1. 1 Introduction

The history of Tropical Cyclone (TC) research is an age old story of civilization. Since the birth of conscious in man he has tried to understand the wonders of weather for his own good. Probably the most ancient records of weather are those given in Vedas as identification of monsoon advent and withdrawal patterns (Asnani, 2003; Emanuel, 2005). Knowledge of such planetary flows were earlier utilized by sailors across the world especially by traders of India, Egypt, China to steer their ships over the tropical seas. Thus seasonal visits of tropical cyclonic storms have always been recognized weather events since then. From the time of Aristotle to Galileo followed by Boyle, Hadley, Ferrell to Piddington study of atmosphere, weather and climate is a sound subject. Industrial revolution and modern composite technologies have now-a-days made several modifications to the atmosphere in terms of its composition and characteristic flow patterns in climatological as well as instantaneous scale. Tropical regime is the breeding ground of cyclonic storms occurring over oceans generated from meso-scale convective systems (Maddox, 1980; Houze, 2004). These storms reside at the edge of meso-scale and synoptic scale of atmospheric motion. Orlanski (1975) classified them in meso-\(\alpha\) scale as they are larger in dimension than cumulonimbus convection systems but smaller than extra-tropical cyclones. TCs pose circulatory motion with winds flowing in anti-clockwise in north and clockwise in southern hemisphere (Hennon, 2006). Often they are called as meso-scale convective complexes (MCCs) with high wind gust and torrential rainfall
with a distinct circular feature at storm center referred as ‘eye’ of the storm. Sir Henry Piddington (1869) rightfully named these characteristic storms as CYCLONEs after the ‘one eyed monster’ named “Cyclops” in ancient Greek mythology in one of his publishing ventures at Calcutta. The genesis, maturation and movement trail of these storms have fascinated meteorologists around the world throughout the ages. The spatial and temporal variability along with their structural dynamics is speculated, analyzed and explored through almost all possible measures. These storms are now studied in optimized techniques with the technological advancement based on years of theoretical research. The dawning of satellite era opened new directions of studying these storms in terms of both morphological and climatological point of view. Today no weather event escapes the eye of the monitoring network of satellites. Enormous numbers of approaches are made to validate a flawless forecasting of these ‘solitary creatures’ as addressed by Sir H. Ooyama (1969). Weather forecasting has touched new horizons of success today but there are still blocks to fill up on regional and seasonal basis.

1.2 Meso-scale Convective Systems: The birth place of Tropical Cyclones

Meso-scale Convective Systems (MCSs) are defined as “A cloud system that occurs in connection with an ensemble of thunderstorms and produces contiguous precipitation area ~100 km or more in horizontal scale in at least one direction” (Houze, 2004). These weather systems are largest convective storms producing both upper and CG discharges (Bhattacharya et al, 2007 and Bhattacharya et al, 2009). Atmospheric kinetic energy spectrum ensures the existence of MCS in an intermediate range of energy transfer i.e. from large to micro scales of atmospheric motion and vice versa (Orlanski, 1975, Stull, 1988, Thunis and Bronstein, 1996 and Lin, 2007). Thus they behave as system-mediating and sometimes system-
Milestones of Meso-scale Convective Storm Research

generating entities in atmospheric kinetic energy transfer spectrum. These systems are non-quasi-geostrophic and hydrostatic in nature by birth (Raymond et al, 2007). Their life span varies from a few hours to days. Figure 1.1 shows a satellite infrared image of an MCS over Missouri (Houze, 2004). A subset of MCS may have larger horizontal span (>10^5 km^2) and higher life time (>6 hrs) (Bartels and Maddox, 1990). Maddox

Fig. 1.1 An Infra-red (IR) view of a Characteristic MCS over Missouri (Source: Houze, 2004)

(1980) identified them as Meso-scale Convective Complexes (MCCs). These systems appear together with weak mid-tropospheric trough, low-level easterly jet streams, tropical low pressure systems etc. depending upon topographical and climatological regime of generation. Figure 1.2 gives the global distribution of MCCs after Laing and Fritsch (1993). MCCs are basically multi-cell storms with individual cells at interactive
proximity. Initiation stages of an MCC involve unorganized and sporadic cell generation before dissipation of matured cells for a long lived MCC. They exert both convective and stratiform rain pattern (Laing and Fritsch, 1993; Bister, 1996). Natural Convective activities inside the system often are observed to form mid-level vortex (Bosart and Saunders, 1981; Mapes

Fig. 1.2 Global locations of MCS occurrence (Source: Laing and Fritsch, 1993)

Fig. 1.3 A and B are two meso-scale vortices during the development of Tropical Cyclone Oliver in vicinity of North Australian coast. Satellite imagery from 0900 UTC 4 February to 0000 UTC 5 February 1993 (Source: Ritchie et al., 2003)

and Houze, 1995; Bister, 1996). These vortices are likely to trigger precursors of cyclogenesis. Hence MCCs often act as birth places of
Tropical Cyclones (TCs). Manifestation of MCSs into TCs has been reported by a good number of researchers around the world from satellite observations (Payne and McGarry, 1977; Velasco and Fritsch, 1987; Zehr, 1992; Bister, 1996; Simpson et al, 1997; Richie et al, 2003; Schumacher and Houze, 2003). An example of development of TC OLIVER (1993) from two pre-existing meso-scale vortices by overlapping satellite observations is given in Figure 1.3. Thus MCSs are now considered to be an important subject of research as they can provide substantial information about tropical convection, atmospheric moisture circulation and identification of an infant tropical cyclonic storm.

1.3 Tropical Low Pressure Systems

Tropical regime (23.5°N to 23.5°S) holds some characteristic favorable conditions viz. (a) high insolation, temperature and moisture content (b) instability due to lower temperature at upper troposphere (c) collision-coalescence process as principal dominating factor in deciding rainfall pattern (d) sparse predictability due to absence of any dominant wave motions similar to mid-latitudes (Henon, 2005). These conditions inspire development of a good number of Low Pressure Systems (LPSs). They consist of several meso-scale convective clusters surrounding a low pressure area. LPSs produce intense tropical storms when are subjected to adequate environmental steering (Merrill, 1984; Kumar and Dash, 1999). Generally concentric isobars at 2 hPa intervals over land are referred as LPS in meteorology. Presence of two such isobars is known as Depression and if the number is > 3 then it is called cyclonic storm. Wind strength is considered for classification of these weather systems over sea (Mahapatra and Mohanty, 2004). Depending upon the season and geographic region of occurrence LPSs are often metamorphosed into a warm core vortex as a
result of release of latent heat of condensation and fall of temperature due to evaporation in the subsiding air around the core (Yanai, 1963; Mowla, 1968). Tropospheric trough at 200 hPa level and monsoon trough play significant role in maturation of LPS (Krishna, 2009; Wang et al, 2013). Several studies have been made on LPS characteristics particularly over Indian sub-continent during monsoon season due to large numeric abundance (Ramage, 1959; Dagupatti and Sikka, 1977; Sarkar and Choudhury, 1988; Rajamani and Sikdar, 1989). There exists a good

co-relation between Indian Summer Monsoon Rainfall (ISMR) and total number of LPS days (Mooley and Shukla, 1989). This rainfall amount primarily governs the Indian agricultural production (Kumar and Dash, 1999; Mohapatra and Gupta, 2000). These systems contribute largely to monsoon trough activity and their frequency is maximum over north-west part of the Bay of Bengal and adjacent sea in monsoon months (Mahapatra and Mohanty, 2004). Figure 1.4 depicts a LPS over the Bay of Bengal

Fig. 1.4 Locations of LPSs over South-East Asia (Source: Thai Meteorological Department) on October 8, 2012
Milestones of Meso-scale Convective Storm Research

during monsoon. LPSs are often categorized as developing tropical storms if they do not mature into TCs. Roy Bhowmick et al (2007) and Kotal et al (2009) set a differential criterion between LPSs and TC category storms in terms of Genesis Potential Parameter (GPP) of value 8 for the Bay of Bengal. Thus the probability of metamorphosis is estimated and forecasting has been made better.

1.4 Tropical Cyclones

Tropical Cyclones (TCs) are often described as tropical meso-scale cyclonic weather systems (Wang et al, 2007). TCs are an especial kind of MCS with adequate spatial span to involve Corioli’s force and pressure gradient force come into play simultaneously. In spite of categorizing them to meso-α scale Pielke (2002) introduced a new sub-class of synoptic scale range and designated it as ‘Regional Synoptic Class’ (Lin, 2007). To be more specific downscale (synoptic to meso-α) and upscale (meso-γ to meso-β) energy flows ultimately decide the formation of the storm. The following figure represents a multispectral view of TCs in atmospheric

Fig. 1.5 Scale specific residence of TC as per horizontal atmospheric dimension (Source: Montogomery and Smith, 2010)
classification (Montogomerry and Smith, 2010). However their fields of geophysical flow are transient in nature and basically show fine meso-scale structure. Emanuel (1987) described TCs as natural example of Carnot’s cycle involving a feedback mechanism of enthalpy fluxes and ocean surface winds. Lighthill (1998) gave a similar view based on the heat intake over the ocean that exerts adiabatic work at its’ eye-wall region and heat loss at near stratospheric altitudes. World Meteorological Organization defines TCs as “Warm core cyclonically rotating wind systems in which the maximum sustained winds are 35 kt or 40 mph or greater” (WMO Glossary, 1959).

