Chapter I
General Introduction
1.1. Background and motivation:

The oceans affect both the genesis and intensification of tropical cyclones (TCs), which in turn apply wind stresses to the ocean, that induce sea-surface cooling (SSC) during their passages. Numerous numerical modeling studies leave no doubt that SSC affects both the evolution of TC and prediction of their intensities. Nevertheless, uncertainties remain in the use of numerical models to predict TC intensity: these are related to initial atmospheric and oceanic conditions, the spatial and temporal resolution of the models and the physical processes incorporated into the models. However, best-track intensity is not always valid, particularly in the Indian Ocean where there is a lack of direct observation for measuring TC intensity directly. Furthermore, a coupled model that has successfully calculated TC intensities in one situation may provide erroneous results in another situation because of unexpected interactions among the specifications, physical processes, and initial and boundary conditions used in the model. One particular combination of model specifications and parameters may thus not always be valid for other TC predictions.

However, studies using a numerical model provide us scientific explanations on dynamical and physical processes associated with TC intensification. Mesoscale models are favored over the global models because they can resolve small-scale phenomena like tropical cyclones, with horizontal scale of about 100 – 200 km. In addition, advancement of high power computing facility, high-resolution mesoscale models are being used for the accurate prediction of structure, intensification and movement of tropical cyclones. Prediction of cyclone structure involves the analysis of the present conditions and the estimation of changes in the future. Several methods have been developed for the prediction of track and intensity of tropical cyclones. In recent years, a number of very high resolution non-hydrostatic three-dimensional asymmetric numerical models have been developed. Such models include the National Atmospheric and Oceanic Administration’s Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model, Pennsylvania State University-National Center for Atmospheric Research mesoscale model (MM5), and the Weather Research and Forecasting (WRF) model. MM5 was replaced by WRF after its conception in 2002, and was initially not regarded suitable for hurricane research. However in the present study, Weather Research and Forecasting
(WRF)- Advanced Research WRF (ARW) is utilized to understand TCs genesis, track, intensity and associated characteristic features, and improve the accuracy of such forecasts.

1.2. Introduction to Tropical Cyclones:

TCs are rotating low pressure systems form in warm water bodies (Bay of Bengal; hereafter BoB and Arabian Sea) of tropics. They occur between Tropics of Cancer and Capricorn. These cyclones are generated by the condensation of water vapor produced by the raised moisture from the warm water bodies. They are characterized by deep convection and a closed circulating surface winds about a low pressure center. Because of the Coriolis force the TCs have clock wise rotation in southern hemisphere and counterclockwise in the northern hemisphere. TCs are mentioned by other various names, such as hurricane, typhoon, tropical storm, cyclonic storm, and tropical depression depending on their location and strength. These cyclones cause immense damage to property and serious shipping hazard through gale winds and torrential floods while crossing the coast/landfall. The TCs play an important role in global atmospheric circulation mechanism by carrying the heat and energy away from the tropics towards temperate latitudes. They are important sources of rainfall for agriculture and other water applications over the regions of subtropics and tropics.

1.3. Genesis of Tropical Cyclones:

A broad zone of low pressure system can be seen in tropics, because of the intense heating by sun radiation. If the sea surface temperature in tropics increases beyond 26.5\(^{\circ}\)C, the air above it will be blown off to higher levels from the area of low pressure. Because of the trade winds a high level divergence can be seen in tropics. This high level divergence couples with the low level convergence gives rise to vertical motion taking moist air upwards. This upward moving moisture will spin due to Coriolis force produced by the earth’s rotation. These moistures condense at higher levels and give out latent heat of condensation. Due to release of heat of condensation the area warms up resulting into further fall in pressure giving a depression. As the depression strengthens it becomes a tropical storm and then a Cyclone.
Though the dynamics of the TC is complex, there are certain meteorological conditions favors for their formation and they are:

- Warm sea surface temperature (SST) greater than 26.5°C – 27°C.
- A pre-existing low pressure system or a near-surface weather disturbance with sufficient vorticity (rotation) and convergence.
- The Coriolis force must be strong enough to initiate the cyclone's rotation and should prevent filling of the central low pressure.
- Low vertical wind shear to support the structural of TC.
- An atmosphere which cools fast enough with height such that, it is potentially unstable to moist convection. It is the thunderstorm activity which allows the heat stored in the ocean waters to be liberated for the TC development.
- Deep convection organized over an area with large-scale updrafts and mid-tropospheric high humidity.

1.4. Physical Structure of Tropical Cyclones:

TCs are associated relatively low pressure in the troposphere, with the largest pressure agitations occurring at low altitudes near the surface. The environment near the center of TC is warmer than the surroundings at all altitudes. The physical structure of TC is shown in Fig.1.1.

