CHAPTER 1

GENERAL CHARACTERISTICS OF CYCLONES

A tropical cyclone is a meteorological term for a storm system characterized and driven by the release of large amounts of latent heat of condensation, which occurs when moist air is carried upwards and its water vapour condenses. This heat is distributed vertically around the centre of the storm. Thus, at any given altitude (except close to the surface, where water temperature dictates air temperature) the environment inside the cyclone is warmer than its outer surroundings.

The adjective "tropical" refers to both the geographic origin of these systems, which form almost exclusively in tropical regions of the globe, and their formation in Maritime Tropical air masses. The noun "cyclone" refers to such storms. The cyclones have counter clockwise rotation in the Northern Hemisphere and clockwise rotation in the Southern Hemisphere.¹ Depending on their location and strength, tropical cyclones are referred to by various other names, such as hurricane, typhoon, tropical storm, cyclonic storm, and tropical depression.

¹ Henry Piddington, The Sailor’s Horn-Book for the Law of Storms, New York, 1848, p.23
In 1828, Heinrich Wilhelm Dove Physicist and Meteorologist, showed that cyclones in the southern hemisphere rotate clockwise, that is, the winds move in the direction of the hands of a clock, while in the northern hemisphere the movement is counter clockwise.

Types of Cyclones

Tropical Cyclones

Air in motion is wind. Any weather system having strong wind is a storm. A tropical cyclone is an atmospheric system in which very strong winds prevail over a large part. Therefore, it is often called a tropical cyclonic storm. It is just a small vortex of heat over water, unattended somewhere in the doldrums which gives birth to the mightiest of all wind storms. As more thunderstorms form and gather, the storm develops rain bands which start rotating around a common center. As the storm gains strength, a ring of stronger convection forms at a certain distance from the rotational center of the developing storm.
It graduates from a depression to a tropical storm and begins to move, like a rapidly spinning top, slowly off in a definite direction.\textsuperscript{2}

**Extra Tropical Cyclones**

Extra tropical cyclones or low pressure cells have characteristics of tropical cyclones and mid latitude cyclones, drawing some energy from evaporation and condensation over warm ocean waters, and some from atmospheric temperature gradients. They move away from tropical regions towards Polar Regions, bringing precipitation and high winds.\textsuperscript{3} These are also known as mid latitude or baroclinic storms.

**Subtropical Cyclones**

It is a weather system that has some characteristics of a tropical cyclone and some characteristic of an extra tropical cyclone. They can form in a wide band of latitude, from the equator to 50\textdegree. As such, they may have an eye, but are not true tropical storms. Subtropical storms can be very hazardous, with high winds and seas, and often evolve into true tropical storms.

**Mid-latitude Cyclones**

These are generated by the temperature difference between warm and cold air masses, with warm water at high latitudes generally providing that differential. These storms have a cold core (low pressure centre) unlike tropical and extra tropical cyclones.\textsuperscript{4}

**Arctic Cyclones**

Arctic cyclones are vast areas of low pressure in Polar regions that have a weak cyclonic rotation.


\textsuperscript{4} Ibid ,p.119.
Mesocyclones

A Mesocyclone is a vortex of air, approximately 2 to 10 miles in diameter (the mesoscale of meteorology), within a convective storm. They are often found in the right-rear flank of super cell thunderstorms, and are visible as a hook echo on Doppler weather radar.

Origin of the word Cyclone

The word has struck fear in the hearts of many facing its fury. For others, it means only a swirl of counter clockwise winds around the low pressure center. It surfaced in the Indian city of Calcutta in the mind of an Englishman. While serving as President of the Marine Court of Calcutta, Henry Piddington, a former sea Captain, studied the stormy weather of the Indian Ocean. He had particularly focused on the devastating tropical storm of December 1789 that inundated the coastal town of Coringa with 3 monstrous storm waves that killed more than 20,000. In the presentation to the Asiatic Society of Bengal around 1840 Piddington described that 1789 storm as a ‘Cyclone’ a storm derived from the Greek word ‘Kyklon’ which means moving in a circle, like the ‘Coil of the snake’. The air, flow in association with cyclone and the spirally shaped cloud bands resembles the coil of a few snakes. This spiral shape of the cloud bands was first noticed by Piddington on an examination of several cloud and wind reports from ships which encountered cyclonic storms in the Bay of Bengal. It was he who named these atmospheric systems cyclones. The name which is very much supported by the present day satellite cloud images and radar echoes, with their spiral bands spread with gaps, thus resembling the coil of a snake.

Piddington introduced the word in 1848 the mariners’ book, *The Sailors Horn Book for the law of storms* whose purpose was to explain to mariners the theory and practical use of the Law of Storms. In 1875, the International Meteorological Organisation adopted the term to describe the low pressure system.

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Different names of cyclones

All is in air disturbances that begin as low pressure area at hot spots in the tropical oceans in late summer and grow into great spirals of hungry air are called cyclones. Cyclones occur in different parts of the tropical oceans. They bear different names. There is no difference between hurricanes, cyclones and typhoons. The word ‘typhoon’, used today in the Northwest Pacific, has two possible and equally plausible origins. The first is from the Chinese which means ‘great wind.’ The Chinese term tàifēng, and taifū in Japanese, has an independent origin traceable variously to hongthai, going back to Song (960-1278) and Yuan (1260-1341) dynasties. The first record of the character appeared in 1685’s edition of Summary of Taiwan. Alternatively, the word may be derived from Urdu, Persian and Arabic tūfān which in turn originates from Greek tuphōn (Τυφών), a monster in Greek mythology responsible for hot winds. The related Portuguese word tufão, used in Portuguese for any tropical cyclone, is also derived from Greek tuphōn. In the North Atlantic they are called Hurricanes. The word ‘hurricane’ originally came from the natives of the West Indies, the early navigators while following the time of Columbus, the word was variously given as ‘aracan’ ‘huriranyucan’ ‘Uricon’ ‘huracan’ etc. According to Professor Lehman Nitsche, the god of stormy weather was ‘Hunrakan’ to the Indians of Guatemala, from whom the word hurricane came. One of the first human records of hurricane appears in Mayan ‘hierophics’. The Mayans also practiced a kind of mitigation and risk reduction by building their major settlements away from the hurricane prone coastline. In fact, it is the Mayan word ‘Hurakan’ that became our word ‘hurricane.’ The word hurricane started as a name of a native Caribbean Amerindian storm god.