1.4.1 Tropical Cyclogenesis

Entire process of TC generation from some individual or collective cloud systems is known as Cyclogenesis. This process has been described as the amalgamation of adequate thermodynamic and dynamic atmospheric and oceanic factors (Palmen, 1948; Riehl, 1963; Gray, 1968, 1988; Bosart and Bartlo, 1991; Gray, 1998; Emanuel, 2005). The criteria of Cyclogenesis are (Gray, 1968; Wang et al, 2007) as given below –

- Sea Surface Temperature (SS) must be $\geq 26^\circ$C. This is necessary to sustain TC wind speed.
- Depth of ocean mixed layer should be sufficiently large.
- Mid-tropospheric Relative Humidity (RH) levels should be large for development and maintenance of eye-wall structure. RH must be $\geq40\%$ at 500 hPa levels otherwise Cyclogenesis will be hindered.
- Vertical Wind Shear (VWS) i.e. the magnitude difference between 200 hPa and 850 hPa level winds should be less than 8 ms$^{-1}$. This will provide space for released heat of condensation to be accumulated inside a vertical column.
- Pre-existence of large cyclonic vorticity is required to encourage convergence of mass and water vapor generating an upward vertical motion.
- Corioli’s force should be effective enough i.e. system development is likely to happen beyond 5° latitude to maintain the cyclonic motion.
Fig. 1.6 Pathways of Cyclogenesis (reproduced after Gray, 1968)
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Fig. 1.7 Region respective sources of tropical Cyclogenesis (a) Before and early 20th century, (b) Late 20th century to early 21st century
(Source: University Corporation of Atmospheric Research)
Gray (1968) analyzed the chain of reactions responsible for producing a matured TC utilizing the six conditions mentioned above. Several positive and negative trails are identified. Such consecutive pathways are shown in Figure 1.6 (After Gray, 1968). Once the storm is generated the concern becomes about the extent of its intensification. Nolan (2007) emphasized on the initiation trigger and also on the timing of initiation. Complete saturation of mid-troposphere level is suggested to be the key factor. However, existence of easterly waves (Atlantic Ocean), Monsoon trough (Indian Ocean) or westward moving waves are reported to be necessary and even described as ‘TC Originator’ by Sir, J. Lighthill (1998). Figure 1.7 depicts different precursors of Cyclogenesis over tropical oceans. These propositions were also accompanied by idea of potential vorticity (PV) (Hoskins et al., 1985). Large value of PV is suggested to be associated with TC development. Satellite observations have verified that retention of such high vorticity region and clusters of deep convection in vicinity of central zone of low pressure system guides the maturation of the storm. The time difference between birth and its intensification to a named storm stage is of 1-3 days. Zehr (1992) and Gray (1998) presented entire process to be sub-divided into two stages. They argued that a secondary trigger is utmost necessary for TC maturation from preliminary MCS clusters. Figure 1.8 depicts two stage development of pre-tropical storm JOE. Thus agglomeration of deep convective MCS clusters in presence of a guiding external agent and necessary environmental steering ultimately give birth to an incipient storm. An externally forced convergence (EFC) creates the stage for internally forced convergence (IFC) to come in to play and become self-sufficient to hold the storm conditions (Gray, 1998). This conception is presented in Figure 1.9. Thus system chain reaction is maintained and TC development takes final place.
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Fig. 1.8 Depiction of TC size and intensity variation as a function of convection strength (After Zehr, 1992)

Fig. 1.9 Development of TC from MCS convective schemes (After Gray, 1998)
1.4.2 Structural features

Extensive studies have been carried out to reveal the structural features of TC. The following two figures give schematic cross-sectional view of a TC

Fig. 1.10 Cross-sectional view of TC

Fig. 1.11 Spatial distribution of surface rain rates (mm hr\(^{-1}\)) in TC GEORGES from TMI observations of TRMM associated with best track maximum sustained wind speed (solid black line) and rainfall in concentric bins around the center of the cyclone (vertical bars) (Source: Laing, 2000)
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(Fig. 1.10). The air-flow pattern and occurrences of different cloud types with their respective positions are highlighted. Principal rain cloud *i.e.* Cumulonimbus and Nimbostratus remain at lower altitudes. Cirrostratus and Cumulus stay in the out-skirt of the system. High clouds *viz.* Cirrus develop the anvil of the storm. Certain developing structures of eye-walls remain visible during life cycle of TC GEORGES as evident from Figure 1.11. During the intensification process a secondary eye-wall is formed outside the primary one. This secondary one contracts and substitute the former eye-wall and gives the dominant and secondary maximum wind field (Willoughby and Black, 1996; Kossin and Velden, 2004). Thus a replacement cycle is performed and storm gains more strength. Two characteristic morphologic elements of a TC are - (a) The eye and (b) The rain-bands

(a) The eye: The intensification schemes convey the system to maturity and make it axisymmetric with the strongest wind field just around the center of the storm. This central region show relatively calm weather than its surrounding and is called ‘The Eye’ of the storm. Figure 1.12

![Image](image-url)  

**Fig. 1.12** Visible (VIS) range and Scatterometer observation of the Eye of TC KATRINA (2005) *(Source: NASA)*
give a closer look into the eye of a cyclonic storm with its eye-wall and
associated wind fields from QUICKSCAT Scatterometer observations. It is
roughly a circular area sometimes acquire elliptical and elongated shape.
Wind fields are also comparatively low at the centre and holds fair weather
situations with no precipitation event. Pressure at the surface level is least
with a departure from ambient as high as ~40 hPa. Haurwitz (1935)
suggested such drop can achieve ratio of 0.1 value to that of the ambient
surrounding atmospheric pressure. The difference in temperature at surface
level varies from 0° to 2°C but with warmer temperature aloft. At altitude
~12 km this difference can be as high as 10°C. Eye exhibit a wide range of
diameter ~8-200 km with maximum occurrence in 30-60 km range. It is
surrounded by deep convection circle called the Eye-wall. It rears the
strongest surface wind fields in the entire system. Inside the eye low-level
sinking air flows whereas in the eye-wall air flows in net upward motion
(Palmen, 1948; Gray, 1979; Merrill, 1993).

(b) The Rainbands: The deep convections in the eye-wall maintains the
structure of the eye. These convection schemes organize the meso scale
complexes in formation of small pockets of atmospheric vorticity due to
breakage of large the long, narrow rain-bands. This structural feature was
first revealed by air-bourne Radar observations (Wexler, 1947). Figure
1.13 give a composite radar profile showing squall line structure of MCS
inside a TC. These bands become concentric and move spirally with the
horizontal wind. That is why they are sometimes called spiral winds (Rao
and Rajamani, 1975). They are characterized by maximum convergence at
low level and prominent divergence at the upper level. Several theories are
proposed to explain the development of these rainbands. Numerical
simulation confirmed the theoretical assumption of generation of these
bands from inertia-gravity waves (Abdullah, 1966; Diercks and Anthes, 1966). Rossby waves are also held responsible behind development of

![Fig. 1.13 Composite RADAR echoes revealing squall line structure of a TC (Source: STORM Project Plan, India Meteorological Department)](image1)

spiral bands (Montogomery and Kallenbach, 1997). Ultimately aircraft reconnaissance measurements give an improved postulation and suggest continuous development and dissipation of meso-scale squall lines around

![Fig. 1.14 Eye-wall replacement cycle of TC SUDAL (2004) (Source: Hawkins et al, 2006)](image2)
the inner core of the system (Powell, 1990). Such formations of Eye and rain-bands are often explained in relation to interaction with existing cyclone momentum vortex motions having adequate coupling between cyclone motions and surrounding environment (Willoughby et al., 1982; Molinary and Volaro, 1989; Knaff and Zehr, 1997).

Fig. 1.15 The wind field structure of TC SIDR (2007) (Source: Regional Meso-scale Meteorology Branch, NOAA)

Thus entire structure is diluted in the form of squall lines and inner core of the storm. However wind speed decreases with altitude inside the storm. Figure 1.15 shows the top-sectional wind field of TC SIDR (2007) over the Bay of Bengal from Multi-satellite composite observations (Regional Meso-scale Meteorology Branch, NOAA). Development of concentric eye-walls is clearly visible showing the highest wind speeds at the first circulatory motions inside the storm.
1.4.3 Potential Intensity

Once the system generates the only concern becomes the maximum potential of its intensification. The theoretical upper-bound of maximum intensity or the Potential Intensity (PI) of a storm is never met in real time basis (Hubert, 1955; Holland, 1997). Bister and Emanuel (1998) presented PI as a function of the balance between dissipative forces and surface flux generated energy fields. This parameter is also found sensitive to heat and momentum transfer equations involved in air-sea interactions (Emanuel, 1986; 2000). Merrill (1988) with Holland (1984) gave a clear view of the intensification at different phases of the life cycle of a TC w.r.t. the tangential component of the wind speed and radial distribution of intensity (Figure 1.16). It defines the dynamic structure of intensification of the storm. Kepert (2010) described the equations governing the motions of a cyclonic storm (axisymmetric) core. Those equations are given in Box 1.1. Some behaviors of atmospheric motions can be explained through these equations placed statically on the earth surface at the cyclone core location or moving with it. This may again vary for individual storm case based on geostrophic, hydrostatic and angular momentum flux involved boundary conditions.