**Center/eye of the cyclone:** The unique feature of TC is the eye. At the center of the TC, air is sinking, which makes it dry and often cloud free, and there is little or no wind at the surface. The eye of the TC is characterized by a lowest pressure with no wind and cloudless sky. The shape of the eye may be either circular or elliptical with diameter ranging from less than 10 km to more than 100 km. The boundary of the eye will have highest speed, called as eyewall and is associated with thunderstorm cloud clusters. The eyewall appears like a funnel with its narrow section near to the surface of the sea and its broader section vertically upward. In intense TCs, the eyewall may vary time to time in the eyewall replacement cycle. When the primary eyewall weakens, the TC weakens.
temporarily. The outer eyewall eventually replaces the primary one at the end of the cycle, at which the storm may return to its original intensity.

![Diagram of radar reflectivity and eyewalls](image)

**Fig.1.1:** *Schematic illustration of radar reflectivity in a TC with concentric eyewalls [From Houze, (2010)].*

**Rainbands:** Rainbands are bands of showers and thunderstorms that are spiral cyclonically toward the storm center. High wind gusts and heavy downpours often occur in individual rainbands, with relatively calm weather between bands. Convection in TCs is organized into long, narrow rainbands which are oriented in the same direction as the horizontal wind. These bands seem to be spiral into the center of the TC, they are called *spiral bands.*

The region between the eyewall and an outer rainband, such as a secondary eyewall rainband is generally referred as *moat.* The moat is the relatively light rain region between the rainband and the eyewall.

**Wind field:** The near-surface wind field of a TC is characterized by air rotating rapidly around a center of circulation while also flowing radially inwards. At the outer edge of the storm, air may be nearly calm; however, due to the Earth's rotation, the air has non-
zero angular momentum \textbf{(Fig.1.2)}. As air flows radially inward, it begins to rotate cyclonically in order to conserve angular momentum. At an inner radius, air begins to ascend to the top of the troposphere.

\textbf{Fig.1.2: The schematic representation of TC showing eye, eyewall and rainbands.}

\textbf{Size:} The size of a TC is determined by measuring the distance from their center of circulation to their outermost closed isobar. The most common method of measuring the size of TC is in terms of the radius of outermost closed isobars (ROCI), and the radius of vanishing wind. Size plays an important role in modulating damage caused by a storm. The size of the TC is weakly related to the storm intensity, radius of maximum wind, latitude, and maximum potential intensity. The classification of the TCs on the basis of ROCI is given in \textbf{Table 1.1.}

\textbf{Intensity:} The maximum wind speed in the TC is known as intensity. This speed is taken as either a 1-minute or a 10-minute average at the standard reference height of 10 meters. The choice of averaging period, as well as the naming convention for classifying storms, differs across forecast centers and ocean basins.
1.5. Life Cycle of Tropical Cyclones:

Cyclones evolve through a life cycle of different stages from birth to death. The life cycle of a TC usually spans about 5 days or may be only 2 or 3 days or more than 20 days. They may initiate as a cluster of thunderstorms over the tropical oceans. Once this disturbance becomes a tropical depression, it reaches the next stage the tropical storm. Atmospheric and Oceanic conditions play a major role in determining these events. There are several schemes that describes the average life cycle of a TC. The four stages in the life cycle of a TC are: i) Formation, ii) Intensification, iii) Mature and iv) Dissipation/Decay.

Formation: The formation of a TC is dependent upon a number of favorable environmental conditions which are frequently present in the Inter Tropical Convergence Zone (ITCZ).

- Ocean water must be warmer than 26.5°C. The heat and moisture from this warm water is ultimately the source of energy for cyclones.
- High relative humidities in the lower and middle troposphere are also required for cyclone development. These high humidities reduce the amount of evaporation in clouds and maximizes the latent heat released because there is more precipitation.
- The vertical wind shear in a TC's environment is also important. Wind shear is defined as the amount of change in the wind's direction or speed with increasing altitude.
**Intensification:** Intensification of a cyclone is a process in which a cyclone deepens with time. In this stage, the central pressure of the TC falls and the maximum surface wind speed increases. If the ocean and atmosphere environment continues to be favorable, the cyclone may continue to intensify and the cloud system becomes more circular in shape and develops as a distinct eye at the center of the cyclone. The warm, saturated air rising in the center of the circulation tends to keep rising as long as the surrounding air is cooler and heavier. This vertical movement allows deep convective clouds to develop. The rising air in the core also draws in some air from the surrounding atmosphere at altitudes of around 5 kilometers. If this external air is relatively humid, the circulation will continue to intensify. If it is sufficiently dry, then it may evaporate some of the water drops in the rising column, causing the air to become cooler than the surrounding air. This cooling will result in the formation of strong downdrafts that will disrupt the rising motion and prevent development.

**Mature:** The mature stage is usually defined as the time of maximum potential intensity determined from the ocean-atmosphere interaction, and the rate of heating in the storm system (Emanuel, 1988). This is the stage during which the central pressure of the eye is deepest. The maximum wind speed is also at peak intensity. A well developed eye will be present which has little or no cloud caused by subsiding dry air. An eye wall of most intense wind speed and heavy convective thunderstorms will radiate out from the eye. A number of significant spiral rain bands are generally present, separated by areas of light precipitation.

