Synopsis
Tropical storm (TS) is a giant, warm-core and complex atmospheric vortex with co-existing cumulus convection and boundary layer turbulence. It forms over data sparse tropical oceans or seas, where it spends most parts of its life. The term "Tropical Storm" has been used in this thesis to represent all storms which form over tropical oceans irrespective of their intensity or size as have been treated by Riehl (1954) in his pioneer book on Tropical Meteorology and other workers. The term "Cyclone" or "Tropical Cyclone" is also applied to all tropical storms although they are known as "Cyclonic Storm" in the Bay of Bengal and Arabian Sea, "Hurricane" in the Atlantic and Eastern Pacific, "Typhoon" in the Western Pacific, "Willy-Willy" in the Australian Seas and "Baguiou" in the Philippines. It is also known as "Tropical Revolving Storm". Its intensity is classified according to its maximum sustained winds. For operational needs, in India it is called "Cyclonic Storm" (35 to 47 kts), "Severe Cyclonic Storm" (48 to 64 kts) and "Severe Cyclonic Storm with core of Hurricane winds" (65 kts and above); while in USA, as "Tropical Storm" (35 to 64 kts) and "Hurricanes" (65 kts and above). Intensity classification of TS using satellite cloud imagery (T-number) is graded still in more number of steps (Table 6.1). Generally, an eye appears when a storm intensifies into the Hurricane stage; sometimes it appears even at the stage of Severe Cyclonic Storm. Since this work is not concerned with operational detail, and we are to refer works of different countries, so to avoid any confusion, above terms will be used synonymously. While referring to, or quoting any work, the terms or units of physical quantities used in that work will be kept as they are.
Though with the advent of modern technology the gross features of the tropical storm have become known, many characteristic features are not yet well understood or least well documented. Some of them are physical mechanism of its initial formation (genesis), wind structures in the boundary layer and outflow layer, creation of an eye and eyewall clouds, its movement, influence of orography and interaction with other vortices. Most of these points are of key importance in forecasting purpose. No doubt, these are very intricate problems, yet one can try to get some insight about it. Numerical modelling of primitive equations itself is a challenging problem.

With a hope of getting some understanding, an humble attempt has been made in this thesis to study a few problems related to Tropical Storm and other Vortices applying analytical and numerical methods and utilizing satellite and conventional data. We have also attempted to develop a numerical model suitable to simulate tropical storm, and a technique to reduce the time of integration.

As indicated by the title of the thesis and the project for the work which was duly approved by the University, we intended to study a few aspects of the tropical storm and other vortices and did not confine our attention to a particular topic only (which may be the convention elsewhere). The storms in Chapters II & III are matured, axisymmetric and in steady state; so the studies in these Chapters are made on a two dimensional vertical plane. The model in Chapter IV is three-dimensional and for unsteady case. To test the efficiency of the model, numerical time integration was performed only for the initial development of a
TS specifying heat due to forced subsidence. Thus the vortex in Chapter IV is quite different from that in Chapter II or III. The vortex in Chapter V is a two dimensional rectilinear vortex in perfect fluid (friction less) which has only rotational motion. While the vortex in Chapter VI is a natural one, and studies for its entire life cycle have been made using satellite and conventional data.

Lots of works have been done on different aspects of tropical storm, modelling, and other vortices, so while reviewing earlier works or discussing the results in respective Chapters, only the most pertinent works are referred. Assumptions, values of physical quantities etc. are also stated in respective Sections. The contents of the thesis are arranged under seven chapters. A brief description of them and results obtained are given below.

Chapter I is of review nature and deals with general description and structure of a tropical storm, its climatology and associated problems in forecasting. A very brief survey of literature on tropical storm and other vortices and the reasons which necessitated to take up the problems in this thesis have been described so that the works presented could be seen in their proper perspectives.