Fig. 1.16 Radial distribution of tangential wind and intensity of a TC life-cycle (Source: Merrill, 1984)
Milestones of Meso-scale Convective Storm Research

Box 1.1

\[
\frac{du}{dt} - \left( f + \frac{v}{r} \right) v = - \frac{1}{\rho} \frac{dp}{\partial r} + \frac{\partial u w^v}{\partial z} \ldots (1.1)
\]

\[
\frac{dv}{dt} + \left( f + \frac{v}{r} \right) u = - \frac{1}{\rho} \frac{dp}{\partial \lambda} + \frac{\partial v w^v}{\partial z} \ldots (1.2)
\]

\[
\frac{dw}{dt} = \frac{1}{\rho} \frac{dp}{\partial z} \ldots (1.3)
\]

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial \rho u}{\partial r} + \frac{1}{r} \frac{\partial \rho v}{\partial \lambda} + \frac{\partial \rho w}{\partial z} = 0 \ldots (1.4)
\]

\[
\frac{d\theta}{dt} = \Theta'' + \frac{\partial \theta w^\theta}{\partial z} \ldots (1.5)
\]

\[
\frac{dq}{dt} = E + \frac{\partial q w^q}{\partial z} \ldots (1.6)
\]

\[
\rho = \left( \frac{p_0}{p} \right)^{\frac{R}{C_p}} \ldots (1.7)
\]

\[
p = \rho R \theta \ldots (1.8)
\]

\[
T_v = T \left[1 + q \left( \frac{1}{\varepsilon} - 1 \right) \right] \approx T \left(1 + 0.60 \bar{\theta}_q \right) \ldots (1.9)
\]

Where, u is the radial velocity
v is the azimuthal velocity
w is the vertical velocity
r is the radial co-ordinate
\( \rho \) is the air density in height co-ordinates
f is the Coriolis’ parameter
u’w’ is the vertical turbulent flux of u
v’w’ is the vertical turbulent flux of v
p is the pressure
\( \lambda \) is the azimuth measured anti clock wise from the positive axis
g is the gravitational acceleration
\( \Theta \) is the potential temperature
\( \Theta'' \) is the diabatic heating rate
\( \Theta w^\Theta \) is vertical turbulent flux of \( \Theta \)
q is the specific humidity
E is the net evaporation rate (excluding the condensation)
T is the temperature
\( p_0 \) is the central pressure
R is the Gas constant
C_p is the heat capacity of air at constant pressure
\( R_g \) is Gas constant for dry air
T_v is the virtual temperature
\( \varepsilon \) is the ratio of molecular weight of water to that of dry air
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However Emanuel with his analogy of Carnot’s engine for a developed TC gave a theory which ultimately deduced the expression for PI given as follows

\[ v_m^2 = \frac{\left( T_S - T_0 \right)}{T_0} \frac{C_S}{C_D} \]  

(1.10)

Where \( v_m \) is the maximum azimuthal wind, \( T_S \) is the surface temperature, \( T_0 \) is the outflow temperature, \( C_E \) is the Enthalpy transfer co-efficient, \( C_D \) is the drag co-efficient, \( K \) is the radial wave number and \( k_{0}^{*} \) is the saturation specific enthalpy at sea surface. Emanuel (1987) established PI to be the unattainable upper limit of cyclone intensity. He also defined the interval of storm intensity between the lower margins of intensity to the estimated PI value of a storm.

1.4.4 Kinetic Energy

The amount of damages it can cause over the path it follows and the surrounding is the major concern associated with TC (De et al., 1999). The potential of destruction of such storms are directly dependent on the surface wind velocity. However the intensification status of the storm relies on 500 hPa wind level (Gray, 1976). Mid-tropospheric level wind fields (700-500 hPa) are found to be best co-related with wind field and direction of movement of the storm (Chan and Gray, 1982). TC generates severe gale winds and cause to form huge wave drag and sea spray over ocean and severe wind gust over land (Emanuel, 1991; 2000; 2003). Most of its energy is dissipated when it enters land region due to large surface friction. Such impacts elude the extent of Kinetic Energy (KE) of the entire system. KE of the storm at one hand describes the destructive nature of the storm and at the other it also measures the horizontal span of the system through spread of high energy wind fields. Malkus and Riehl (1960) based
on such assumptions gave a KE budget along the radial component of the system taking the balance of KE overcome by work done by the system and ground friction. In a recent study Maclay et al (2008) illustrated the zonation of such energy fields on integration of the KE of an air parcel over the volume of disk following the given equation

\[
KE = \int_{z_1}^{z_2} \int_{0}^{2\pi} \int_{0}^{R} \frac{1}{2} \rho (u^2 + v^2) r dr d\theta dz \quad (1.11)
\]

Considering the constant air density boundary condition is modified as

\[
KE = \frac{\rho_0}{2} \Delta z \int_{0}^{2\pi} \int_{0}^{R} (u^2 + v^2) r dr d\theta \quad (1.12)
\]

Where \( \rho_0 = 0.9 \text{km/m}^3 \) at 700 hPa (Standard reconnaissance flight level). They analyzed estimated KE with corresponding wind speed. The correlation between the two parameters is given in Figure 1.17. The best fit equation for KE is evaluated to be

\[
KE = 3 \times 10^{13} (v_{\text{max}}^{1.872}) \quad (1.13)
\]

Equation (1.13) is observed to explain 82% variance of the \( R^2 \) and significant also. The deviations of the estimated KE from the observed KE give indicated the growth or dissipation of storm (Fig. 1.17).

1.4.5 Land Interactions

Massive energy of TC is only apprehended when they make their landfalls and the eye of the storm traces its devastating power signature over the surface of the earth. Traditionally storms weaken as they move near or over land region. A storm undergoes several types of behavioral and structural
changes during landfall and after it. There are also several controversies in estimation of the accurate energy structure of the storm during this decay.

Fig. 1.17 Evaluation of Best-fit relation between TC maximum tangential wind speed and KE (Source: Maclay *et al*., 2008)

This tarnishing phase is called Cyclolysis (Treut and Kalnay, 1990). Anthes (1982) suggested three basic reasons for intensity reduction of TC after landfall –

- Reduction in evaporation due to fall in latent heat supply for movement of the system from oceanic surfaces.
- Cooling of low-level air by the relatively cold surrounding air over land mass.
- Overcoming the increased surface roughness or friction.
In earlier studies surface friction was more emphasized to be responsible for this abrupt tarnish of storm intensity (Jelesnianski, 1972). But later a good number of observational and numerical studies revealed the main sink of energy is the suppression of evaporation and absence of constant oceanic heat source. Outcomes of numerical model analysis made by Rosenthal (1971) and Tuleya and Kurihara (1978) established the importance of evaporation during this decay phase. Some studies made on individual storm basis reflected influences of surface terrain characteristics, existing horizontal pressure gradient and extent of rainfall on diminishing the TC (Powell, 1982; Shapiro, 1983; Willoughby and Black, 1996 and Schneider, 1998).

1.5 Chronological summary of Tropical Cyclone research

Due to immense damage potential and unpredictability of intensification of tropical storms almost every aspect of foreseeing such storm development has been attempted. Following chronicle summarizes some of the most important TC researches in a single collage (Bhattacharya et al, 2014).