**Dissipation:** TCs dissipate when they can no longer extract sufficient energy from warm ocean water. A TC can contribute to its own demise by stirring up deeper, cooler ocean waters (below 26.5°C) and recurving. Dissipation can also occur if a storm remains in the same area of ocean for too long, mixing the upper 30 meters (100 feet) of water. In addition, a storm that moves over land will abruptly lose its fuel source and quickly lose intensity. Most strong storms lose their strength very rapidly after landfall and become disorganized areas of low pressure within a day or two, or evolve into extra-TCs.
1.6. Classification of Tropical Cyclones:

The low pressure systems over Indian region are classified based on the maximum sustained winds speed and the number of closed isobars associated with the system. The pressure criterion is used, when the system is over land and wind criteria is used, when the system is over the sea. The system is called as low if there is one closed isobar in the interval of 2 hPa. It is called depression if there are two closed isobars, a deep depression if there are three closed isobars and cyclonic storm if there are four or more closed isobars. The detailed classification based on wind criteria are given in the Table 1.2 below. Considering wind criteria, the system with wind speed of 17-27 knots (8.7-13.9 m/s) is called as depression and the low pressure system with maximum sustained 3 minutes surface winds between 28-33 knots (14.4-17.0 m/s) is called a deep depression. The system with maximum sustained 3 minutes surface winds of 34 knots (17.4 m/s) or more is called as cyclonic storm.

Table 1.2: Classification of tropical cyclones formed over Indian Ocean

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>System</th>
<th>Pressure drop hPa</th>
<th>Associated wind speed Knots (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low pressure area (L)</td>
<td>&lt; 1.43</td>
<td>&lt;17 (&lt;32)</td>
</tr>
<tr>
<td>2</td>
<td>Depression (D)</td>
<td>1.43 - 3.61</td>
<td>17-27 (32–50)</td>
</tr>
<tr>
<td>3</td>
<td>Deep Depression (DD)</td>
<td>3.91–5.40</td>
<td>28-33 (51–61)</td>
</tr>
<tr>
<td>4</td>
<td>Cyclonic Storm (CS)</td>
<td>5.73 – 10.95</td>
<td>34-47 (62-88)</td>
</tr>
<tr>
<td>5</td>
<td>Severe Cyclonic Storm (SCS)</td>
<td>11.43 – 19.69</td>
<td>48-63 (89-117)</td>
</tr>
<tr>
<td>6</td>
<td>Very Severe Cyclonic Storm (VSCS)</td>
<td>20.00 – 49.00</td>
<td>64-119 (118-220)</td>
</tr>
<tr>
<td>7</td>
<td>Super Cyclonic Storm (SuCS)</td>
<td>≥ 50</td>
<td>≥120 (≥221)</td>
</tr>
</tbody>
</table>

1.7. Frequency of Cyclones over the Indian Ocean:

Indian sub-continent is the worst affected region of the world, having a coast line of 7516 kms (5400 kms along the mainland, 132 kms in Lakshadweep and 1900 kms in Andaman and Nicobar Islands) and is exposed to nearly 10% of the world’s TCs. There are 13 coastal states/Union Territories encompassing 84 coastal districts which are affected by cyclones. Four States (Andhra Pradesh, Odisha, Tamil Nadu and West
Bengal) and one Union Territory (Pondicherry) on the East Coast and One State (Gujarat) on the West Coast are more vulnerable to cyclone disasters. About 40% of the total population lives within 100 km of coastline.

The average annual frequency of TCs in the north Indian Ocean (NIO; both BoB and Arabian Sea) is about 5-6% of the Global annual average. Out of them, about 35% of disturbances intensified into cyclonic storms, 16% into severe cyclonic storms and 7% into very severe cyclonic storms. The average life span of a typical TC in the north Indian Ocean is about 4–5 days. The monthly frequency of TCs in the north Indian Ocean display a bi-modal characteristic with a primary peak in November and secondary peak in May. The months of March-May and October-December are known to produce cyclones of severe intensity. TCs developing during the monsoon months (June to September) are generally not so intense. The frequency in cyclone occurrence is more in the BoB than in the Arabian Sea and is in the ratio of 4:1. This is possibly because of the lack of seedling disturbances and relatively dry middle tropospheric environment found in the Arabian Sea. The northern part of the BoB is known for its potential to generate dangerous high storm tides when associated with cyclonic storms.