In the Indian Ocean they have been known as cyclones. The word cyclone from the Greek word Kuklos means ‘circle’, ‘wheel’. The other view is that ‘cyclone’ which was derived from the Greek word ‘Cyclos’ means the ‘Coil of the snake’. The word ‘cyclone’ just means ‘turning wind with one eye’. It relates to the word ‘Cyclops’ that one eyed creature in an ancient Greek story. Although

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Piddington proposed the name ‘Cyclone’ because it expressed sufficiently what he described as the tendency to circular motion. He was not the first to refer to tropical cyclones as whirlwinds.\textsuperscript{11} In his sailors Hornbook he credited Captain Langford with the earliest published statement to that effect, in the Philosophical transaction in 1698. Nearly fifty years before, however, a German Geographer, Bernhardus Varenouis, treated hurricane as ‘whirlwinds’ in a book entitled \textit{Geographia Naturalis}. The principle of the barometer was discovered by Torricelli in 1643 and very soon thereafter it was recognized that its variations were associated with changes in the weather. The fact that storms, both tropical and extra-tropical, are cyclonic wind systems which move progressively from place to place, was not definitely established until the event of the weather map. Benjamin Franklin conceived the idea that the northeast storms of the New England and Middle Atlantic states come from the west and southwest. Invention of the synoptic weather chart, about 1819, has been credited to H.W.Brandes, a professor at the University of Breslau. There being no telegraph, weather maps first was drawn from observations gather by mail. Charts by Brandes were from observations taken in the year 1783. Circulation of the winds in cyclonic storms was depicted on these weather maps which threw a flood of light on the problems that had disturbed earlier investigations. In Tamil it is called ‘Puyal’, ‘Kaduvalli’ ‘Suravali’, ‘Suravari’, ‘sura’ means puyal, ‘perungkarru’, ‘peruvalli’, chithiraisulzhi’, ‘suzhalkarru’, ‘vali’ means wind. In the China Sea, they call them \textit{Typhoon}, from \textit{Tyfung} or great wind. Perhaps the Hindi word \textit{Toofan} has come from the word Typhoon, in the Phillippines \textit{baguoi}, in Japan \textit{Reppu}, and \textit{asifa-t} in the Persian Gulf, \textit{willy-willy} in Australia.\textsuperscript{12} While their names are varied, all tropical cyclones are essentially similar in origin, structure, and behavior.

William Dampier, a master seaman and world voyager, wrote an excellent description of the winds and other conditions that he experienced in a typhoon of the China Coast in the year 1687. He came to the conclusion that ‘there was no difference between typhoons and hurricanes except the names.’\textsuperscript{13}

\textsuperscript{13} Op.cit I.V. Tannehil, Hurricanes, p.4
Regions of Tropical Cyclones

These storms are classified into five definite regions on the earth’s surface, three in the Northern Hemisphere and two in the Southern Hemisphere. These are:

1. The West Indies, the Gulf of Mexico and the coasts of Florida, where they are called hurricanes.
2. The seas on both sides of India that is the Arabian Sea and the Bay of Bengal.
3. The China Sea and the Coasts of Japan, where they are known as typhoons, and over the Philippine Islands, where they are called bagnios.
4. The Indian Ocean to the east of Madagascar and Mauritius;
5. The Pacific Ocean to the east of Australia and Samoa.

Tropical Cyclone Climatology of Tamilnadu

Tamil Nadu, one of the maritime states of India consists mainly of plains stretching from SW to NE between 8°N and 14°N. It is surrounded by the North Indian Ocean to the East and South and on the West by the Western Ghats South of the Nilgiris. There is a break of about 30 km in the Western Ghats known as the Palghat Gap. The climate of Tamil Nadu is mainly of tropical semi-arid type. Tamil Nadu, being located in a highly vulnerable part of peninsular India, is frequently subjected to cyclone in the coastal districts, and of severe droughts chronically in some areas and periodically in several others. Due to its proximity to the sea the summer is hot and winter is less cold. The maximum daily temperature rarely exceeds 43°C while the minimum daily temperature seldom falls below 18°C. The state is exposed to both south west monsoon and North East monsoons.

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The rainfall received in Tamil Nadu is distributed in four different periods. (i.e.) Summer (March-May), South West Monsoon (June-September), North East Monsoon (October-December), Winter (January-February). Significant variability in rainfall, temperature, and wind are noticed. The climate of Tamil Nadu is basically tropical. Among the four aforesaid periods, North East Monsoon pours heavy rain which is 48% of the total rainfall followed by south west monsoon (33%) summer (14%) and winter (5%)\textsuperscript{17}. The annual average precipitation in the State is 100 cm. As mentioned earlier the principal rainy seasons are NE and SW monsoons. Fifty five percent of the annual total rainfall occurs during the NE monsoon.\textsuperscript{18} The rainfall decreases from 75 cm in the east to 20 cm in the western sector, the narrow rainy coastal belt receiving about 100 cm. November has the maximum amount of rainfall. But the coefficient of variability in rainfall during the Northeast Monsoon season is more during cyclonic nature of Northeast Monsoon.

The North East monsoon on the Coromandel Coast begins during the last half of the month of October. It usually opens with a severe storm; coming from the North-north-west or from the north, and veering afterwards to north-east and east. In the south-east of the Bay of Bengal out at sea, it begins often from the south-west or west, showing that the centre is to north-west and north. These storms are most destructive. In November and December the wind of the Coromandel Coast blow mostly from north-west, inclining a little from the land, in the afternoon it inclines seaward. In January the winds on the east coast draw to east-north-east during the day and blow along ashore from the north or incline a little from the land in the morning. But sometimes in December and January the north-east winds continues for three or four days together without much variation in direction or force. The north-east wind is felt but slightly in the interior and on the west coast. In February the north-east monsoon ends or is much interrupted by southerly breezes. Early in March the south-east or along the shore, the wind of the Coromandel Coast establishes itself. This occurs about noon each day.\textsuperscript{19}

\textsuperscript{17} Imperial Gazetteer of India Provincial series, (Madras, 1908.) Vol. I
\textsuperscript{18} Op.cit P.A. Menon,\textit{Our weather}, p. 141
Jones in his memories of the India Meteorological Department described the north-east monsoon thus, “During the last week in September and the first 2 weeks in October, the south west monsoon currents withdraw from upper India and Bengal and fine weather sets in over these areas”. These changes are accompanied by increase in pressure over these areas and the distribution becomes very unsure over the Bay in consequence. These conditions over the Bay favor the formations of cyclonic storms, these storms determine the distribution of the North-east monsoon rainfall. The high pressured areas in Northern India extends gradually southwards, and the manner in which this extension takes place exercises a very powerful effect on the position and cause of the storms, and hence on the distribution of north-east monsoon rainfall from October to December.

The special feature of Madras according to Jones shows the pressure distribution, for e.g., the ‘Pongal Showers’, which are sometimes received during January, are shown to be due to a pressure distribution similar to that of the north-east monsoon. Then there are the ‘Mango Showers’ of March and April which are precipitated from the south winds prevailing on the coast during this period. These south winds are formed by a low pressure area brewing in the north of the presidency and are popularly known as the ‘long shore’ winds. The ‘Blossom Showers’ of the coffee growing districts are generally considered to be due to the same causes as the Mango Showers.

**Classification of tropical disturbances over the Indian seas**

Tropical cyclones do not form all of a sudden. They have a life history of their own. They pass through different stages like low- pressure area, depression, deep depression, cyclone, severe cyclone, very severe cyclone to eventually become a Super cyclone, on the basis of maximum sustained winds. The criteria followed by the India Meteorological Department (IMD) to classify the tropical disturbances are on the basis of maximum sustained winds. Though systems are found to rapidly intensify they never change their intensity by more than two stages at any point of time. Blandford, Eliot (1890) proposed the nomenclature “cyclone” for severe cyclonic storms and ‘Cyclonic storms’ for moderate ones.

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Evolution or Life cycle of a tropical cyclone

A tropical cyclone has a definite life cycle. The complete life cycle of a tropical cyclone usually spans about 9 days but may be only 2 or 3 days or more than 20 days: The average span of life of cyclones in the Indian area is 2 to 3 days, extending even to 6 days with recurring storms. Some of them have lasted only for a few hours. The evolution has four phases. The cyclone of 23rd, 24th and 25th of April 1859 at Tranquebar, the hurricane lasted for three days. Another cyclone formed on 12th December 1884 in Nagapatanam, and crossed the coast only on 19th December. The cyclone lasted for 7 days.