Table 1.1 Chronological account of Tropical Cyclone research

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1281</td>
<td>First TC description in Hakata bay by naval armada of Kublai Khan and contemporary Japan. This storm is famous as ‘divine storm’ in Japanese history.</td>
<td>Cervany, 2007</td>
</tr>
<tr>
<td>1502</td>
<td>Violent sea storm recorded and described by famous expeditor C. Colombus in Atlantic Ocean.</td>
<td>Emanuel, 2005</td>
</tr>
<tr>
<td>1559</td>
<td>Florida storm detailed with landfall characteristics along with record of casualties.</td>
<td>Smith et al, 1995; Emanuel, 2005</td>
</tr>
<tr>
<td>1565</td>
<td>San Mateo TC reported with detailed description.</td>
<td>Barnes et al, 1983; Sandrik and Landsea,</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Reference</th>
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<tbody>
<tr>
<td>1609</td>
<td>Bermuda TC reported and circulated for future reference by William Strachey. William Shakespeare utilized its information in one of his creations.</td>
<td>Emanuel, 2005</td>
</tr>
<tr>
<td>1667</td>
<td>First detailed TC record on Virginia TC based on storm surge, rainfall, wind and casualty.</td>
<td>NOAA, 2001</td>
</tr>
<tr>
<td>1686</td>
<td>Characteristic wind patterns around equator and tropics are identified and reported.</td>
<td>Halley, 1686</td>
</tr>
<tr>
<td>1735</td>
<td>Tropical wind flows described, trade wind patterns identified.</td>
<td>Hadley, 1735</td>
</tr>
<tr>
<td>1737</td>
<td>Hoogly river (India) TC reported at synoptic interval. Wind speed, Storm surge, rainfall and track of the storm was evaluated.</td>
<td>Piddington, 1869; Rao, 1995</td>
</tr>
<tr>
<td>1839</td>
<td>First memoir published for TC over the bay of Bengal in June 1839.</td>
<td>Piddington, 1869</td>
</tr>
<tr>
<td>1856</td>
<td>Wind and ocean current patterns are addressed.</td>
<td>Nashville and Ferrell, 1856; Charnock, 1955</td>
</tr>
<tr>
<td>1858</td>
<td>San Diego TC is reported in detail and first assumption is made on association between El Nino and TC formation. Warm ocean waters are observed to be an important criteria.</td>
<td>Chenworth and Landsea, 2004</td>
</tr>
<tr>
<td>1869</td>
<td>Theoretical and practical TC experiences were first published in the “Laws of Storms” over tropical oceans and the name CYCLONE is coined.</td>
<td>Piddington, 1869</td>
</tr>
<tr>
<td>1875</td>
<td>Meteorological stations established in tropical region started functioning to forecast severe storms.</td>
<td>Asnani, 2003</td>
</tr>
<tr>
<td>1893</td>
<td>First detailed wind estimation made on Sea island TC.</td>
<td>Sandrik and Landsea, 2003</td>
</tr>
<tr>
<td>1926</td>
<td>Formation and structure of TCs are analyzed in detail from thermodynamic point of view.</td>
<td>Cline, 1927</td>
</tr>
<tr>
<td>1935</td>
<td>Vertical limit of tropical cyclone growth is proposed and formation of the eye is described based on Manila cyclone, 1882.</td>
<td>Haurwitz, 1935</td>
</tr>
<tr>
<td>Year</td>
<td>Milestone Description</td>
<td>Reference</td>
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<td>------</td>
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<tr>
<td>1939</td>
<td>Vorticity equations are developed and movement of TCs is explained using them.</td>
<td>Rossby, 1939</td>
</tr>
<tr>
<td>1944</td>
<td>Tracks of tropical cyclones are investigated in terms of upper air flows viz. westerlies and polar troughs.</td>
<td>Riehl and Shafer, 1944</td>
</tr>
<tr>
<td>1947</td>
<td>The association of latent heat released along the central eye wall is first observed by Radar profiles.</td>
<td>Wexler, 1947</td>
</tr>
<tr>
<td>1948</td>
<td>Horizontal and vertical structure of TC is explained theoretically in terms of solinoidal ensemble.</td>
<td>Palmen, 1948</td>
</tr>
<tr>
<td>1948</td>
<td>Radio-sonde measurement is taken inside the eye of TC.</td>
<td>Riehl, 1948</td>
</tr>
<tr>
<td>1948</td>
<td>First attempt made to describe the criteria of atmospheric and oceanic circulation for TC formation.</td>
<td>Palmen, 1948</td>
</tr>
<tr>
<td>1949</td>
<td>Cyclogenesis is explained through mechanical processes.</td>
<td>Abdullah, 1966</td>
</tr>
<tr>
<td>1950</td>
<td>Mechanisms of TC squall lines proposed.</td>
<td>Tepper, 1950</td>
</tr>
<tr>
<td>1951</td>
<td>Radar observations are made on TCs to highlight their reflectivity structure.</td>
<td>Ligda, 1951; Lin, 2007</td>
</tr>
<tr>
<td>1952</td>
<td>Dynamics and structure of TC eye is explained.</td>
<td>Simpson and Riehl, 1958</td>
</tr>
<tr>
<td>1952</td>
<td>Low level wind structure of TC is explained.</td>
<td>Hughes, 1952</td>
</tr>
<tr>
<td>1953</td>
<td>An experimental study carried out to validate a proposed numerical model for TC formation.</td>
<td>Soyno, 1953</td>
</tr>
<tr>
<td>1953</td>
<td>Nomenclature of TCs are formed for Atlantic and Pacific ocean. Separate lists are created for eastern north, central north and western north Pacific ocean.</td>
<td>National Hurricane Centre, NOAA</td>
</tr>
<tr>
<td>1954</td>
<td>Pressure-height distribution is observed through radio-sonde observations made inside a TC.</td>
<td>Jordon And Jordon, 1954; Knaff and Zehr, 2007</td>
</tr>
<tr>
<td>1955</td>
<td>Studies made on TC from aircraft reconnaissance by Radar.</td>
<td>Simpson and Starrett, 1955; Fletcher et al., 1961</td>
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</tbody>
</table>
### Chapter I

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>Budget of angular momentum balance of TCs is proposed.</td>
<td>Palmen and Riehl, 1957; Holland, 1983</td>
</tr>
<tr>
<td>1958</td>
<td>A theoretical model is proposed to estimate temperature and humidity variation inside TC system and eye-wall momentum structure of a mature TC is described.</td>
<td>Malkus, 1958</td>
</tr>
<tr>
<td>1958</td>
<td>Importance of mid-tropospheric ventilation in intense TC formation is described.</td>
<td>Simpson and Riehl, 1958</td>
</tr>
<tr>
<td>1958</td>
<td>Prototypes of TIROS and VANGUARD were created.</td>
<td>NASA report, 2011</td>
</tr>
<tr>
<td>1959</td>
<td>On February 17 first weather satellite VANGUARD-II launched by NASA</td>
<td>NASA report, 2011</td>
</tr>
<tr>
<td>1960</td>
<td>Steady-state maintenance of a TC maturation is described by hydrostatic calculations. The process of surface pressure drop is explained up to 75%</td>
<td>Malkus and Riehl, 1960</td>
</tr>
<tr>
<td>1960</td>
<td>On April 1, TIROS-1 launched by NASA</td>
<td>NASA report, 2011</td>
</tr>
<tr>
<td>1960</td>
<td>First identification of TC through satellite TIROS III</td>
<td>NASA report, 2011</td>
</tr>
<tr>
<td>1961</td>
<td>Detailed descriptive analysis is made on mature TC formation. The maintenance of the warm core structure of the storm is explained through latent heat release. Influences of large scale atmospheric flow patterns is also addressed.</td>
<td>Yanai, 1961, 1964</td>
</tr>
<tr>
<td>1963</td>
<td>First attempted aircraft reconnaissance on TC rainbands. Importance of convective flows established.</td>
<td>Gentry, 1964</td>
</tr>
<tr>
<td>1963</td>
<td>Association of TC winds with its thermal structure explained.</td>
<td>Riehl, 1963</td>
</tr>
<tr>
<td>1964</td>
<td>Growth of a cyclone from a depression system is described.</td>
<td>Charney and Eliasson, 1964</td>
</tr>
<tr>
<td>1964</td>
<td>On August 28, NIMBUS 1 launched to collect</td>
<td>Fritz et al, 1966; NESC</td>
</tr>
<tr>
<td>Year</td>
<td>Milestone</td>
<td>Reference(s)</td>
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<tr>
<td>1965</td>
<td>The inadequacy of only latent heat release as a driver in convective processes in TC formation is described.</td>
<td>Kuo, 1965</td>
</tr>
<tr>
<td>1966</td>
<td>Dependence of existing squall lines for rainband formation is established. Mechanical energy is solely reported to be responsible for maintenance of band structure.</td>
<td>Abdullah, 1966</td>
</tr>
<tr>
<td>1968</td>
<td>Climatology of all active tropical cyclonic basins revealed with detailed formation specifics. Entire process of genesis is explained with climatological requirements.</td>
<td>Gray, 1968</td>
</tr>
<tr>
<td>1968</td>
<td>Importance of warm pool in development of TC is reported over North Indian Ocean.</td>
<td>Mowla, 1968</td>
</tr>
<tr>
<td>1968</td>
<td>First successful numerical simulation is achieved for the dynamic state of TC life cycle.</td>
<td>Ooyama, 1969</td>
</tr>
<tr>
<td>1969</td>
<td>Tele-connections are suggested between atmospheric parameters and TC frequencies over Pacific Oceans. Effect of regional periodicity are addressed.</td>
<td>Bjerknes, 1969</td>
</tr>
<tr>
<td>1969</td>
<td>NIMBUS –III launched to obtain temperature information through tropospheric column over eastern Atlantic and Pacific.</td>
<td>NASA report, 2011</td>
</tr>
<tr>
<td>1971</td>
<td>TC model outputs were revisited with varying initial conditions and domain size.</td>
<td>Rosenthal, 1971</td>
</tr>
<tr>
<td>1972</td>
<td>Pioneering approach made to predict storm surge of TCs over the Bay of Bengal through development of surge prediction model utilizing available observations.</td>
<td>Das, 1972</td>
</tr>
<tr>
<td>1972</td>
<td>Vernon Dvorak and his colleagues first proposed a storm cloud identification pattern from satellite observations. Now it is famous by the name of Dvorak’s technique to estimate storm intensity.</td>
<td>Dvorak, 1972, 1975; Kossin and Velden, 2004; Velden et al, 2006</td>
</tr>
<tr>
<td>1972</td>
<td>Potential of recurvature of storms occurring over</td>
<td>Burrouh and Brands, 1972</td>
</tr>
</tbody>
</table>
Chapter I

The western north Pacific ocean has been studied as a function of time of occurrence, storm character and surrounding synoptic weather conditions.