The BoB is a potentially active region for the formation of TCs. The climatology of cyclone genesis shows that a total of 613 cyclonic disturbances formed in the BoB (data collected from the website [http://www.rsmcnewdelhi.imd.gov.in/index.php?option=com_content&view=article&id=48&Itemid=194&lang=en](http://www.rsmcnewdelhi.imd.gov.in/index.php?option=com_content&view=article&id=48&Itemid=194&lang=en) during 1891 to 2013). Out of 613 cyclones, 325 (54%) crossed India, 95 (16%) Bangladesh, 61 (10%) Myanmar, 25 (4%) Sri Lanka and as many as 100 (17%) dissipated over the sea without making landfall on any of the above countries.

1.8. Destoructions Caused By Tropical Cyclones:

The strong winds, heavy rains and large storm surges associated with tropical cyclones are the factors that eventually lead to loss of life and property. Cyclones are known to cause severe damage to infrastructure through high wind speeds. Very strong winds which accompany a cyclonic storm damages installations, dwellings, communications systems, trees etc., resulting in loss of human life and economy. Gusts are short but rapid bursts in wind speed are the main cause for damage. Squalls on the
other hand, are longer periods of increased wind speed and are generally associated with the bands of thunderstorms that make up the spiral bands around the cyclone. Torrential rainfall (more than 30 cm/hour) associated with cyclones is another major cause of damages. Unabated rain gives rise to unprecedented floods. Rain water on top of the storm surge may add to the fury of the storm. Rain is a serious problem for the people which become shelter less due to cyclone. Heavy rainfall from a cyclone is usually spread over wide area and cause large scale soil erosion and weakening of embankments. A Storm surge can be defined as an abnormal rise of sea level near the coast caused by a severe tropical cyclone; as a result of which sea water inundates low lying areas of coastal regions drowning human beings and life stock, causes eroding beaches and embankments, destroys vegetation and leads to reduction of soil fertility. In addition, coastal inundation and floods due to storm surges pollute drinking water sources causing outbreak of epidemics. Although Tropical cyclones are known for destruction they cause, when they strike they also bestow certain benefits to the climatic conditions. The tropical cyclones relieve drought conditions. They carry heat and energy away from the tropics and transport it towards temperate latitudes, thus help to maintain equilibrium in the Earth’s troposphere and maintain a relatively stable and warm temperature worldwide.

The casualty figures due to past TCs are illustrated here: About 130 lakhs of people affected and 10,000 people died due to the BoB super cyclone that crossed Orissa (India) coast on 29 November 1999. Due to very severe cyclone Sidr (15 November 2007) over the BoB, more than 3,360 deaths occurred and about 2.5 millions of acres crop was damaged. Very severe cyclone Nargis over the BoB caused more than 1,38,000 people have died in Myanmar. Severe cyclone Aila (25 May 2009) over the BoB was responsible for 270 deaths and thousands of injuries in West Bengal, India and Bangladesh. The severe cyclone Laila (20 May 2010) over the BoB caused a storm surge of 2 to 3 meters inundated the low lying areas leading to 6 deaths and damage to agriculture and fisheries in the coastal region of Andhra Pradesh and Tamil Nadu.

1.9. Tropical Cyclone Forecasting Methods/Techniques:
Forecasting of TCs is highly complex which includes different aspects of the cyclone such as the structure, track, intensity, associated weather and the storm surge.
Generally the emphasis is given more on cyclone motion which is governed by highly nonlinear dynamics. The dynamics involves different scales of motion which are difficult to observe. Prediction of cyclone structure involves the analysis of the present conditions and the estimation of changes in the future. The various methods available for TC track forecasting are: i) methods based on Persistence, Climatology and both Climatology and Persistence ii) Synoptic – Empirical iii) Satellite techniques iv) Statistical techniques using climatology, persistence & synoptic and v) Dynamical models.

In the persistence method, the future motion is assumed to be similar to the past motion if the vortex, the large scale flow and the interaction processes remain undisturbed. Though this method has inherent limitation due to the assumptions of various processes this technique gives reasonable forecasts up to 24 hours. The climatological forecasts assume that the present storm will move with the average direction and speed of all past storms near that location. In the Climatology and Persistence method persistence is given weight in the early stages and climatology for periods extending over 36 hours or more. The synoptic method has several techniques for forecasting the movement of a cyclonic system. The rate of pressure variation or 24 hours pressure change along coastal stations can be taken to detect the approaching cyclone, as the pressure falls slowly during the initial stages and rapidly in the advanced stages when the storm is approaching a station. In another method of steering current concept the TC tends to move with the speed and direction of the deep layer of environmental flow in which it is embedded which is generally correlated well at middle levels (Srinivasan and Ramamurthy, 1973; Neuman, 1979; Sanders et al., 1980; Holland, 1984 a, b). The reliability of estimates from this method depends on the correlated layers. The statistical methods provide cyclone component motion over some future time interval and make the use of one or more sources of predictive information like climatology, persistence, synoptic data (Elsberry, 1987). In the absence of reliable conventional observations over oceans the satellite observations (imagery) are used to infer the size and intensity characteristics of cyclones. Dvorak, (1975) developed a technique to estimate the intensity of TCs based on satellite imagery. This technique involves interpretation of the satellite imagery for various cloud features such as moisture, cloud pattern, their time changes to estimate the cyclone intensity and it’s evolution.
In the dynamical method, the non-linear mathematical equations representing the atmospheric motion are solved by appropriate numerical methods for the prediction of the future state of atmosphere. In 1970, a Numerical Weather Prediction (dynamical) model was used in operational track prediction for the first time. By the late 1980’s, simple barotropic models are designed for track forecast of TCs. Many previous studies used the barotropic vorticity equation (Sikka, 1975) and barotropic primitive equation model (Singh and Saha, 1976) for the prediction of track over the Indian seas. Because of its void in providing 3-dimentional (3D) structure of pressure/wind distribution, inner core structure and rainfall pattern associated with the cyclone, baroclinic models which can be capable of providing these, came into existence. The baroclinic models are mainly divided in to two types: regional/limited area models (LAM) and global/general circulation models (GCM). The advantage in the global models is that it does not require lateral boundary condition. The disadvantage is their coarser resolution. Unlike global models, the regional models require lateral boundary conditions which are obtained from global models. Regional models can be operated at higher resolutions as compared to global models.