Formative Stage

A cyclone formation works very much like a heat engine that is fuelled by the energy liberated during the condensation of water vapor (latent heat). There is an enormous amount of energy involved. The release of latent heat warms the air and provides buoyancy for its upward flight. The result is to reduce the pressure near the surface that encourages a more rapid inward flow of air. To get this engine started, a large quantity of warm, moisture-laden air is required and a continual supply is needed to keep it going. It thus appears that two conditions are necessary for the formation of a cyclonic depression: Firstly, physical cause which is sufficient to remove vertically large masses of air, and secondly, a strong upper current which can carry off the ascended air sideways, so as to get rid of sufficient air to produce a lowering of pressure over the region in question. Although the formation of cyclone is the topic of extensive ongoing research and is still not fully understood, there are six main requirements for tropical cyclogenesis: sufficiently warm sea surface temperatures, atmospheric instability, high humidity in the lower to middle levels of the troposphere, enough Coriolis force to develop a low pressure center, a preexisting low level focus or disturbance, and low vertical wind shear. In the South Indian Ocean,

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22 *Proceeding of the Board of Revenue*, dated 19 December 1884, G.O.No.4367
the area of cyclone formation lies between 10°s and 15°s and does not shift with the advance of season. Though some tropical cyclones in the South Bay are believed to have formed as a consequence of interaction between wave trains in higher and lower latitudes, no firm conclusions can be arrived due to the absence of adequate data. The area in the south of the Bay (south of Lat. 12°) was one of uniform and low pressure. The cyclone of 25th November 1846 appears to have been formed about 300 miles east by north of Madras. The wind veered from N.N.E. to east and south east, thus showing that Madras was placed on the right hand semicircle of the November 1865 storm. The vortex crossed south west of Madras.

During the cyclone of 1888, the logs of fourteen vessels show that in the area, frequent rain-squalls accompanied the north and east winds which prevailed, and these winds were unusually strong and steady. The winds were of force 4 to 6, the last being observed on board the Chupra (vessel) in Lat.12° 19’N, and Long. 84° 42’E. As already stated, frequent showers were falling at this time in the coast districts. The weather in the south-west of the Bay and the adjacent coast districts was as it usually prevails during a strong burst of the cyclones.


north-east monsoon (and really the retreating south-west monsoon). In the area defined by the parallels of 6°N, and 12°N, and the meridians of 88° and 92°E, the weather was also squally, but the squalls were more severe than further to the west, and accompanied very variable winds and almost constant rain. As this area was the birth-place of the cyclone, the full data of the five ships which were traversing it immediately before its formation are of great interest. The wind observations in this part of the Bay stood in marked contrast to those taken on board ships in the rest of the Bay. The most remarkable feature of this area was the variability of the winds. They were also, as might be expected, much lighter than in any other part of the Bay.

The weather was somewhat unsettled and squally with heavy rain on the 24th, 25th and 26th. The area extended to some distance northwards on these days, the weather became more unsettled, the squalls heavier and more frequent, and the rainfall more intense. The disturbance developed rapidly, and the barometric depression thus produced intensified into a cyclonic storm which began to form on the 27th, and increased in extent and intensity on the 28th and 29th, and was a severe cyclone on the 30th and 1st.29

**Prematurity stage**

There is rapid fall in the central pressure, reaching the lowest limit. Clouds and rain get organized into spiral bands. Area of strong winds remains small but winds attain the maximum speed. The entire process is very quick.30 Three tropical cyclones at different stages of development, the weakest (left), demonstrate only the most basic circular shape. A stronger storm (top right) demonstrates spiral banding and increased centralization, while the strongest (lower right) has developed an eye.31

![FIGURE: 3 TROPICAL CYCLONES AT DIFFERENT STAGES OF DEVELOPMENT](image)

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29 Appendix
Full maturity stage

If the oceanic and atmospheric environments continue to be favorable, the cyclone may continue to intensify. The cloud system becomes more circular in shape and develops a distinct eye. This is the severe cyclone stage where the cyclone is at its most dangerous.

Decay or Dissipating stage

Tropical cyclones normally decay when they move into a less favorable environment that is lower than 26°C, either over land or the cooler waters in higher latitudes. The rate of decay varies with the circumstances. Similarly, a cyclone moving over land normally dissipates rapidly due to loss of its energy source, namely the warm ocean surface. The winds decrease, the cyclone fills up and weakens, though the rainfall may persist for a day or two.

Over land, three major physical changes occur after decaying of the cyclones.

1. Considerable reduction in evaporation as the storm leaves the ocean.
2. As the land is cooler than the ocean, the low level air is cooled rather than warmed by the underlying surface.
3. Increase in roughness of the land.

Over the Indian seas, except in a very few cases, the decay of tropical cyclones was not due to the low sea surface temperature. Generally cyclones weaken rapidly after entering land. Some of the tropical cyclones decay over the ocean by entering into the strong vertical wind shear zone generally prevailing over northern parts of the Bay of Bengal in late November and December.  

The heavy rainfall during this season is mainly attributable to the tropical cyclones which hit the Tamil Nadu coast or come very close to the coast. Most of the cyclones which strike the coast travel inland for considerable distance and hence the rainfall distribution also extends well inland. Over a period of 100 years only 34 cyclones have crossed Tamil Nadu coast. November month was the predominant cyclone season with about 64% of the cyclones reaching severe cyclones intensity. Among the 34 cyclones, 16 cyclones struck the coast of

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32 Pisharoty, Tropical Cyclones, (Bombay: Bharatiya vidhya Bhavan, 1993) p.26
Tamil Nadu in the month of November (20th November 1814, 16th November 1839, 25th November 1846, 26th November 1848, 20th November 1856, 27th and 28th November 1864, 25th November 1865, 15th and 16th November 1869, 6th and 7th November 1871, 21st November 1880, 12th November 1881, 1st to 3rd November 1885, 12th to 16th November 1886, 12th to 16th November 1888, 14th November 1896, 12th November 1889. Of these 7 cyclones occurred in between 12th and 16th of November. Another 7 cyclones struck from 20 to 28th of November. Only one cyclone struck on 1st of November. Nine cyclones struck the coast of Tamil Nadu in the month of October, Viz 24th October 1818, 9th October 1820, 30th October 1836, 30th October 1842, 20th October 1846, 19th October 1863, 16th October 1884, 8th October 1887. Except two cyclones, other cyclones struck on the latter part of October. The Chingleput district is peculiarly liable to cyclones, the months of May and October being the usual periods of visitation. 8 cyclones struck the Coast of Tamil Nadu in the month of May i.e. 2nd May 1811, May 1827, May 1840, May 1858, 1st May 1872, 5th May 1874, 21st May 1879, 23rd 1886. Of these the cyclones of May 1872 was the most destructive one. In the month of December there were 6 cyclones occurred in the coastal area, 5th December 1803, 9th December 1807, 2nd December 1830, 9th December 1886, 12 to 16 December 1888, 19th to 27th December 1888. In the year 1888 two cyclones hit the area in the same month.33