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>Radar observations made on TCs are reported. Eyewall and core structures are revealed from reflectivity profiles.</td>
<td>Atlas et al., 1973; Raghavan, 1990; Tabata et al., 1992</td>
</tr>
<tr>
<td>1973</td>
<td>TCs are classified based on their intensity and maximum sustained wind speed.</td>
<td>Saffir, 1973; Simpson, 1974; Saffir, 2003</td>
</tr>
<tr>
<td>1975</td>
<td>A new scale of horizontal atmospheric motion is proposed. TCs are classified in meso-α scale.</td>
<td>Orlansky, 1975</td>
</tr>
<tr>
<td>1976</td>
<td>Development of TC rainbands are explained to be generated from inertia-gravity waves from a non-linear model diagnostics. Incapability of potential kinetic energy transfer and latent heating in maintaining TC rainbands is highlighted.</td>
<td>Diercks and Anthes, 1976</td>
</tr>
<tr>
<td>1976</td>
<td>Movement of TCs over western north Pacific ocean are found to follow the 500 hPa level wind directions at a radial distance distributed up to 1-7º latitude.</td>
<td>George and Gray, 1976</td>
</tr>
<tr>
<td>1977</td>
<td>Easterly waves are reported to be involved in TC formation.</td>
<td>Shapiro, 1977</td>
</tr>
<tr>
<td>1977</td>
<td>Large scale structure of TCs are studied from radiosonde observations and flight data. A constant circulatory flow is observed irrespective of storm intensity.</td>
<td>Frank, 1977</td>
</tr>
<tr>
<td>1977</td>
<td>Relationship between minimum sea level pressure and surface level wind speed is explored.</td>
<td>Atkinson and Holliday, 1977</td>
</tr>
<tr>
<td>1978</td>
<td>Mechanism of TC rainband formation is demonstrated.</td>
<td>Willoughby, 1978</td>
</tr>
<tr>
<td>1978</td>
<td>Outcomes od hydrodynamic model results are</td>
<td>Anthes and Warner, 1978;</td>
</tr>
</tbody>
</table>
### Milestones of Meso-scale Convective Storm Research

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>Precipitation efficiency of cyclonic storm clouds are estimated from satellite and ground observations. Its association is validated with storm size, intensity, stage of maturation and a TC precipitation model is developed.</td>
<td>Robinson and Lutz, 1978</td>
</tr>
<tr>
<td>1981</td>
<td>Lower potential temperature fields are first observed in mature TCs.</td>
<td>Jorgensen, 1981</td>
</tr>
<tr>
<td>1981</td>
<td>TC formation is examined by differentiating basic characteristics of developing and non-developing storms.</td>
<td>McBride and Zehr, 1981; McBride, 1995</td>
</tr>
<tr>
<td>1982</td>
<td>First air-bourne Radar study is made on TC eye wall and wind fields are measured. NOAA WP-3D aircraft was used embedded with pulse Doppler Radar. Meso-scale structures at 3 km level were found to drive the inner core.</td>
<td>Frank and Houze, 1984</td>
</tr>
<tr>
<td>1982</td>
<td>Direction of movement of TCs are found to be correlated with mid-tropospheric (700-500 hPa) wind and also upper level winds. Importance of large scale circulations are also recognized.</td>
<td>Chan and Gray, 1982</td>
</tr>
<tr>
<td>1982</td>
<td>Formation and life cycle of eastern north Pacific TC are realized from a vorticity approach. Initiation is studied from easterly waves.</td>
<td>Pan, 1982; Davis and Emanuel, 1991; Whitney and Hobgood, 1997; Molinari et al, 1997; Rappaport et al, 1998; Molinari et al, 2000a, 2000b</td>
</tr>
<tr>
<td>1983</td>
<td>Meso-scale structure of TC is revealed. Both convective and stratiform rainfall regions inside the TC are described.</td>
<td>Barnes et al 1983</td>
</tr>
<tr>
<td>1984</td>
<td>Atlantic TCs are explored in terms of size, strength</td>
<td>Merrill, 1984, 1988</td>
</tr>
</tbody>
</table>
and intensity. The control of angular momentum on growth and maturation of the storms rather than their intensity is highlighted.

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>Dynamics of TC structure is explored.</td>
<td>Holland and Merrill, 1984; Wang and Holland, 1996</td>
</tr>
<tr>
<td></td>
<td>Atlantic TC activity is investigated. Formation criteria track re-curvature and land fall locations are addressed. Effects of several climatological phenomena viz. ENSO modoki, warm pools, multi-decadal oscillation, meridional modes are studied over some indigenous parameters viz. regional SST, vertical wind shear, mid-tropospheric humidity, relative vorticity etc. are investigated. Thus positive and negative effects on TC intensification and track re-curvature are found.</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>Response of TC activity over western north Pacific ocean due to EL NINO outbreaks are studied.</td>
<td>Chan, 1985</td>
</tr>
<tr>
<td>1986</td>
<td>Maintenance of TC structure was revisited from the point of ocean latent heat transfer and Conditional Instability of Second Kind (CISK) availability.</td>
<td>Emanuel, 1986</td>
</tr>
<tr>
<td>1987</td>
<td>TC intensity estimations are made as a function of 40-50% rise in atmospheric CO₂ content and increment is found from Generation Circulation Model outputs.</td>
<td>Emanuel, 1987; Knutson and Tuleya, 2004; Emanuel et al, 2008</td>
</tr>
</tbody>
</table>
### Milestones of Meso-scale Convective Storm Research

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>An exact equation is developed to explain the maximum potential drop in TC central pressure is developed.</td>
<td>Emanuel, 1988a, 1988b</td>
</tr>
<tr>
<td>1988</td>
<td>Dependence of TC intensity on surrounding environmental conditions is explored. It is observed to be an increasing parameter as a function of Sea surface temperature. Role of less vertical wind shear is also found adequate for intensification.</td>
<td>Merrill, 1988; DeMaria, 1996; Frank and Richie, 1999; Zhang and Wang, 2003</td>
</tr>
<tr>
<td>1988</td>
<td>Semi-circulatory flow patterns from primary eye wall to concentric feeder bands are described with explanation about eye wall replacement cycle phenomena.</td>
<td>Willoughby, 1988; Wayne et al, 2007</td>
</tr>
<tr>
<td>1989</td>
<td>TC activity over Indian Ocean are investigated. Special emphasis is given to Bay of Bengal as it holds 80% of the basic activity and has experienced most deadly storms in TC history. Studies involve variation with SST MJO and regional intra-seasonal oscillations. Monsoon TC activity is also highlighted. Certain atmospheric and oceanic parameters viz. sea level pressure, temperature, vertical wind shear, thermocline depth etc. also investigated. Probability of track recurvature is addressed sincerely.</td>
<td>Nishi, 1989; Sarma et al, 1990; Gupta et al, 1991; Gupta and Muthuchami, 1991; Desai and Waikar, 1997; Singh et al, 2000, 2001; Srivastava et al, 2000; Goswami et al, 2003; Krishna, 2009; Hoarau et al, 2011; Rajeevan, 1989; Rao and McAurther, 1994; Suresh and Kumar, 2013</td>
</tr>
<tr>
<td>1990</td>
<td>Upper ocean response on cyclonic storm over the bay of Bengal are evaluated during Indian TOGA programme. An increase of 1º C in temperature up to 50 m depth of the bay is reported near storm center.</td>
<td>Gopal Krishna et al, 1993</td>
</tr>
<tr>
<td>1991</td>
<td>Relationship between TC frequency and ELNINO and Quasi Binennial Oscillation is found.</td>
<td>Gray and Sheaffer, 1991</td>
</tr>
<tr>
<td>1991</td>
<td>The formation of Atlantic hurricanes from African easterly waves is suggested and a good co-relation is found.</td>
<td>Avila and Pasch, 1992</td>
</tr>
<tr>
<td>Year</td>
<td>Research Findings</td>
<td>References</td>
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<tr>
<td>1992</td>
<td>Influences of ENSO on TC formation are reported based on general circulation model.</td>
<td>Wu and Lau, 1992; Gualdi et al, 2008</td>
</tr>
<tr>
<td></td>
<td>Efficiency of Gray’s seasonal genesis parameter is validated through general</td>
<td>Ryan et al, 1992</td>
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<td></td>
<td>circulation model outputs for TC frequency forecasting.</td>
<td></td>
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<tr>
<td>1993</td>
<td>TC flood forecasting model is suggested and validated for some bay storms taken</td>
<td>Flather, 1993</td>
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<td></td>
<td>as case studies.</td>
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<td></td>
<td>Frequency of basin specific TC counts along with their modulating parameters are</td>
<td>Neumann, 1993</td>
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<tr>
<td></td>
<td>highlighted. Regional forecasting of these storms are emphasized on climatological</td>
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<td></td>
<td>scale.</td>
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<tr>
<td>1994</td>
<td>Effects of variations of sea surface temperature on TC frequency are established.</td>
<td>Lighthill et al, 1994</td>
</tr>
<tr>
<td></td>
<td>TC frequency over western north Pacific ocean is investigated and their seasonal</td>
<td>Gray et al, 1992; Chan, 1995; Chen et al, 1998;</td>
</tr>
<tr>
<td></td>
<td>variation is highlighted. Possible teleconnections with ENSO, MJO, El NINO</td>
<td>Chan, 2000, 2005; Yomoto and Matsuara, 2001;</td>
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<tr>
<td></td>
<td>modoki, quasi-binnel oscillation etc. are investigated from time to time. Such</td>
<td>Wang and Chan, 2002; Wu et al, 2004, 2005;</td>
</tr>
<tr>
<td>1995</td>
<td>associations are found to linger storm life expectancy by lengthening tracks.</td>
<td>Camargo and Sobel, 2005, 2010; Chang-Hoitto et</td>
</tr>
<tr>
<td></td>
<td>Probable landfall locations are also thus changed.</td>
<td>al, 2006; Wu and Zhang, 2007; Camargo et al,</td>
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<td>2008; GuangHua, 2009; Choi et al, 2010; Yeh et</td>
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<td>al, 2010; WeiBiao et al, 2010</td>
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<tr>
<td>1996</td>
<td>Evolution of TCs from meso-scale convective systems are hypothecated and</td>
<td>Bister, 1996; Simpson et al, 1997</td>
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<tr>
<td></td>
<td>experimented from model outputs.</td>
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<tr>
<td>1996</td>
<td>New scales of atmospheric motions are proposed. TCs are classified in Macro-γ</td>
<td>Thunis and Bornstein, 1996</td>
</tr>
<tr>
<td></td>
<td>scale.</td>
<td></td>
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<tr>
<td>1997</td>
<td>Equations are developed to explain TC life cycle from energy generation to</td>
<td>Emanuel, 1997; Sinclair, 1997</td>
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<td></td>
<td>boundary layer.</td>
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</table>
Milestones of Meso-scale Convective Storm Research