A non-hydrostatic regional model with nesting/moveable nesting dynamics at sufficiently high-resolution can further provides more detailed structure of TCs. The advantages of using fully or quasi non-hydrostatic system of equations as compared to the traditional hydrostatic approximation in mesoscale models have been demonstrated in many studies (Juang, 1992; Dudhia, 1993). The limitation of the non-hydrostatic models is that it can not be useful for longer forecast and hence these models are useful for three or five days forecast. In recent years, a number of very high resolution three-dimensional asymmetric numerical models have been developed. These have improved the treatment of model governing equations, and have been used for hurricane research also. Such models include the National Atmospheric and Oceanic Administration’s Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model, Pennsylvania State University-National Center for Atmospheric Research mesoscale model (MM5), and the Weather Research and Forecasting (WRF) model. Several researchers compared the performance of MM5 and WRF models and reported that the WRF model is superior to MM5 model.
in the simulation of track and intensity of cyclones. However in the present study non-hydrostatic dynamic model is used to study the structure and movement of the TCs.

1.10. Previous Research on Tropical Cyclones:

1.10.1 Global Research on cyclones:

Globally, several studies were carried-out by using different numerical models to simulate the structure, intensity, track of Hurricanes and Typhoons (Willoughby et al., 1984; Harr and Elsberry, 1996; Braun, 2002; Atlas et al., 2005; Krishnamurti et al., 2005). The high-resolution mesoscale models were being increasingly used for sensitivity studies of Hurricanes and Typhoons structure, intensification and movement with different physical processes (Braun and Tao, 2000; Li and Pu, 2008). Fovell and Su, (2007) shown that the alteration of microphysical parameterization (MP) and cumulus parameterization (CP) significantly influenced the track and land fall of Hurricane Rita for WRF model at 30 and 12 km resolution. Different parameterization schemes have been developed by several researchers but most of them have certain limitations (Frank, 1983; Emanuel and Raymond, 1993; Zhang et al., 1994; Kuo et al., 1997) for Cyclone forecasts.

Forecast of TC intensity still remains a challenging problem in both operational and research communities (Bender and Ginis, 2000; Krishnamurti et al., 2005; Rogers et al., 2006). Several studies demonstrated that the maximum intensity of a TC is closely related to the environmental conditions such as sea surface temperature, moisture distribution, and vertical wind shear (Gray, 1968; Emanuel et al., 2004; Wang and Wu, 2004). Hill and Lackmann, (2009) suggested that the environmental relative humidity controls the structure of the TC. The importance of relative humidity in surface entropy flux has been supported by the observational study of Kossin and Sitkowski, (2009).

The primary energy source for the TC is the air–sea surface flux exchanges of moist enthalpy via surface latent heat and sensible heat fluxes (Emanuel, 1986). The rapid deepening of TC is due to the warming of the ocean surface through latent and sensible heat fluxes (Davis and Emanuel, 1988). Braun and Tao, (2000) showed that the surface fluxes plays a major role in the intensity of Hurricane Bob (1991) compared to the
vertical mixing in the Planetary Boundary Layer (PBL). The dependency of structure and intensity of TC on heat from the rainbands have also been reported in several other studies (Wu et al., 2009; Moon and Nolan, 2010). Xu and Wang, (2010a) studied the link between the surface entropy flux and the activity of spiral rainbands in the simulated storms. They found that the entropy flux in the eye region contributes little to the storm intensity but reduces the radius of maximum wind. Although surface entropy fluxes under the eyewall contribute greatly to the storm intensity. Further outward, the surface entropy fluxes are crucial to the growth of the storm inner-core size but can reduce the storm intensity. Further, Xu and Wang, (2010b) found that the initial vortex and initial latent heat flux determines the size of the TC. They also reported that the strong outer winds in a storm with a larger initial size lead to large entropy flux which favors the development of active spiral rainbands. But Rozoff et al., (2012) stated that the size of TC is decided by the latent heating outside the primary eyewall which promotes the secondary eyewall formation leading to expansion of the outer wind field. The influence of atmospheric temperature on TC size in an idealized framework where the virtual atmospheric temperature profile was increased or decreased relative to constant 29 °C sea surface temperature (SST) was studied by Stovern and Ritchie, (2012). They concluded that increased surface moisture fluxes, higher potential vorticity and outer rainbands generation and larger wind field are due to cooler atmosphere. Recently, Benjamin et al., (2014) simulated Hurricane Katrina (2005) using Weather Research and Forecasting (WRF)–Advanced Research WRF (ARW) model and found that the surface flux had a significant effect on structure and intensity of the Hurricane.