**Physical structure of a tropical cyclone**

On a weather map cyclones are represented by a series of closed, oval-shaped isobars. Although no two cyclones are exactly the same, they are usually egg shaped; they generally range in size from 1000 to 1500 miles (1610 - 1690 km) in diameter along the longer axis and 500 to 800 miles wide. The size of a tropical cyclone is determined by measuring the distance from its center of circulation to its outermost closed isobar. If the radius is less than two degrees of latitude (120 nm, 222 km), then the cyclone is ‘very small’. Radius of 2–3 degrees (120–180 nm, 222–333 km) are considered ‘small.’ A radius between 3 and 6 latitude degrees (180–360 nm, 333–666 km) is considered ‘average sized.’ Tropical cyclones are considered ‘large’ when the closed isobar radius is

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33 Appendix
6–8 degrees of latitude (360–480 nm, 666–888 km), while ‘very large’ tropical cyclones have a radius of greater than 8 degrees (480 nm, 888 km). In the Bay of Bengal, the usual size of the vortices is from 300 to 350 miles. Other methods of determining a tropical cyclone's size include measuring the radius of gale force winds and measuring the radius of the central dense overcast34. A considerable cyclone passed over Madras and Chengleput and a portion of the North Arcot District on October 31st, 1836. The outer storm area was from 200 to 250 miles in diameter from east to west and the inner storm area 80 to 90 miles in diameter. The outer storm area was from 200 to 250 miles in diameter from east to west and the inner storm area 80 to 90 miles in diameter.

**FIGURE: 4** A CROSS SECTION DIAGRAM OF A MATURE TROPICAL CYCLONE, THE ARROWS INDICATING AIR FLOW IN AND AROUND THE EYE.

**Eye:**

A strong tropical cyclone will harbor an area of sinking air at the center of circulation. If this area is strong enough, it can develop into an eye. The weather in the eye is normally calm and free of clouds, and fair weather found at the centre of a severe tropical cyclone though the sea may be extremely violent. The eye is normally circular in shape, and may range in size from 30–65 km in diameter, usually situated at the geometric center of the storm. Although the winds are calm at the axis of rotation, strong winds may extend well into the eye. 35

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Eye Wall

The eye of a storm is surrounded by the eyewall, where the most severe weather of a cyclone occurs. It contains the storm's strongest winds. The cyclone's lowest barometric pressure occurs in the eye, and can be as much as 15% lower than the atmospheric pressure outside the storm. The eye is possibly the most recognizable feature of tropical cyclones; the eye and the air directly above it are warmer than their surroundings. Incessant lightning keeps the entire eye wall illumined, making it a fascinating and awesome spectacle. This is a region of violent thunder squalls; torrential rains etc., with mountainous waves reaching 20 metres or more in the sea. The eye and eyewall together constitute the core of the cyclone.

In weaker tropical cyclones, the eye is less well-defined, and can be covered by the central dense overcast, which is an area of high, thick clouds. Weaker or disorganized storms may also feature an eye wall which does not completely encircle the eye, or have an eye which features heavy rain.

When cyclones reach peak intensity they usually—but not always—have an eyewall and radius of maximum winds that contract to a very small size, around 10–25 km (5 to 15 miles). At this point, some of the outer rainbands may organize into an outer ring of thunderstorms that slowly moves inward and robs the inner eyewall of its needed moisture and angular momentum. During this phase, the tropical cyclone weakens (i.e., the maximum winds die off somewhat and the central pressure goes up), but eventually the outer eye wall replaces the inner one completely. The storm can be of the same intensity as it was previously or in some cases, it can be even stronger after the eye wall replacement cycle.

Even if the cyclone is weaker at the end of the cycle, the storm may strengthen again as it builds a new outer ring for the next eyewall replacement.

Moats

A moat in a tropical cyclone is a clear ring outside the eyewall, or between concentric eyewalls, characterized by slowly sinking air, little or no precipitation, and strain-dominated flow.[14] The moat between eyewalls is just one example of a *rapid filamentation zone*, or an area in the storm where the rotational speed of the air changes greatly in proportion to the distance from the storm's center.

Rainbands

Rainbands are bands of showers and thunderstorms that spiral cyclonically toward the storm center. High wind gusts and heavy downpours often occur in individual rainbands, with relatively calm weather between bands. Tornadoes often form in the rainbands.

Outer Ring

Beyond the eye wall is an “outer ring” of the cyclonic circulation where the wind speed decreases steeply and clouds, rain etc. diminish rapidly outwards. In the periphery of the storm, it is an outermost field of weak cyclonic circulation and scattered clouds. The cyclones vary in size. The smallest ones are only about 150 km in diameter. These are ‘midget’ cyclones. Big cyclones can have a diameter of 1,500 km.\(^{37}\)

Madras District has been visited by a violent hurricane. It commenced with rain early on the morning of the October 30th 1888 and was followed by severe gusts of wind during the forenoon, it ceased not till midnight with the exception of a temporary lull between 7 and 8 in the evening. The town of Madras being frequently touched by the centre of the storm, from the S.S. East, the cyclones afterwards assume a West or West South Westerly direction. The area within which their action is usually felt extends from 109 miles N to 120 miles south of Madras. A common mistake, especially in areas where hurricanes are uncommon, is for residents to wander outside to inspect the damage while the eye passes over, thinking the storm is over. They are then caught completely

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by surprise by the violent winds in the opposite eye wall\textsuperscript{38}. At seven Pagodas Light-house, about 45 miles south of Madras, the weather, which had been previously fine, assumed a monsoon’s appearance on the morning of the October 30\textsuperscript{th} 1888. Heavy rain with moderate north-west winds prevailed from the afternoon of that day until about 7 pm of the 31\textsuperscript{st}, when the wind freshened and gradually increased in violence till 11 pm, when it began to blow a whole gale, which lasted till 3 am. At 4 am the wind shifted to south-east and abated. This Light-house was probably just outside the inner storm area. At the Pulicat Light-house, 30 miles to the north of Madras, similar weather was experienced. On the 30\textsuperscript{th} it rained heavily all day, but the sea was smooth through the day. It rained very heavily and without intermission on the 31\textsuperscript{st}, and the sea rose rapidly. At 4.30 pm (when the centre was about 60 miles to the east-south-east) the first heavy squall of wind was experienced. The wind increased in force till 1.25 am, when it shifted to south-east. At the Armaghan Light-house, 60 miles north of Madras, the weather was fair till 8 am of the 31\textsuperscript{st}, at which hour it became gloomy and the wind began to freshen up, and blow in gusts or squalls from the north. It increased gradually in force, and at 2 pm was blowing with much violence. It continued with unabated force till 3-30 am of the 1\textsuperscript{st}, when it began to abate.\textsuperscript{39}

The barometric readings showed clearly that the Light-house was in the outer storm area, where the barometer fell very slightly, although violent winds were experienced. The fall of the barometer from to 10 am to 10 pm (when it was lowest) was only 15”, or very little more than the amount of the diurnal oscillation in India. These facts, hence, show that the storm consisted of an inner storm area, which was probably not more than 80 to 90 miles in diameter, and of an outer storm area which extended to distances of 150 miles to north and west, and was approximately 250 to 300 miles in diameter. The depression at the centre when crossing the Madras coast was nearly one inch in amount.