In Chapter II, a simple equation has been devised to find out the temperature anomaly field in any vertical plane through the centre of a matured steady state symmetric tropical storm from a few known values above the boundary layer and a technique has been developed to calculate the wind and pressure distributions on it. This could be achieved after studying a number of works with real data. It was not derived from any other equation or
law. Two nomograms have also been presented to determine the maximum tangential velocity and minimum sea level pressure from known maximum temperature anomaly. These have been compared with real storms data (Table-2.1) and found to be in good agreement.

In Chapter III, a method has been devised to find out the tangential, radial and vertical velocity distributions and angle of inflow from it in the boundary layer of a tropical storm starting from the periphery to its centre without assuming any profile for them. This could be accomplished by critically analysing different types of flow inside and outside the eye. The numerical method consists of solving two point boundary value problem for two systems of simultaneous non-linear differential equations by finite difference with very fine resolution. The velocity profile above the boundary layer is taken from the result of Chapter II. Different types of eddy coefficients of viscosity for turbulence are also tested. It is found that if the eddy coefficient of viscosity is assumed to vary with the superimposed flow above the boundary layer, the solutions compare favourably well with observations. The results show an outflow from the inner core region above the inflow layer which is favourable for creation of an eye and eyewall of a tropical storm.

Chapter IV is devoted in designing a triply-nested three dimensional primitive equation numerical model suitable to simulate tropical storms, and study small scale weather phenomena. Each of the three meshes consists of 32x32 point array of momentum points enclosing 31x31 array of mass point with grid lengths 18km, 54km and 162km. In order to reduce the time of integration a semi-implicit method is used. The speed of the solution of the
system of Helmholtz equations arising out of the semi-implicit scheme has been increased appreciably by devising an iterative method of solution. In order to get better accuracy of the solution and suppress non-linear instability, an improved finite difference scheme has been applied. Proper matching of the solutions between grids of different lengths is achieved by adopting two-way interactive method. A comparison of the present model with those of Mathur (1974) and Madala and Piacsek (1975) is shown in Table 4.II. To examine the role of surface friction as postulated by Yamasaki (1977) and forced subsidence (not condensational release of latent heat) as hypothesised by Gray (1977) and Yanai (1983) at the initial stage of formation of a tropical storm, numerical integration has been performed with this model. It is observed that surface friction may not be an essential factor at the initial stage of development when frictional convergence is small. Initial development could be initiated by forced subsidence. But in the subsequent stage, friction plays an important role in inducing mass convergence in the boundary layer and in reducing the horizontal scale of the disturbance.

Chapter V is concerned with the study of motion of a two-dimensional vortex in perfect fluid in presence of a few idealized topographical boundary walls. The influence of topography on the motion of tropical storm, low pressure or other atmospheric vortices is a very complicated phenomenon. It is not easy to isolate this effect from other influences of the atmosphere or the internal force of the vortex itself. Mathematical treatment of such problems is also very difficult. In the situations, three "classical" and difficult hydrodynamical problems related to the
motion of a vortex are solved analytically.

It is found that under favourable direction of environmental flow, a vortex can make loops inside a concave boundary, near the corner of a convex boundary or around an island. It can also remain stationary at some particular positions. From mathematical point of view, the works of this chapter are also not less significant.

In Chapter VI, studies of an unusual tropical storm in the Bay of Bengal are made using satellite and conventional data. Satellite cloud imagery analysis indicates that initial genesis was spawned by cross equatorial surge and forced subsidence occurring in the relatively cloud free area between deep layer convective cloud masses. This justifies the result got in numerical studies in Chapter IV. Subsequent intensification was favoured by high sea surface temperatures and favourable synoptic settings. It appears that initial movement of the storm was guided by the $\beta$-effect and subsequent movement by its environmental steering current. New convective cloud mass growth was observed in the direction of movement. During change of its direction of movement its speed became slower or it remained stationary for sometime. Elongation of associated cloud mass northeastwards towards the later part of its life indicated its interaction with subtropical westerly flow. This finally led to its dissipation right over the sea, where sea surface temperature was also relatively low.

As suggested by the foreign examiner, a new Chapter-VII has been added to present a summery and to discuss the increase of understanding of tropical storm, the originality and usefulness of the works for future studies, limitations etc.