dissipation. Maximum possible wind velocity is evaluated and it is found to be regardless to eye-
formation dynamics.

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>A complete account of TC surge characteristics and effects are given for north Indian ocean TCs. A storm surge prediction model is proposed and tested by hind casting method.</td>
<td>Dube et al., 1997</td>
</tr>
<tr>
<td>1997</td>
<td>On November 27, TRMM launched as a joint venture of NASA and JAXA</td>
<td>Ciah et al., 1997</td>
</tr>
<tr>
<td>1998</td>
<td>The entire process of Cyclogenesis is revisited in terms of fluid mechanics. The importance of the ‘Third fluid’ i.e. the Ocean-spray is introduced in TC maturation and further development.</td>
<td>Lighthill, 1998</td>
</tr>
<tr>
<td>1998</td>
<td>Increase in intense storm frequency than that of weak storms are highlighted and suggested to be associate with global warming.</td>
<td>Sellers et al., 1998</td>
</tr>
<tr>
<td>1998</td>
<td>The famous criteria comprising six basic parameters for TC formation is set profoundly. The Genesis Potential parameter is formulated. The entire Cyclogenesis is examined taking developing ad non-developing TCs as subjects.</td>
<td>Gray, 1998</td>
</tr>
<tr>
<td>1998</td>
<td>The relationship between TC vortex structure with vertical and horizontal shear is explored in terms of beta drift and lower and upper boundary forcing</td>
<td>Bin et al., 1998</td>
</tr>
<tr>
<td>1998</td>
<td>A new parameter of ‘Dissipating heating’ is suggested for inclusion in numerical prediction models as it is observe to control the kinetic energy density up to 50% of a TC</td>
<td>Bister and Emanuel, 1998</td>
</tr>
<tr>
<td>1998</td>
<td>TC frequency of western Pacific including south China sea is revealed seasonally and their general character is described.</td>
<td>Chan et al., 1998</td>
</tr>
<tr>
<td>1998</td>
<td>A contrast in activity scenario is suggested between Atlnatic ocean and other regions of storm-development. This relationship is very profound in</td>
<td>Lander and Guard, 1998; Kimberlain, 1999, 2000</td>
</tr>
</tbody>
</table>
### Chapter I

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>On June 19, QuickSCAT launched with initial 3 year mission requirement to measure the surface wind speed and direction over the ice-free global ocean</td>
<td>Spencer et al, 2000; Wang et al, 2008</td>
</tr>
<tr>
<td>1999</td>
<td>Variations of TC activity is investigated over eastern north and central north Pacific ocean and several climatological inter-relationship are found in terms of frequency, recurrvature and land fall location.</td>
<td>Irwin and Davis, 1999; Collins and Mason, 2000; Molinary et al, 2000; Chu, 2002; Elsberry et al, 2007; Adachi and Kimura, 2007; Kao and Yu, 2009; Lee et al, 2010</td>
</tr>
<tr>
<td>2000</td>
<td>TC activity is investigated in relation to global warming. Present trend future potency of intensity increase are investigated in global scale. The frequency of intense category storms are found to correlate significantly with global rise in sea surface temperature. Accumulated cyclone energy of active cyclonic basins also show increasing trends for intensification.</td>
<td>Bell et al, 1999; Cheung and Kyle, 2000; Landsea, 2000; Levitus et al, 2000; Lal, 2001; Saunders et al, 2000; Trenbarth, 2005; Pielke et al, 2005; Yoshimura et al, 2006; Landsea et al, 2006; Oouchi et al, 2006; Goswami et al, 2006; Lau et al, 2008; Vecchi et al, 2008; Yu et al, 2009</td>
</tr>
<tr>
<td>2000</td>
<td>Cyclogenesis over the bay of Bengal is studied with respect to thermal structure at near surface water level. Effective Oceanic Layer for Cyclogenesis is defined and its’ influence in determining storm movement trail is presented.</td>
<td>Murty et al, 2000; Sadhuram, 2004</td>
</tr>
<tr>
<td>2000</td>
<td>Accumulated Cyclone Energy is formulated to identify climatological signals on TC frequency.</td>
<td>Bell et al, 2000</td>
</tr>
<tr>
<td>2000</td>
<td>Importance of 200 hPa level wind is determining the adequate vertical shear environment for TC formation is highlighted.</td>
<td>Xavier and Joseph, 2000</td>
</tr>
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<td>Year</td>
<td>Milestone</td>
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<tr>
<td>2000</td>
<td>An out of phase relationship is suggested between monsoon TC frequency and sea surface temperature anomalies.</td>
<td>Rajeevan et al, 2000</td>
</tr>
<tr>
<td>2000</td>
<td>Simulation of TC are performed from regional scale models</td>
<td>Patra et al, 2000; Pattanayak and Mohanty, 2008</td>
</tr>
<tr>
<td>2001</td>
<td>Increasing TC frequency is observed in peak activity seasons over the bay of Bengal however annual frequency is suffering from decrement.</td>
<td>Singh et al, 2001</td>
</tr>
<tr>
<td>2001</td>
<td>A combination of both atmospheric and oceanic parameters is used for hindcasting two devastative storms over the bay of Bengal. Establishment of more buoy stations in the development prone region is highly suggested.</td>
<td>Chinthalu et al, 2001</td>
</tr>
<tr>
<td>2002</td>
<td>TC frequency and modulation of genesis and track patterns are investigated as a function of SST and ENSO</td>
<td>Clark and Chu, 2002</td>
</tr>
<tr>
<td>2003</td>
<td>Structure of matured TCs along their sub-structural features are revisited and horizontal wind distribution is described.</td>
<td>Emanuel, 2003</td>
</tr>
<tr>
<td>2004</td>
<td>Importance of inter-relationship of necessary environmental factors for TC intensification is highlighted while exploring a simple coupled model.</td>
<td>Emanuel et al, 2004</td>
</tr>
<tr>
<td>2004</td>
<td>Cyclonic activity in all active tropical basins are studied with respect to modulation by ENSO. Regional frequencies are revealed with basin specific modulating sub-parameters. Alteration of genesis, landfall and tracks are highlighted.</td>
<td>Chu, 2004</td>
</tr>
<tr>
<td>2004</td>
<td>Potential intensity of TCs are evaluated from</td>
<td>Free et al, 2004</td>
</tr>
</tbody>
</table>
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radiosonde and reanalysis data. However no significant change is found in decadal scale.