**Movements**

Tropical cyclones move as a whole body. Ideally they move in a direction between west, northwest and north northwest. The average speed is 15-20 km ph (360-480 km per day), Two or three days later about half of them change their


direction and more towards north. During the change, their speed decreases to about 10 km or less. During the Southwest monsoon season they move generally west North West wards from the head of the Bay of Bengal across north India; some of them reserve overland towards north or north east and break up against the Himalayas. In South Indian Ocean they are generally of recurring type, the point of recurvature shifting eastwards in the southern spring and autumn. A large fraction of such storms turn towards northeast and speed up to 25 kmph (Kilo meter per hour) or more. In individual cases it is often difficult to forecast the precise location and direction of movement 48 hours in advance or at times even 24 hours ahead.  

Rotary and Progressive movements

These two distinct movements, one rotary and the other progressive, create confusion in the minds of many people in regions subject to hurricane visitation. The progressive movement is comparatively slow. Although the winds of the hurricane blow around and incline inwards towards centre at high velocities, this movement must not be confused with the progressive change of position of the storm itself, which averages only about 12 miles an hour. The hurricane may be likened to a top which spins rapidly but changes its position slowly. They conclude that the storm is moving forward at a rate of 50 to 100 miles an hour or even more and when 1000 miles away, it will arrive in 10 to 20 hours. In reality the storm may be moving forward at a rate of only 12 miles an hour, and thus be distant more than 80 hours in time. From any region in which tropical cyclones originate they move outward in more or less divergent paths of those which intersect the paths of these which come from another area. In the Bay of Bengal the storms travel at a rate of from little more than 2 to 39 miles per hour, but this last very high rate has occurred only in one instance, and from 3 to 15 miles may be taken as the usual rates. But in the Arabian sea the rate of progression is from 4 to 16 miles per hour.

40 P.Koteswaram, Movement of Tropical storms over the Indian Ocean, Regional Seminar on Tropical Cyclones, (Tokyo, 1962),p.1
Track of storm centre

MAP: 2 TRACK OF STORM CENTRE

Track of a storm is the path or line in which it travels, like the track of a ship. Between the Andamans and Madras the track usually appears to be nearly from SouthEast and East to the Westward and Northwest-ward: but when storms occur in about 6° or 8° of Latitude North, and to the Eastward as far as 90° East, they seem first to travel from the S.S.E. or S.E., and then to curve away to the Eastward towards the Coast of Cyclone, or the Southern Part of the Coromandel Coast.\(^{44}\) The average daily velocity of the wind, for the 2nd half of April, 1872 was 198 miles i.e., a little more than 8 miles an hour.\(^ {45}\) On the 2nd of May, the velocity of the wind was, according to Mr. Pogson, Master attendant, 716 miles, or on an average, nearly 30 miles an hour. At 3:30 a.m., the wind blew at the rate of 27 miles per hour; at 8:30 a.m., 53 miles per hour; at 9:45 a.m., 40 miles an hour; at noon, 34 miles per hour; in the afternoon, 22 miles per hour. At 8:30 a.m., the velocity of the wind was six times greater than it was during the previous fortnight and, in the afternoon, it was about 3 times greater than the average rate.\(^ {46}\)

\(^{46}\) Report on the administration of the Madras Presidency during the year 1872-73, p.214
The storm formed on the 26\textsuperscript{th} and 27\textsuperscript{th} in the year 1888, about Lal.10\textdegree N, and Long. 90\textdegree E, began to move along the usual path taken by storms, which form near and to the north-west of the Nicobar Islands. It was in Lat.11 1/2 \textdegree N, and Long. 89\textdegree E. at noon of the 28\textsuperscript{th} and continued to move in West and North course with approximately uniform velocity from that date until it struck the Madras Coast during 1888. Its velocity averaged about 9 miles per hour during this period. It did not increase much in velocity as it approached the coast, although it probably increased in intensity.\textsuperscript{47}

\textbf{MAP: 3 FORMATION OF CYCLONE ON 26\textsuperscript{TH} OCTOBER TO IST NOVEMBER 1888}

\textsuperscript{47} Appendix
Height of the Tropical Cyclone

During the height of the storm the rain fell in torrents, the lightning darted in awful vividness from the intensely dark masses of clouds that pressed down, as it were, on the troubled sea. Hurricanes do not readily cross mountainous regions, and on reaching continental areas frequently dissipate. They appear to be temporarily destroyed on reaching these mountains, but in some instances redevelopment takes place on the other side. This phenomenon has been explained by supposing that cyclone is forced into the higher atmosphere until
the mountains are crossed when it again return to the surface. Elliot estimated
the height of cyclones of the Bay of Bengal at about one mile. Redfield estimated the height of the hurricane at one mile. Vines, who made observation of many hurricanes, and Algue, who studied cyclones of the Far East, were both of the opinion that the height is considerably more than a mile. From a consideration of temperature change with attitude, Koppen and Hourwity think that the presumed difference between centre and periphery of the hurricane does not disappear until considerably higher altitude be reached, probably six miles or more. It depends on the area of spread of the piled up water. The height is determined by various factors. The shape of the coastline is important. The height gets amplified if the water is funneled into an enclosed region such as bays and estuaries, the continental slope should be gentle, and the angle between the coastline and the right semicircle of the storm track is $90^\circ$ or less.

When a cyclone hit Madras at 4 A.M. of the 21st October 1846, the wind together with the rain, began to subside and to draw round to southward, in which quarter it remained strong and variable till between 7 and 8 A.M. of the 22nd when it backed round to the North west, the Barometer gradually rising till the 25th when it attained its previous height of 30.00. On board the ships Ann Armstrong, Edward Bilton, Lady McNaughten and Eleanor Lancaster, between 30 and 40 miles from the land, reported the Barometer to have ranged between 28 and 29 inches during the height of the gale, giving as mean of the whole 28.67. This shows a difference of nearly an inch from the height registered on shore.

**Features of Cyclone**

**Signs of the Approaching Hurricane**

In coastal regions, one of the first signs is the storm swell. The winds in the distant storm create waves on the sea moving outwards from the storm area. They traverse great distance and break upon the shore 400 to 500 miles or more to from the storm. When the wind is light, the booming sound of the surf at

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fairly regular intervals is ominous clouds. Changes of the wind, barometric pressure, rise of tide and other phenomena, in relation to the distant cyclone occur.

**Cloud Sequences**

Clouds are gigantic hieroglyphics spelling out the story of the weather on the open book of the sky. Clouds are, however, visible signs of definite schemes of motion followed by the air and reflect ever-changing conditions of temperature, moisture, and movements of the air at different levels above the surface of the earth. These are among the first precursory signs.

Best known of all cloud sequences are those which ordinarily precede and accompany the passage of a cyclone, or storm. Their development is interesting, and their presence may prove more or less ominous, depending upon the intensity of the disturbance which they foretell.