Several theoretical and modeling studies indicate that the vortex Rossby waves are important for the secondary eyewall formation (Montgomery and Kallenbach, 1997; Chen and Yau, 2001; Wang, 2002a, b; Martinez et al., 2011; Menelaou et al., 2012). Qiu et al., (2010) also found that secondary eyewall formation occurs near vortex Rossby wave (VRW) stagnation radius in a convectively active region of the TC. This sustained activity of VRW leads to the outward expansion of beta skirt which provides the adequate radial extent for the axis symmetrization for the convection moving in from outer rainbands. However, Moon et al., (2010) questioned whether these overly simplified and highly idealized assumptions are truly applicable to real-world TCs. Moreover, Judt and
Chen, (2010) showed that VRWs may have contributed very little to the secondary eyewall formation on the basis of high-resolution simulations for hurricane Rita. Further, they concluded that a large accumulation of convectively generated potential vorticity (PV) anomalies in the rainband region plays a major role in the formation of secondary eyewall.

Several researchers studied the importance of balanced and unbalanced boundary layer processes in secondary eyewall formation. Huang et al., (2012) proposed an axisymmetric view for secondary eyewall formation. Sun et al., (2013) hypothesized that the secondary eyewall formation was the combined result of a balanced response to rainband heating and the unbalanced dynamics in the frictional boundary layer. Recently, Menelaou et al., (2014) found that in the absence of background environment and boundary layer process, the sustained heating generated by the potential vorticity (PV) can develop the secondary eyewall which enhances the PV that contains the secondary wind maximum.

Several studies have been carried out with assumptions of MPs accountable for formation, evolution, and destruction of hydrometeors which can influence TC intensity (e.g., Lord et al., 1984; Braun and Tao, 2000; Zhu and Zhang, 2006). The sensitivity of simulated TC structure and intensity with a cloud MP in a two-dimensional non-hydrostatic model was examined by Willoughby et al., (1984) and Lord et al., (1984). These results indicate that the warm-rain-only cloud microphysics scheme produced a rapid intensification, while the mixed-ice phase cloud MP scheme resulted in a slowly developing storm. Brown and Swann, (1997) found that the simulated surface precipitation was sensitive to the mean size and fall speed of graupel and the efficiency for the collection of snow and cloud ice by graupel in the evaluation of key MP schemes in three-dimensional cloud model simulations. Zhu and Zhang, (2006) studied the sensitivity of simulated intensity and inner core structure of Hurricane Bonnie (1998) to various MP processes in MM5 model. They indicated that the weakest storm can be produced by removing all ice particles from the MP processes and the most rapid development of the storm was produced when evaporation processes are removed. Fovell et al., (2010a) presented the interaction of hydrometeors with radiation in different MP schemes and concluded that the motion and structural variation in their MP ensemble.
disappeared when clouds were made transparent to radiation in their semi idealized simulations. Fovell et al., (2010b) demonstrated that the different MP schemes accounts for different amounts and relative distribution of hydrometeors, such as cloud ice, snow, cloud droplets, etc. The main reason is the heating within the inner core of the cyclone, which is influenced by production of graupel hydrometeors in the inner core region. The latent heat released in the formation of graupel mixing ratio is responsible for net middle level heating rate in the cyclone core. Higher net heating in the middle level enhances the divergence in the upper level and convergence in the lower level, which in turn helps in the intensification of the system.

1.10.2. Previous studies on Cyclones over India:

In India, initially, forecasting of TC was carried out by using half persistence and half climatology technique (Sikka and Suryanarayana, 1972). Later, Mohanty and Gupta, (1997) have used multi-level primitive equation models with parameterization of physical processes for the cyclone track prediction. Prasad and Rama Rao, (2003) have evaluated the Quasi-Lagrangian Model (QLM) for track forecast. Several models and methods have been developed to predict the position of the cyclone accurately so that appropriate warning can be issued for disaster management. Timely and reasonably accurate prediction of the track and intensity of TC are challenging problem over the east coast of India and Bangladesh (Asnani, 2005; Pattanayak and Mohanty, 2008; Paul, 2010).