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>Nomenclature of storms over north Indian ocean started</td>
<td>IMD Report, 2005</td>
</tr>
<tr>
<td>2005</td>
<td>Potential destructiveness of TC is explored over a 30 year period in terms of power dissipation index and found to have an incremental tendency.</td>
<td>Emanuel, 2005, 2007</td>
</tr>
<tr>
<td>2005</td>
<td>A technique is developed to quantify benefits of Tropical Rainfall Measuring Mission (TRMM) satellite data in TC forecasting. Approximately survival rate of 500 lives/year is attributed to TRMM research mission.</td>
<td>Adler, 2005</td>
</tr>
<tr>
<td>2005</td>
<td>Variations in TC frequency, life-span and intensity are studied with respect to increasing temperature over all active cyclonic regions during post satellite era. Distinct fall is observed in TC duration after 1995</td>
<td>Webster <em>et al.</em>, 2005</td>
</tr>
<tr>
<td>2006</td>
<td>Active basins of tropical northern hemisphere are explored to identify the trends of TC frequency and intensity in terms of accumulated cyclone energy and sea surface temperature.</td>
<td>Klotzbach, 2006; Maue, 2009</td>
</tr>
<tr>
<td>2006</td>
<td>Credibility of available TC forecasting platforms are reviewed in terms of surrounding environmental conditions.</td>
<td>Rhome and Raman, 2006</td>
</tr>
<tr>
<td>2006</td>
<td>Relation of human induced warming and natural multi-decadal oscillations with TC frequency over western north Pacific is explained.</td>
<td>Wu <em>et al.</em>, 2006</td>
</tr>
<tr>
<td>2006</td>
<td>Some periodic patterns of TC frequency are found, <em>viz.</em> North Atlantic oscillation are revealed</td>
<td>Bell and Chelliah, 2006</td>
</tr>
<tr>
<td>2006</td>
<td>Influence of Madden-Julian Oscillation (MJO) on south Indian ocean TC frequency is investigated. Modulation by different stages of MJO is explained.</td>
<td>Bessafi and Wheeler, 2006</td>
</tr>
<tr>
<td>2006</td>
<td>TC frequency over global active cyclonic basins are</td>
<td>Chan, 2006, 2007, 2009</td>
</tr>
</tbody>
</table>
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addressed in terms of trend identification and intensity forecasting.

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Physical vulnerability maps are created to highlight the affected socio-economic conditions in a TC scenario.</td>
<td>Rao et al, 2007</td>
</tr>
<tr>
<td>2007</td>
<td>Inter-relationship between warming events over Pacific ocean know as ENSO modoki with western north Pacific TC frequency is suggested.</td>
<td>Ashok et al, 2007; Benstad, 2009</td>
</tr>
<tr>
<td>2007</td>
<td>Inter-seasonal oscillations over north Indian ocean are studied in relation to TC frequency. A new index is proposed to identify ENSO signals.</td>
<td>Camargo et al, 2007</td>
</tr>
<tr>
<td>2007</td>
<td>Integrated Kinetic Energy parameter is explored in order to describe the intensity of TCs. A new TC intensity scale is proposed in terms of KE complementing the SSHS scale.</td>
<td>Powell and Reinhold, 2007, 2009; Maclay et al, 2008</td>
</tr>
<tr>
<td>2008</td>
<td>Indian ocean dipole mode is defined and its relation with TC frequency is explored. This index is suggested to be a predictor of TC frequency during monsoon.</td>
<td>Singh, 2008</td>
</tr>
<tr>
<td>2009</td>
<td>A new cyclogenesis parameter is proposed for Indian ocean. A criteria value of 8.0 is evaluated to differentiate between developing and non-developing low pressure systems.</td>
<td>Kotal et al, 2009; Kotal and Bhattacharya, 2013</td>
</tr>
<tr>
<td>2009</td>
<td>Rise in surface temperature is found to be associated with global warming and so as with TC frequency over north Indian ocean.</td>
<td>Muni Krishna, 2009</td>
</tr>
<tr>
<td>2009</td>
<td>Trends of TC frequency over north Indian ocean are investigated on seasonal and annual scale.</td>
<td>Niyas et al, 2009</td>
</tr>
<tr>
<td>2009</td>
<td>Global reduction in TC frequency is observed from general circulation model analysis based on sea surface temperature</td>
<td>Sugi et al, 2009</td>
</tr>
<tr>
<td>2010</td>
<td>Variability of TC frequency is explained through several hydrodynamic and natural oscillations for all TC basins. Influence of ENSO, MJO, PDO,</td>
<td>Klotzbach, 2010</td>
</tr>
</tbody>
</table>
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Relative SST, regional intra-seasonal and inter-annual periodicities is surmised on TC behavior.

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>A multi-linear regression model is developed and validated by hind-casting for 17 years data of TC frequency over western north Pacific</td>
</tr>
<tr>
<td>2010</td>
<td>Entire structure and dynamics during TC life cycle is deliberated through several case studies and derivative of equations of atmospheric motions.</td>
</tr>
<tr>
<td>2010</td>
<td>Storm frequency anomalies are computed for the bay of Bengal and related with sea surface temperature anomalies, vertical shear and mid-tropospheric humidity.</td>
</tr>
<tr>
<td>2010</td>
<td>Intra-seasonal oscillations are suggested to have strong effects on flood and draught occurrence over India. This is also explained in terms of MJO index.</td>
</tr>
<tr>
<td>2011</td>
<td>A new mechanism is proposed to explain TC frequency western north Pacific Ocean.</td>
</tr>
<tr>
<td>2011</td>
<td>TC frequency variability is explained as a function of several thermodynamic factors over active basins.</td>
</tr>
<tr>
<td>2012</td>
<td>Heavy rainfall events caused by TCs is estimated from microwave observations. Rain rate is expressed in relation to regional scattering index and polarization corrected temperature.</td>
</tr>
<tr>
<td>2012</td>
<td>TC Genesis Potential Index is observed to carry a 30-40 periodicity signal which is correlated well with TC formation. The importance of combined effect of seasonal and intra-seasonal variabilities are highlighted.</td>
</tr>
<tr>
<td>2013</td>
<td>Rapid Intensification index is developed based on increasing wind speed rates in 24 HRs time period TCs over the bay of Bengal. Importance of initial wind speed is highlighted.</td>
</tr>
</tbody>
</table>
It is obvious that the vast arena of TC research has faced changes over the ages. Bhattacharya et al (2014) arranged such alterations and highlighted as a function of time.

1.6 Scheme of presentation

Investigations carried out by the author and the results obtained have been presented in this dissertation consisting of different chapters. These chapters contain the following:

*Chapter II* gives the sources of data, study area and analytical techniques utilized for this study. Studies on cyclonic storms have been carried out for the Bay of Bengal and its adjacent coastline. Both climatology and
\textit{Chapter I}

instantaneous cases are addressed. Software and statistical tools utilized during studies are also mentioned.

\textit{Chapter III} investigates the climatological trends of TCs occurring over the Bay of Bengal. Seasonal variations are studied in terms of location of genesis and landfall and numeric abundance. Comparative approach is made for TC occurrence with Sea Surface Temperature Anomalies over the bay.

\textit{Chapter IV} explores storms profiles utilizing multi-satellite observations. A program is developed to identify cloud types from cloud optical depth and cloud top pressure as proposed by International Satellite Cloud Climatology Project. Moisture content on the atmospheric boundary layers are studied in association with precipitation. Simultaneous variation of Cloud Rain Heights and vertical tropospheric upper limit are also investigated.

\textit{Chapter V} contains thermodynamic study of eight significant storms over the Bay of Bengal. Wind fields are studied during pre-cyclonic, cyclonic and post-cyclonic period over the bay. Initial wind shear conditions are also studied over the coastal stations in vicinity of storm development zone. Distribution of Severe Weather Threat Index (SWEAT), Convective Available Potential Energy (CAPE) and Convective Inhibition Energy (CIN) are considered during the cyclonic storms. A comparative analysis is also made on the Kinetic Energy (KE) between weak and intense storms based on wind speed.

\textit{Chapter VI} considers a case study on very severe cyclonic storm PHAILIN 2013 in terms of storm tracking from satellite data and contemporary influences on ionospheric behavior by Very Low Frequency (VLF) measurements. A seasonal summary is presented and developmental stages
of the storm are analyzed from satellite observations. Atmospherics profiles are reported during cyclonic days.

Chapter VII deals with an early monsoon cyclonic storm NAUNAK 2014 over Arabian Sea. Its influence on planetary waves on summer monsoon rainfall over Bay of Bengal and Indian sub-continent is investigated. Such interference in monsoon rainfall is also studied for past years.

Chapter VIII deliberates the cyclone disaster management scenario over India. Available and proposed measures are highlighted. The cause-effect relationship for the aftermath are schematized. Structural and non-structural measures to curb the extent of devastation are collated.

Chapter IX summaries the important outcomes obtained from the present investigations. A concluding note is also outlined regarding future scope of study.