The first indication of the approach of a disturbance is high overhead, under the canopy of a serene blue sky, some faint lines and wisps of a delicate threadlike white cloud known to the sailor as ‘mare’s-tail’ and to science as cirrus. The beautiful feathery creation drifts along generally at a height of about 5 miles and from points west to east they appear at first to thicken gradually into a somewhat confused weed, or to assume varied shapes such as isolated tufts, thin filaments in a blue sky, threads spreading out in the form of feathers, or curved filaments ending in tufts. Finally, as the storm draws nearer, a more definite transformation occurs, the picture changing into the uniform white sheet of cirrostratus. A few hours more, and this white sheet becomes grayer and denser, until eventually it assumes a dark blue-gray color with the sun shining through it as a mere dim spot of light. Considerably lower than was the original cirrus—perhaps no more than 2 miles up—the cloud is now altostratus (thunder cloud). In the interval between the first appearance of cirrus high in a blue sky and the gradual transition into cirrostratus and, now, altostratus, the central portion of the storm is overhead, and it is a matter of only a very short time before nimbostratus, the rain cloud, appears and the rain commences to fall. As a rule the first dark fragments of nimbostratus can be seen approaching below a dense pall of gray altostratus and—as so often-veiling the sun. A streak of this cloud extending in an unbroken layer over the sky may therefore be regarded as
a harbinger of continuous moderate rain. From the time the rain cloud arrives until the passage of the ‘trough,’ an elongated area of low barometric pressure familiarly called ‘low’ on the weather map, rain falls more or less continuously.\(^{51}\)

Once the center of the cyclone has passed, two things happen: the sky begins to clear; and, instead of rain cloud, nimbostratus, broken or hapless shaggy portions of various types of cloud form. From some of these types-notably cumulus and cumulonimbus, massive heaps of clouds resembling mountains sheering into the blue-occasional showers fall. As the atmosphere becomes more settled, or less cyclonic, the cumulus, or “heap” clouds- lowering, perhaps, around the horizon-may assume the form of long hands of stratocumulus. The foregoing is the most common sequence of clouds when a cyclone is passing directly over an area. \(^{52}\)

**Wind**

The pressure exerted upon a plane surface normal to the direction of the wind increases with the square of the wind velocity. Wind is air in Motion. Despite its tenurity, air becomes, when moving at high velocities, a very destructive agent, partly because of the force exerted by the wind itself but also because of solid objects which are carried along with it. In tropical storms, water, both from the increased violence of the sea and the torrential rainfall, becomes an additional and important agent of destruction. In January and till about the middle of February, North East winds prevail, and then the South East and Southerly, till the middle of May, when the land winds set in, and continue at about W.S.W(West South West) till September, relieved by sea breezes in the evening, which die away about 10 p.m. From September to the end of October, the winds are light and variable form South West to South East with calms. About the last week of October, the North East Monsoon sets in with heavy rain and lightning. The rainy season closes in December, but the wind continues at North East till the end of January. \(^{53}\)

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The maximum velocity of the wind at Madras was 83 miles per hour, on the occasion of the great storm in May 1871. In 1871 November, the velocity of the wind was 34 miles per hour. As a matter of fact, the wind in Madras does not flow from the north and the north east for more than few months of the year, from October to February, the direction of wind during the remaining eight months being more or less southerly. At noon of 30th October 1888 the wind (from north) began to increase in force, and at 8 pm the barometer began to fall, at first very slowly. The weather became more unsettled during the night, with constant rain. The wind had now shifted to North West and increased steadily in force. By the noon of the 31st the weather was very stormy, and the barometer began to fall rapidly; the wind remained steady at north-west, and the squalls became more violent and were extremely severe between 6 pm and 9 pm. There was a lull of half an hour from about 9.30 pm to 10 pm, and almost immediately after 10 pm, the wind began to come from east. 54

One important feature of the winds in the November and December cyclones is the great strength of the winds at very considerable distances from the centre in the north quadrant. It is very probable that the cyclonic rainfall which is due to the southerly or humid winds enter quadrant. Hence ascension movement is most active in the western quadrant and the horizontal movement is comparatively feeble.

The below table shows that weather was unsettled and squally with heavy rain on the 29th, 30th and 31st, 1st, 2nd of November 1888. The area extended to some distance northwards on these days. The weather became more unsettled, the squalls heavier and more frequent, and the rain fall was more intense. The disturbance developed rapidly, and the barometric depression thus produced intensified into a cyclonic storm which began to form to a severe cyclone on the 30th and 31st. The wind velocity increased from 6 to 32 in Madras from 29th of October to November 1888.

TABLE: 1 UNSETTLED AND SQUALLY WEATHER WITH HEAVY RAIN ON THE 29TH, 30TH AND 31ST OF OCTOBER 1888, 1ST, 2ND OF NOVEMBER 1888.

<table>
<thead>
<tr>
<th>STATION</th>
<th>DISTRICT OF STATION FROM THE TRACE OF THE STORM</th>
<th>AVERAGE VELOCITY OF THE WIND IN MILES PER HOUR FOR THE 24 HOURS ENDING 8 A.M. OF</th>
<th>AVERAGE WIND VELOCITY PERIOD 29 OCT 2ND NOV 1888</th>
<th>RATIO OF WIND VELOCITY PERIOD TO NORMAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>29TH OCT</td>
<td>30TH OCT</td>
<td>31ST OCT</td>
</tr>
<tr>
<td>NEGAPATAM</td>
<td>160 MILES SOUTH OF PATH</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>SALEM</td>
<td>140 MILES SOUTH OF PATH</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>MADURAI</td>
<td>260 MILES SOUTH OF PATH</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>TRICHINOPOLY</td>
<td>190 MILES SOUTH OF PATH</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>BANGALORE</td>
<td>40 MILES SOUTH OF PROLONGATION OF PATH</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>MADRAS</td>
<td>NEAR PATH</td>
<td>6</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>MASULIPATNAM</td>
<td>210 MILES NORTH OF PATH</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>COCANADA</td>
<td>290 MILES NORTH OF PATH</td>
<td>15</td>
<td>22</td>
<td>28</td>
</tr>
</tbody>
</table>

Source: Bay of Bengal and Arabian sea cyclone P.P.274

Storm surge

Storm surge is defined as the abnormal rise of the sea caused by a Cyclone moving over a continental shelf and is generated by the interaction of air, sea, and land. The cyclone provided the necessary driving force in the form of strong horizontal pressure gradient and very strong surface winds. As a result the sea level rises and continues to rise as the cyclone moves over shallow water and reaches a maximum on the coast near the point of landfall.

Winds create waves upon the sea which move with a speed that is only a little less than the speed of the wind which produce them. Waves quickly outrun the tropical storm in which the wave form. When wind begins blowing over a water surface it produces at first a series of ripples moving with the wind. As the ripples move forward with the wind, they steadily increase in size as long as the
wind continues. The ultimate size of the waves depends upon the force of the wind and the “fetch” or length of water surface windward.

After the wave move beyond the influence of the winds which cause them, there is a change in their form. The most rapid change at first is a decrease in height. The wave becomes a relatively low, undulating movement of the sea surface known as a swell and distinguished by two features: first, its relatively smooth, undulating from without the steep and raging crests characteristic of waves actively driven by the wind and, second, the movement of winds and waves in different directions indicating that the waves have been formed elsewhere by winds from another quarter.55

After waves are formed by winds in any part of the storm area, they move straight forward while the winds are deflected to the left in the northern hemisphere and to the right in the southern hemisphere. To the mariner the direction of movement of the storm swelling in the open sea is significant to the observer on shore. The direction of movement of storm swells and is not a dependable indication of the direction in which the storm centre lies, unless he understands the effect of shallow water on the direction of wave movement. The period of waves created by a storm at sea does not change materially as the waves move out of the storm field. Even when the swells reach shore, where they move more slowly, they become shorter so that the line interval is not affected. If the shore line does not lie at right angles to the direction from which the wave comes, then one end of the wave reaches shallow water and is related first so that the remainder of the wave gains up on it, this results in a burning movement that tends to bring the wave front parallel to the shore line.