Since, last decade, mesoscale models are being used for sensitivity studies of TC structure, intensification and movement (Trivedi et al., 2002; Mohanty et al., 2004; BhaskarRao and Hari Prasad, 2007; Srinivas et al., 2007; BhaskarRao et al., 2009; Pattanaik and Rama Rao, 2009; Shen et al., 2010).

In the last few years, with the rapid advancement of high-performance computing high-resolution non-hydrostatic mesoscale atmospheric models such as MM5, WRF is being used for forecasting of structure, intensification and movement of TC (Prasad and Rama Rao, 2003; Mohanty et al., 2004; Trivedi et al., 2006; Reale et al., 2009; Pattanaik and Mohanty, 2010; Raju et al., 2011a, Osuri et al., 2013). Prater and Evans, (2002) studied the TC Irene (1999) with various CP schemes in MM5 model and concluded that the Kain-Fritsch (KF) scheme produces relatively accurate storm compared to

Several researchers investigated the impact of CP and PBL schemes on the cyclone track and intensity prediction. Rao and Bhaskar Rao, (2003) and Mandal et al., (2004) studied the Orissa super cyclone using MM5 model. They showed that the MM5 model can predict the intensification up to 48 hours but underestimate it thereafter. Sensitivity study conducted using MM5 model for the Orissa super cyclone (BhaskarRao and Hari Prasad, 2007) and for Andhra severe cyclone (Srinivas et al., 2007) revealed that the combination of Mellor-Yamada-Janjic (MYJ) scheme for PBL and Kain-Fritch 2 scheme for CP give the best results for intensity and track prediction. However, Krishna et al., (2012) studied the model sensitivity for the north Indian Ocean cyclones using WRF-ARW model and showed that a combination of Yonsei University (YSU) PBL and KF CP scheme simulated less track and intensity errors. Similarly a sensitivity study is conducted with different CP and MP schemes in MM5 model for Orissa super cyclone (1999) and concluded that the variations in track and intensity are sensitive to the choice of CP schemes rather than the MP schemes used in the model (Deshpande et al., 2012). They also showed that KF scheme simulated the track and intensity better compared to other schemes. Mukhopadhyay et al., (2011) studied the influence of moist processes on track and intensity forecast of cyclones Gonu and Sidr over the north Indian Ocean and found that hybrid moist convection treatment (which included CPS and MPS both) produces better simulation. A similar study conducted by Reddy et al., 2014 for TC JAL revealed that the simulated track and intensity are sensitive to the choice of CP schemes rather than MP schemes used in the model.

The effect of CP, MP and PBL schemes on the track and intensity of cyclone NARGIS was studied using WRF-ARW model (Raju et al., 2011b) and Weather Research and Forecasting- Non-hydrostatic Mesoscale Model (WRF-NMM) model (Pattanayak et al., 2012). Raju et al., (2011b) concluded that the CP schemes controls the cyclone intensity and MP schemes influences the track prediction whereas all the schemes under predict the intensity of the cyclone. However, Pattanayak et al., (2012) showed that the CP schemes influences the movement of the cyclone, PBL schemes.
controls the intensity of the cyclone. Among these schemes, Simplified Arakawa Schubert CP scheme produced the better track and YSU PBL scheme simulated the intensity of the cyclone. Further, variations in the MP schemes produce similar type of results and among all these MP schemes, Ferrier (FERR) produces the track and intensity well compared to other schemes. Recently, Chandrasekar and Balaji, (2012) simulated the track and intensity of TC JAL using different CP, MP, PBL, land surface, long wave and short wave parameterization scheme. They concluded that the CP, PBL and MP schemes play a major role in both the track and intensity predictions. However, the track error is sensitive to CP, PBL, MP and long wave radiation parameterization schemes and the intensity is sensitive to the choice of CP schemes compared to other physics options in the model. In a similar way, Srinivas et al., (2012) studied the performance of WRF-ARW model with different PBL, CP, MP and SF schemes for 21 cyclones during 2000-2011. They concluded that CP and PBL schemes have larger impact, MP and land surface physics schemes have minimum impact on the intensity and track predictions using five severe cyclones (Sidr, Khaimuk, Nargis, Jal and Thane).

Kumar et al., (2011) investigated the influence of lateral and boundary forcing on the track and intensity prediction of cyclone SIDR and found that the reduction in the domain size improves the predicted track and intensity of the cyclone. Pattanayak et al., (2012) simulated the cyclone MALA using different initial conditions in Hurricane Weather Research and Forecasting (HWRF) model and showed that the high resolution inner nest domain produces the higher intensity of the cyclone. Mohanty et al., (2010) performed a sensitivity study using different initial and boundary conditions of WRF model for the five cyclones over BoB and concluded that the land fall error in the Final Analyses (FNL) data is less compared to Global Forecast System (GFS) data and National Centre for Medium Range Weather Forecasting (NCMRWF) data. However the NCMRWF data simulated intensity well compare to other data.
1.11 Scope and Outline of the Thesis:

From the previous studies, it is evident that the best set of parameterization schemes for one Oceanic region may not be suitable to other region. Moreover, the parameterization schemes differ for individual TC. In addition, the horizontal and vertical resolutions are also very important factors, since different parameterization schemes can give different results for different model resolutions. Hence, sensitivity experiments are the only logical way to identifying the best set of physics schemes for a particular region.