References


Chapter I


5. Anthes, R. A., 1982, Tropical Cyclones: Their evolution, structure, and effects, Meteorological monograph, American Meteorological Society, 19(41), 208


7. Asnani, G. C., 1993, Tropical Meteorology, Published by G. C. Asnani, Indian Institute of Tropical Meteorology, Pashan, Pune


Milestones of Meso-scale Convective Storm Research


15. Benstad, R. E., 2009, On tropical cyclone frequency and the warm pool area, Natural Hazards Earth System Science, 9, 635-645


Chapter I

Journal of Innovative Research in Science Engineering and Technology, 3(2), 207-210


28. Burroughs, L. D. and Brand, S., 1972, Speed of tropical storms and typhoons after recurvature in the western north Pacific ocean, ENVPREDRSCHFAC, Tech. Paper No. 7-72, Naval Post-graduate School, California

Milestones of Meso-scale Convective Storm Research


33. Cerveny, R., 2007, Weather and Mongols – How the forces of nature helped shape an empire, Weatherwise (July/August), 23-27

34. Chan, J. C. L. and Gray, W., 1982, Tropical cyclone movement and surrounding flow relationships, Monthly Weather Review, 10, 1354-1374


Chapter I

39. Chan, J. C. L., 2005, Interannual and interdecadal variations of tropical cyclone activity over the western North Pacific, Meteorology and Atmospheric Physics, 89, 143–152


Milestones of Meso-scale Convective Storm Research


Chapter I


64. Davis. C. A. and Emanuel, K. A., 1991, potential vorticity diagnostics of cyclogenesis, 1929 - 1953

Milestones of Meso-scale Convective Storm Research


Chapter I

78. Emanuel, K., 1988a, The maximum intensity of hurricanes, Journal of Atmospheric Science, 45, 1143-1155
Milestones of Meso-scale Convective Storm Research


95. Gentry, R. C., 1964, A study of hurricane rainbands, National Hurricane Research Report No. 69, NTJSPB168417, Hurricane Research Division, Miami, Florida
Chapter I


98. Gopal Krishna, V. V., Murty, Sarma, M. S. S. and Sastry, J. S., 1993, Thermal response of upper layers of Bay of Bengal to forcing of a severe cyclonic storm: A case study, Indian Journal of Marine Sciences, 22(3), 8-11


102. Goyal, S., Mohapatra, M. and Sharma, A. K., 2013, Comparison of best track parameters of RSMC, New Delhi with satellite estimates over north Indian Ocean, Mausam, 64, 25-34


112. GuangHua, C., 2009, Inter-decadal variation of tropical cyclone activity in association with summer monsoon, sea surface
temperature over western North Pacific, Chinese Science Bulletin., 54(8), 1417-1421


116. Hadley, E., 1735, Concerning the cause of the general trade winds, Philosophical Transactions, 29, 58-62

117. Halley, E., 1686, An historical account of the trade-winds and monsoon observable in the seas between and near the tropics with an attempt to assign the physical cause of said winds, Philosophical Transactions, 26, 153-168


120. Hennon, C. C., Tropical Meteorology: A First Course, Asheville: UNCA, 2006

Milestones of Meso-scale Convective Storm Research


Chapter I

133. ITU-R recommendation P.837-6, Characteristics of precipitation for propagation modeling, P series, Radiowave propagation, 2012


136. Jorgensen, D. P., 1981, Meso and convective scale characteristics common to several mature hurricanes, Pre-prints, 20th Conference on Radar Meteorology, Boston, American Meteorological Society, 726-733


140. Kepert, J. D., 2010, Tropical cyclone structure and dynamics, Global perspective on tropical cyclones. From science to mitigation, World Scientific series on Asia-Pacific Weather and Climate, 4, 3-53


Milestones of Meso-scale Convective Storm Research

Conference on Hurricanes and Tropical Meteorology, 250-253, Boston: American Meteorological Society


145. Klotzbach, P. J., 2010, Tropical cyclone variability on seasonal time scales (Observation and forecasting), Seventh International Workshop on tropical cyclones, WMO/CAS/WWW No. 3.2


150. Kotal, S. D., Kundu, P. K. and Roy Bhowmik, S. K., 2009, Analysis of cyclogenesis parameter for developing and non -

151. Kotal, S. D. and Bhattacharya S. K., 2013, Tropical Cyclone Genesis Potential Parameter (GPP) and it’s application over the North Indian Sea. Mausam, 64, 149-170

152. Kotal, S. D., and Roy Bhowmik S. K. 2013, Large-Scale Characteristics of Rapidly Intensifying tropical Cyclones over the Bay of Bengal and a Rapid Intensification (RI) Index, Mausam, 64, 13-24


154. Kumar, J. R. and Dash, S. K., 1999, Interannual and seasonal variation of some characteristics of monsoon disturbances formed over the Bay, Mausam, 50, 555-62


Milestones of Meso-scale Convective Storm Research

159. Lal, M., 2001, Tropical cyclones in a warmer world, Current Science, 80, 1103-1104


Chapter I


170. Lighthill, J., 1998, Fluid mechanics of tropical cyclones, Theoretical and Computational Fluid Dynamics, 10, 3-21


172. Liu, K. and Fearn, M., 2000, Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records, Quarterly Research, 54, 238-245

173. Longshore, David, Encyclopedia of hurricanes, Typhoons and cyclones, (Ed.1), Routledge, USA, 2009


177. Malkus, J. S. and Riehl, H., 1960, On the dynamics and energy transformations in the steady state hurricane, Tellus, 12, 1-20

Milestones of Meso-scale Convective Storm Research

179. Mandal, G.S., 1995, Tropical cyclones and their damage potential, Status of Wind Engineering in India, Indian Society of Wind Engineering (ISWE), Roorkee


181. Mann, M. E. and Emanuel, K., 2006, Atlantic hurricane trends linked to climate change, EOS, 87(24), 233-244


188. Merrill, R. T., 1988, Environmental influences on hurricane intensification, Journal of Atmospheric Science, 45, 1678-1687
Chapter I


190. Meteorological agenda for Natural Disaster and Crisis management, Workshop report, Indian Institute of Chemical Engineers (Kolkata), August, 31, 2002


**Milestones of Meso-scale Convective Storm Research**


202. Mooley, D. A. and Shukla, J., 1989, Main features of the westward moving low pressure systems which form over Indian region during the summer monsoon season and their relation to monsoon rainfall, Mausam, 40, 137-152


204. Muni Krishna, K., 2009, Intensifying tropical cyclones over the north Indian Ocean during summer monsoon, Global warming, 65, 12-16

205. Murty, T. S., 1984, Storm surges-meteorological ocean tides, Canadian bulletin of fisheries and aquatic sciences, No. 212, Ottawa, Canada, 897, 1984
Chapter I

206. Murty, V. S. N., Sarma, M. S. S. and Tilvi, V., 2000, Seasonal cyclogenesis and the role of near-surface stratified layer in the Bay of Bengal, PORSEC Proceedings, 1, 453-457

207. Murty, V. S. N., Sarma, M. S. S. and Tilvi, V., 2000, Seasonal cyclogenesis and the role of near-surface stratified layer in the Bay of Bengal, PORSEC Proceedings, 1, 453-457


211. National Environmental Satellite Centre (NESC), Mariners Weather Log, January, 1970, 14(1), 12-15


Milestones of Meso-scale Convective Storm Research


Chapter I

231. Piddington, H., 1869, The Sailor’s Horn Book for the Law of Storms: Being a practical exposition of the theory of the law of storms and its uses to marines of all classes in all parts of the world shown by transparent storm cards and useful lessons, Williams and Norgate, 5th Ed., U.K.
Milestones of Meso-scale Convective Storm Research


238. Raghavan S., 1990, Structure of tropical cyclones in the Bay of Bengal, Mausam, 41, 325-328

239. Raghavan, S., 1997, Radar observations of tropical cyclones over the Indian seas, Mausam, 48, 169-188

240. Rajamani, S. and Sikdar, D. N., 1989, Some dynamical characteristics and thermal structure of monsoon depressions over the Bay of Bengal, Tellus, 41A, 255-269


Chapter I


246. Rao, K. V. and Rajamani, S., 1975, Computation of vertical velocity in comparing release of latent heat of condensation, Mausam, 26, 369-374


259. Roy Bhowmick, S. K., 2003, An evaluation of cyclone genesis parameter over the Bay of Bengal using model analysis, Mausam, 54, 351-358

Chapter I


266. Sarkar, R. P. and Chowdhury, A., 1988, A diagnostic structure of monsoon depression, Mausam, 39, 9-18


Milestones of Meso-scale Convective Storm Research


275. Simpson, R. H. and Riehl, H., 1958, Mid-tropospheric ventilation as a constraint on hurricane development and maintenance, Bulletin of American Meteorological Society, 39, 499

276. Simpson, R. H., 1974, The hurricane disaster potential scale, Weatherwise, 27, 169-186


Chapter I


281. Singh, O. P., Khan, T. M. A. and Rahman, M. S., 2000, Changes in the frequency of tropical cyclones over the north Indian Ocean, Meteorology and Atmospheric Physics, 75, 11-20


Milestones of Meso-scale Convective Storm Research

289. Suresh, K. G. and Ramesh Kumar, M. R., 2013, Tropical cyclones over north Indian Ocean during El Nino Modoki years, Natural Hazards, 68(2), 1057-1074

290. Syono, S., 1953, On the formation of tropical cyclones, Tellus, 5, 179-195


293. Tepper, M., 1950, A proposed mechanism of squall line – the pressure jump line, Journal of Meteorology, 7, 21-29


298. Treut, H. L. and Kalnay, E., 1990, Comparison of observed and simulated cyclone frequency distribution as determined by an objective method, Atmosfera, 3, 57-71
Chapter I


306. Wang, Y. and Wu, C. C., 1997, Current understandings of tropical cyclone structure and intensity changes- A review, Meteorology and Atmospheric Physics, 87, 257-278


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Milestones of Meso-scale Convective Storm Research


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