scale circulation in which they are embedded. Their findings are:

(a) Winds in the mid-troposphere (500-700 hPa) at 5° to 7° latitude radius from the cyclone centre have the best correlation with the cyclone movement.

(b) Northern hemisphere tropical cyclones move approximately 10° - 20° to the left of their surrounding mid-tropospheric flow at 5° - 7° latitude radius. In southern hemisphere they move approximately 10° to the right. In general, the cyclones move 1 m/s faster than this current.

(c) These reationships get modified by the vertical shear of the surrounding current.

(d) The mean tropospheric flow (*i.e.*, surface to 100 hPa) at 5° - 7° latitude radius also correlates well with cyclone movement in most cases.

(e) For cyclones embedded in an environment with relatively small vertical wind shear, the 500-700 hPa flow is a good predictor of cyclone movement as the mean tropospheric flow.

(f) The mean of 200 hPa wind and 900 hPa wind also correlates reasonably well with the cyclone movement.

The movement of the tropical cyclones can be generally inferred from the satellite pictures making use of the fact that the cloudiness often extends ahead in the direction of movement of tropical cyclones. This corresponds to the depiction of the warm moist tongue or thickness steering used in other techniques.

The westward moving cyclones sometimes interact with the troughs in the westerlies and recurve towards northeast. Studies over western north Pacific using satellite imageries indicated that the recurvature of the cyclones can be determined using the following parameters:

(a) D/d, where "*D*" is the diameter of the central dense overcast of the cyclone and '*d*' is the average width of the cloud band associated with the interacting trough. In a north-south extending cloud band occurring ahead of westerly trough, the average width of the cloud band is taken as a mean of the width of the cloud band at different latitude locations. The intensity of the trough is indicated by the larger width of the cloudiness. Hence the influence of the trough in receiving the cyclone is given by this ratio.

(b) θ, the angle between the axis (orientation) of the cloud band (associated with the trough) and the latitude of the tropical cyclone centre. When the value of θ lies between 30° and 40° it is highly probable that a tropical cyclone will recurve if *D/d* is less than 1.5.

Since the pressure distribution in the field of tropical storm is well defined and has a large gradient, the pressure changes and their gradients may constitute an objective and reliable aid for predicting their movement. Though this is not of much help when the system is over mid-ocean due to lack of ships observations, the pressure changes provide a good guidance when the cyclone is approaching the coast/when the coastal observations start responding to the cyclone circulation. Here again it is claimed that 3 to 6 hourly pressure changes are superior to 24 hour pressure changes. Cyclones move in the direction where there is maximum negative pressure change.

14. Some general forecasting rules

(*i*) An intensifying cyclone expands its gale force wind radius on an average at 40 km/day. A filling cyclone will continue to expand at this same rate as long as the eye exists.

(*ii*) The outer core (1-2.5° radius region) generally strengthens at a rate of 2.5 ms^{-1}/day regardless of whether the cyclone fills or deepens as long as an eye exists.

(*iii*) A developing cyclone intensifies on an average at the rate of 8 hPa/day before it obtains an eye and an average 20 hPa/day after the eye appears.

(*iv*) The eye appears at a pressure of 980 hPa. Out of the 101 cyclones investigated by Weatherford (1987) in the northwest Pacific, in which 750 aircraft missions are undertaken, in nearly 2/3 of the total number of cyclones, eye developed when the sea level pressure ranges from 979 hPa to 988 hPa. As a result of this finding the rapidly deepening cyclones are found to develop an eye near about 980 hPa.

(*v*) For cyclones whose pressure reaches below 955 hPa, the outer core does not begin to weaken until the eye disappears. Even though a cyclone's central pressure fills, as long as the eye exists, momentum continues to be advected through the outer core towards the eye wall thereby strengthening the outer core. Once the eye disappears, the outer core begins to weaken, making the beginning of the decay of the entire vortex.

(*vi*) The sooner the eye appears, the more rapid is its intensification rate. For such cyclones the eye appears typically at 985 hPa. The eye will be smaller in size then the average eye.

(*vii*) The later the eye appears, the slower is the deepening rate.

(*viii*) The more intense the cyclone, the smaller is the radius of maximum wind.

(*ix*) Cyclones that move southwestward are unlikely to intensify more than a storm stage. They move slower.

(*x*) The eye generally contracts with deepening and expands while the cyclone fills.

(*xi*) Elliptical eyes are commonly seen when the cyclone is first forming an eye and then begins to disappear.

(*xii*) Concentric eyes occur, on an average at 925 hPa, but were not found above 950 hPa.

(*xiii*) Cyclone deepening and filling is much more rapid with an eye than without an eye.

15. Summary

The tropical storms develop over warm tropical oceans where the suface temperatures are above 27°C. Not all the disturbances attain the hurricane stage. Though the tracks of the cyclonic storms differ widely in the tropical belt, the predominant direction of movement is to the west. Some of them may recurve when they come under the influence of a westerly trough. Strong winds, heavy rain and storm surges associated with the severe cyclonic storm are the elements which cause plenty of damage to the coastal inhabitants and the structures. For an operational forecaster the pressure changes ahead of the storm, the steering current and the development of cloudiness extending ahead of the direction of the movement of tropical cyclones in the satellite imagery are some of the aids to predict the movement of the storms. Due to improved understanding of the tropical cyclone formation and in tracking, forecasting and warning systems, the operational forecaster is in a better position to forewarn the coastal population about the impending cyclones and thus reducing the damage.

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