Forecasting of tropical cyclones is highly complex which includes different aspects of the cyclone such as the structure, intensity, movement, associated weather and the storm surge that may occur when the system makes landfall at the coast. The strong winds, heavy rains and large storm surges associated with tropical cyclones are the factors that eventually lead to loss of life and property. This loss can be minimized by reducing the forecast error associated with the track and intensity of the TCs, so as to provide more reliable warning for TC disaster management. As far as the 4 – 5 day forecast is concerned, the high-resolution mesoscale models are expected to provide possibly the better forecast for TCs. So, the principal objective of the thesis is to simulate/predict the realistic track, intensity and rainfall during landfall of TCs.

To achieve aforesaid objective, the following studies are carried out:

- Sensitivity experiments by using logical combinations of physical parameterization schemes for better prediction of track and landfall of TCs
- Sensitivity experiments for the prediction of intensity and structure of TCS to reduce the domestic loss due to heavy wind.
- Better prediction of heavy rainfall events associated with the TCs.

To attain these objectives, the present work is divided into six chapters.

Chapter 1 deals with the general introduction of tropical cyclones, their formation, physical structure, life cycle and classification. Further the destructions caused by the tropical cyclones are discussed. The details of the forecasting methods, literature
survey with a special emphasis to the NIO cyclones are discussed. Finally, the scope and objectives of the present study are outlined.

Advanced Weather Research and Forecasting model, physical parameterization schemes used in the model, initial and boundary conditions applied to the model are enlightened in Chapter II. The data and experimental description is also specified in this chapter. Presently available High Performance Computation (HPC) facility at Yogi Vemana University, Kadapa for simulation experiments for TC is also denoted. A brief description of Tropical cyclones developed during 1999-2013 over BoB is documented.

In chapter III, simulation of track and intensity of cyclone JAL, formed over BoB during 04-08 Nov, 2010 is discussed in detail. The JAL cyclone is the only cyclone which passed through a semi-arid region of India for the last decade. The simulation experiments are conducted using logical/scientific combination of convection and micro-physics schemes in the WRF model with different initial conditions and at different resolution (27 and 9 km) to know the effective track and intensity prediction of JAL cyclone. Further, we studied the dependency of intensity of cyclone on surface latent heat flux, convergent inflow in the lower troposphere, divergent outflow in the upper troposphere, vorticity, vertical cross section of wind speed and temperature. Finally for the validation, the model results of meteorological parameters are compared with the areal averaged data collected from Automatic Weather Station (AWS) located in oceanic, in-land and semi-arid regions, respectively at 3 km resolution.

In chapter IV, the simulation studies are performed using 38 cyclones developed in BoB during 1999 to 2013. Initially, we simulated six representative cyclones namely MALA, NARGIS, BIJLI, LAILA, SIDR and WARD developed over BoB with different physical parameterization schemes (CP, PBL and MP schemes). We selected the best set of CP, PBL and MP combinations which simulated the track and intensity of the cyclones. In a similar way we selected the best set of CP, PBL and MP combinations for the entire cyclones developed between 1999 and 2013. Further, the aforesaid six cyclones are simulated with different initial conditions. At 72 hours of prediction, LIN+KF+YSU combination simulated the better track and intensity for the six cyclones. Hence we
simulated the entire cyclones at 72 hours of prediction with different CP and PBL schemes. Further, the simulations are performed with different boundary conditions for the cyclones developed during 2013. Finally we compared the track and intensity predicted using one-way and two-way nesting for four cyclones developed over BoB.

Prediction of cyclone structure involves in the prediction of track, intensity and its movement. Forecasting of intensity of cyclone is more difficult than track forecasting. To understand the variation in intensity of cyclone, in Chapter V we carried out the sensitivity study of cyclones developed during the year 2013. In this chapter, the real-time prediction of track and intensity is accessed for the five cyclones using different physical parameterization schemes in the model. Further, we discussed the intensity of TCs in terms of surface energy flux, specific humidity, temperature, low level convergence, relative vorticity, vertical cross-section of wind speed, temperature, specific humidity & potential vorticity and hydrometeor mixing ratio’s. In addition, the model simulated rainfall is compared with the rainfall observed by Tropical Rainfall Measuring Mission (TRMM) satellite.

Finally the overall summary and conclusions alongwith the further scope of the present study is given in Chapter VI.