As a precursory sign the tide is more worthy. In the coastal regions, one of the first is the storm swell. Ordinarily, a continuation of offshore winds will result in a tide below the normal and winds blowing for a considerable period toward the shore and will cause a high tide. When the, tropical storm approaches the coast, the tide rises even when winds are flowing offshore. The winds locally may be offshore in the front of the cyclone but, farther at sea, the winds in the opposite side of the cyclone blow towards the shore.

FIGURE: 6 STORM SURGES

The observer on shore should give particular attention to the period of the wave. The number of swells per minute should be ascertained by counting for 3 minutes. It is a valuable index to the intensity of the storm. A fully developed hurricane causes swells on shore at some distance from the storm center with a period of 12 to 15 seconds 4 or 5 waves to the minute. In general, the larger the body of water, the longer will be the period of waves observed on its shores. Likewise, the more intense the storm at sea, the longer the period of the swells that break on the shore. The intermittent breaking of heavy swells on the shore when the wind is light is one of the signs of a cyclone. Ordinary waves of small period produce a more or less continuous noise.\(^{56}\)

Impact of a storm surge

During the cyclone of 1884 the sea wave rose to a height of 12 ½ feet above its ordinary level and encroached 260 yards beyond its usual limit.\(^{57}\) Factors that determine the surge heights for land falling tropical cyclones include the speed, intensity, size of the radius of maximum winds, radius of the wind fields, angle of the track relative to the coastline, the physical characteristics of the coastline and the bathymetry of the water offshore.

At least five processes can be involved in altering tide levels during storms. These include the pressure effect, the direct wind effect, the effect of the earth’s rotation, the effect of waves, and the rainfall effect. The pressure effects of a tropical cyclone will cause the water level in the open ocean to rise in regions of low pressure and fall in regions of high pressure.

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\(^{57}\) Proceeding of the Madras Government, *Board of Revenue* dated 19th December 1884, No.4367
In the Bay of Bengal, as is well known condition along the shore are more favorable to storm surges to attain enormous dimensions specially when they coincide with the astronomical tides. Also the storm waves arrive as sudden rise of water sometimes as advancing well water and at other times in the form of bore with very steep points. The characteristic feature of the cyclone is peculiar in Bay of Bengal when compared to other seas. From the historical records, it is seen that there were instances when the height of the storm surges attained 10 meters or more, roughly equivalent to the height of a modern four storied building.\(^{58}\)

### Vulnerable areas of storms surges

By the consideration of past recorded surge values, the entire East Coast of India can be classified into four main coastal stretches which are highly prone to surges due to cyclones in the Bay of Bengal.\(^{59}\)

### Area 1

The first area of importance is the coastal area of Bay of Bengal and Bangladesh at the head of the Bay of Bengal. Some of the important storms which caused phenomenal storm surges are reported only in this area. The cyclone of 31\(^{st}\) October / 1\(^{st}\) November 1876 which crossed the place called Backergunge in Bangladesh. It has been classified by several writers as the most extensive and cyclone of that country. Perhaps in no other part of the globe such phenomenal storm tides have been recorded.

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\(^{59}\) *Hazards of Cyclones, heavy rainfall, strong winds and storm surges*, Indian Meteorological Department, Government of India, August 1989. p.p.6-7
Area II

The second vulnerable area in the East Coastal stretch is between Paradeep and Balasore in Orissa, where the storm surges of ranges 5m to 7m were reported on many occasions. In the case of the false point cyclone (Orissa) cyclone of 22nd September 1885 a surge height of 8m was reported at several places.

Area III

The third area is the Coastal stretch between Bapatta (south of Masulipatnam) and Kakinada in Andra Pradesh. About 30% of the recorded storm surges along the Indian Coast have affected this particular stretch with surge height ranging between 5 m to 7 m, causing complete destruction on several occasions. Most of the 18th Century and some of the 19th century records do not indicate the surge height but there are several awe inspiring accounts about how cyclone after cyclone affected particularly the Koringa and Masulipatnam area which were rebuilt several times after destruction. Finally the November 1864 storm put an end to the Masulipatnam as a Military station of the British due to total destruction.

Area IV

The fourth area is the Pamban to Nagapattinam stretch which also experienced storm surges of the 3m to 5m on several occasions. Originally Pamban gap was bridged by a continuous isthumus, but in the year 1480 a violent storm breached the isthumus and permanently separated the island of Rameswaram from the main land of the Mathura district, thus making a break in the great connection link of islands, rocks, and shoals that separate Ceylon from the main land of India. The 23rd December 1964 storm caused surge of height reaching 5m which washed away the entire Dhanushkodi Islands. 60

Thunder and lightning in Tropical cyclones

Thunder is merely the reverberation, or clap, made by a sudden expansion in the air as the bolt of lightning passes through it; it is the sound caused by the violent agitation of the air along the flash. Thunder may be described as the sound produced by lighting discharge, and lightning as a disruptive electrical

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discharge in the atmosphere.\textsuperscript{61} Inside the storm cloud itself, air currents ascending at a speed possibly over 24 feet a second, consists of a succession of gusts and lulls. Consequently, the large drops of rain as they fall are split up into smaller drops which then fall less rapidly. Tossed by the rising air currents, drops may rise and fall, grow and break up, over and over again.\textsuperscript{62} Sheet lightning includes the expanded flashes which occur during a storm. On 23\textsuperscript{rd} March 1884, the shower was remarkable. It commenced at about 4pm, with a storm of wind thunder and lightning. The sky was black and very heavy rain was evidently falling away to the west along the Gingee and Tiruvannamalai hills.\textsuperscript{63} Frequent and almost continuous lightning had also been observed within the destructive wind circle of many tropical storms. Thunderstorms are most frequently occurred in October, and lightning also seen.

\textbf{Showers and squalls}

Rain fall in the Tropical Cyclone takes place shortly after the bar is formed in the horizon. The Nimbus Clouds of the hurricane begin to overrun the skies with inexhaustible succession and high speed. Showers of short duration begin, and the wind velocity increases from that moment. The barometer that has been falling slowly now drops abruptly. The rain at the beginning is of a showery nature, attended by squalls from 55 to 65 miles an hour, while the mean velocity of the wind is 35 to 40 miles. On the contrary, as the vortex approaches, the rain is always continuous although highly irregular, the showers succeeding each other at short intervals, and always attended by furious gusts of 100, 110, and sometimes 120 miles an hour.

\textbf{Rainfall in Tropical Cyclones}

Heavy rainfall and frequently torrential are the most outstanding phenomena associated with the tropical cyclone. In tropical cyclones, rainfall is always heavy reaching on some occasions to the proportions of what is

\begin{itemize}
\item \textsuperscript{62} Op.cit H. Kimball James, \textit{Cloud and weather Atlas} p.117-118
\item \textsuperscript{63} Report on the Administration of the Madras Presidency, during the year 1887-88, p.190/Annual report of the Dept. of Reo Settlement and Agriculture. 1884-85. p.24-25
\end{itemize}
commonly termed a “cloudburst.” High winds which accompany the cyclone prevent an accurate catch of the rain which falls; in some instances it is probable that not more than 50 to 75 per cent of the rain is caught by the gauge.

**Distribution of rain intensity in the hurricane**

Cline published in 1926 results of an investigation into the distribution of rainfall and other phenomena of the tropical cyclone. He found a decided contrast in the distribution of rainfall between travelling cyclones and those which ceased to advance. According to Cline, rainfall at any given moment in the travelling cyclone is not distributed uniformly about the centre, as would be indicated by a study of total falls in the paths of the cyclone, during the entire period of its passage. Very little rainfall, he finds, occurs in the rear half. Rainfall at the most rapid rate in front and to the right of the line of advance, He found that the area of greatest rainfall shifted to the rear of the cyclone, and that the systematic rainfall distribution of the traveling cyclone was absent. Cline’s conclusion is that energy released by condensation of moisture in the right front quarter of the cyclone is sufficient to account for the continuous redevelopment, or maintenance, of tropical cyclones of the greatest intensity.  

Father Vines did not agree with this view. His observations indicated that the rainfall extents further in advance of the center than it extends to the rear, in most hurricanes, but those there were instances in which the rain area extended itself further backward. Cline maintains that the heaviest rainfall occurs in the right front quarter of the cyclone as the result of convergence of winds there with those coming from the right rear quarter. His observations tend to show that the winds in the right half of the storm are much stronger than those in the left half, and that the circulation in general is not symmetrical about the center of the cyclone as has been asserted by many writers. Tropical cyclones give abundant rainfall. Slow moving and large-scale cyclones produce more rain in comparison to the fast moving small size system. Rainfall distribution around the centre is not symmetric. In several cases rainfall of 40 cm in a day can occur over an area of about 50 km radius around the centre of the cyclone. It can be 20 cm or more a day even at distance of 200 km from the centre. More than 90% rainfall due to a

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cyclone is limited within a 200 km radius of the cyclone beyond 200 km, the average rainfall is less than 10% of the total rainfall. Rainfall is maximum in the left forward section in the case of westward moving cyclones, in the forward sector in the case of cyclones recurring towards northeast or east. Heavy and prolonged rain spell may cause river-floods, which may submerge low-lying areas, cause erosion of structures, washing away of bridges, rail tracks, and roads.

Intensity of rainfall is quite high, particularly within the core of the cyclone. It can be even 10 to 12 cm per hour. Outside the core also intensity of 4 to 6 cm per hour occur but over smaller areas (100 square km) and per shorter durations (an hour or so). When the rainfall intensities are about 1 cm per hour, the raindrops are about a millimeter in diameter and their fall velocities nearly 2 mps. When the rainfall intensities are 6cms or more for hour, the raindrops are 3mm or more in diameter and their fall velocities are 6mps or more.

**TABLE: 2** AMOUNT OF RAINFALL DURING THE STORM OF 1846

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6 pm</td>
<td>Saturday 17th</td>
<td>6 am Sunday 18th</td>
</tr>
<tr>
<td>6 am</td>
<td>18th</td>
<td>6 pm 18th</td>
</tr>
<tr>
<td>6 pm</td>
<td>18th</td>
<td>6 am 19th</td>
</tr>
<tr>
<td>6 am</td>
<td>19th</td>
<td>6 pm 19th</td>
</tr>
<tr>
<td>6 pm</td>
<td>19th</td>
<td>6 am 20th</td>
</tr>
<tr>
<td>6 am</td>
<td>20th</td>
<td>6 pm 20th</td>
</tr>
<tr>
<td>6 pm</td>
<td>20th</td>
<td>6 am 21st</td>
</tr>
<tr>
<td>6 am</td>
<td>21st</td>
<td>6 pm 21st</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total inches – 2931</td>
</tr>
</tbody>
</table>

**Source:** Madras Journal Literature and Science Vol. XIV, 1847
The data gives the amount of rainfall during the storm of 1846. At 4 A.M. of the 21st October 1846, the wind together with the rain, began to subside and to draw round to the southward, in which quarter it remained strong and variable till between 7 and 8 A.M. of the 22nd when it backed round to the North west, the Barometer gradually rising till the 25th when it attained its previous height of 30.00. The total amount of rain fall during this period was 29.31 inches.

The statement given below shows the rainfall in the district during five fusly, the total average fall of rain throughout the whole district fusly 1284 (April 1874 – 1875) was 50 inches or 20 inches more than the proceedings year, the largest quantity that fall being during the north east monsoon.

**TABLE : 3 AVERAGE FALL OF RAIN DURING APRIL 1874 – 1875**

<table>
<thead>
<tr>
<th>Fusly</th>
<th>South West Monsoon</th>
<th>North East Monsoon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>April 1874</td>
<td>May</td>
</tr>
<tr>
<td>1280</td>
<td>0.2</td>
<td>1.5</td>
</tr>
<tr>
<td>1281</td>
<td>0.5</td>
<td>3.5</td>
</tr>
<tr>
<td>1282</td>
<td>0.7</td>
<td>8.5</td>
</tr>
<tr>
<td>1283</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>1284</td>
<td>-</td>
<td>9.0</td>
</tr>
</tbody>
</table>

The total rainfall during this period of 49 hours at the Port Officer was 14.23 inches, of which upwards of 12 inches fell before 31st. The rainfall data shows -

1. That the rainfall was heaviest in and near the path of the centre.
2. That it diminished rapidly in amount from the sea coast to the interior.
3. That it diminished rapidly in amount to the north and south of the path of the centre, and extended much further to the north than to the south of the centre. It was large in amount on the sea coast at distances of 300 to 400 miles to the north of the track of the storm, whilst it was almost nil at a distance of 100 miles to the south.

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4. The rainfall was intense in advance of the cyclone centre, and the line or narrow belt of heaviest and most intense rainfall, so far as can be judged from the limited data, very approximately coincided with the line of advance of the storm centre.

5. The total rainfall for the period of 1884 was 67.96 inches on 4.6 wet days and is more than double of the average 57.91 inches or about 85% fall in 4 weeks, namely 29th, 30th, 32nd, and 38th. Almost all the cyclones are accompanied by heavy rainfall.

Landfall

Officially, landfall is when a storm's center (the center of its circulation, not its edge) crosses the coastline. Storm conditions may be experienced on the coast and inland hours before landfall; in fact, a tropical cyclone can launch its strongest winds over land, yet not make landfall; if this occurs, then it is said that the storm made a direct hit on the coast. Due to this definition, the landfall area experiences half of a land-bound storm by the time the actual landfall occurs. For emergency preparedness, actions should be timed from when a certain wind speed or intensity of rainfall will reach land, not from when landfall will occur. Intense annular tropical cyclones are distinctive for their lack of rainbands. Instead, they possess a thick circular area of disturbed weather around their low pressure center. While all surface low pressure areas require divergence aloft to continue deepening, and the divergence over tropical cyclones is in all directions away from the center, the upper levels of a tropical cyclone feature winds directed away from the center of the storm with an anticyclonic rotation, due to the Coriolis effect. Winds at the surface are strongly cyclonic, weaken with height, and eventually reverse them. Tropical cyclones owe this unique characteristic to requiring a relative lack of vertical wind shear to maintain the warm core at the center of the storm.  

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66 Report on the Administration of the Madras Presidency, during the year, 1885-86 p.56
The major damage and loss of life from most hurricanes occur within 100 to 150 km of the landfall position, the point where the low pressure center crosses the coastline. An exception is when torrential rains continue after a cyclone moves far inland, causing extensive river flooding. On the evening of 25th November, 1865, the vortex was steering in for the land between Madras and Cuddalore, and the unfortunate shipping with a N.N.E. gale and a heavy sea stood out and drafted into the more violent portion of circle, and met with severe disaster. The vortex crossed at the south west of Madras.