Chapter VI
Summary of Results and Future Prospects
6.1. Summary of Results:

Tropical cyclone is one of the most devastating and deadly weather phenomena worldwide. It is an organized convective activity, developed over warm tropical oceans. The Indian region is unique in nature than any other regions of the world, as far as the genesis/period of tropical cyclones and death tolls due to such systems are concerned. The Bay of Bengal is a potentially energetic region for the development of cyclonic storms, accounting for about 6% of the global annual total number of tropical storms. Though considered to be much weaker in intensity and smaller in size as compared to the cyclones of other regions like Atlantics and Pacific, the Bay of Bengal cyclones that cross east coast of India and Bangladesh are highly devastating. It has a significant socioeconomic impact on the countries bordering Bay of Bengal, especially India, Bangladesh and Myanmar. Therefore, reasonably accurate prediction of these storms has considerable importance to avoid the significant loss of valuable lives and damage to properties.

In recent years mesoscale models are extensively used for simulation of genesis, intensification and movement of tropical cyclones. Recently, a series of high resolution, non-hydrostatic, primitive equation mesoscale models such as PSU/NCAR MM5, WRF (ARW & NMM), ARPS, ETA and HWRF are used for the simulation/prediction of tropical cyclones. In the present study, an attempt is made to illustrate the skill of prediction of track and intensity of the tropical cyclones over Indian seas. For this purpose, the widely used state-of-the-art mesoscale Weather Research and Forecasting (WRF-ARW) model with different CP, MP and PBL schemes are used.

In the third chapter, the prediction of tropical cyclone *JAL* formed over BoB is carried out using WRF model with different CP and MP schemes. The result shows that the simulated track and intensity are sensitive to the choice of the CP and MP schemes used in the model. The track/landfall error decreased in some MP and CP combinations and increased in other MP and CP combinations when the initial conditions change from 00 UTC, 03 Nov, 2010 to 00 UTC, 04 Nov, 2010. The track error is more sensitive to the choice of initial conditions, CP and MP schemes. Even there is no much variation in the track predicted using 27 km and 9 km resolutions, model simulates stronger intensity in 9
km resolution compared to 27 km resolution. The track predicted using KF scheme with all MP schemes is in good agreement with the observed track in all the experiments. The landfall error is minimum (-11 km) for the combination of FERR+KF scheme in Exp-D1I4. The simulations of intensity of cyclone are performed in terms of the MSLP and MSW in the model. The BMJ scheme predicted weak intensity and KF & NG schemes predicted strong intensity with all MP schemes in all the experiments. The KF and NG schemes predicted stronger intensity with minimum track error. Whereas, BMJ scheme predicted weak intensity with maximum track errors. Intensity (MSLP and MSW) of the cyclone depends 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.

The decrease in SLP, temperature and increase in relative humidity is observed during the landfall of the cyclone with AWS at oceanic, in-land and semi-arid regions. The model simulations well predicted the variation in meteorological parameters before/after the depression/landfall of cyclone without using CP schemes, but significant variations have been observed during cyclone period using CP Schemes. The model simulations clearly indicated the importance of MP and CP schemes in the simulations of JAL cyclone.

In chapter four, the track and intensity of six cyclones (MALA, NARGIS, BIJLI, LAILA, SIDR and WARD) are simulated different CP, MP and PBL schemes. The predicted track of the cyclones depends on the choice of the CP schemes used in the model. All the CP schemes predicted different track errors for the same cyclone. For the cyclones MALA, NARGIS and LAILA, the best track was produced by NG scheme, for BIJLI, SIDR and WARD, best track was by KF scheme. In the simulation of intensity, KF scheme predicted the observed intensity for cyclones MALA, LAILA, SIDR and WARD, KF and NG scheme predicted well for cyclones NARGIS and BMJ scheme predicted cyclone BIJLI. The track and intensity of the cyclone also depends on the choice of the PBL schemes used in the model. The combination of MYJ & NG schemes simulated minimum track error for the cyclone MALA, YSU & NG for cyclone NARGIS, MYJ & KF for cyclone LAILA and YSU & KF schemes for the cyclones
SIDR, WARD and BIJILI. In a similar way, the combination of NG and MYJ scheme simulated the observed intensity well compared to all other combinations for the cyclones MALA, NARGIS & LAILA and KF & YSU simulated BIJLI, SIDR & WARD. Further, we simulated these cyclones with different MP schemes along with best set of CP and PBL combination. Here, FERR MP scheme simulated the cyclones MALA, NARGIS & LAILA with less track error, THOMP MP scheme simulated cyclones BIJLI & SIDR and LIN & WSM6 simulated cyclone WARD. In the simulation of intensity, THOMP MP scheme simulated well for MALA & NARGIS cyclones. All MP schemes simulated the observed intensity for the cyclone BIJLI & LAILA. FERR MP scheme simulated the observed intensity for cyclone SIDR & WARD. In a similar way, we simulated the cyclones developed between 1999 and 2013 from genesis to weakening of the cyclones with different physical parameterization scheme. Here also different combinations simulated well for different cyclones. So the variations in CP and PBL schemes affect the track and intensity much compared to MP schemes. Further, we simulated the above six cyclones with different initial conditions with best set of CP and PBL schemes. Different schemes simulated the cyclones at 144, 120 and 96 hours of simulations. However at 72 hours of simulation, KF+LIN+YSU combination simulated the track well for six cyclones. Hence we observed the mean track and intensity error for 33 cyclones at 72 hours of prediction with different CP and PBL combinations. Here also KF+LIN+YSU combination simulated with less track (intensity) error for all (most of) the cyclones. We simulated the mean and standard deviation of track and intensity error for all the cyclones using the above combination. The track error decreased from the cyclones in 1999 to cyclones in 2013. However we do not observe this decreasing trend in the intensity error. Hence the performance of the model improves with the incorporation of improved physical parameterization schemes in the WRF model. To observe the effect of boundary conditions on the simulated track and intensity, we simulated the cyclones with FNL and GFS boundary conditions. The simulated track and intensity is almost same in both FNL and GFS boundary conditions.

The real-time prediction of track and intensity is accessed for the five cyclones developed in the year 2013 using different physical parameterization schemes in chapter
five. Different CP schemes predicted different track errors for the same cyclone. For the cyclones VIYARU and LEHAR, the best track was produced by GD scheme, for PHAILIN, BMJ and for HELEN and MADI, the best track was predicted by KF scheme. In the simulation of intensity, GD scheme predicted the observed intensity for cyclone VIYARU, KF scheme predicted well for cyclones PHAILIN and HELEN, KF as well as NG predicted LEHAR and BMJ for MADI cyclone. The track and intensity of the cyclone also depends on the choice of the PBL schemes used in the model. The combination of GD and MYJ scheme simulated the observed track and intensity well compared to all other combinations for the cyclone VIYARU. Similarly, BMJ & YSU simulated PHAILIN, KF & YSU combination for HELEN and KF & MYJ combination simulated the cyclone LEHAR and MADI. Variations in CP scheme and PBL schemes cause the variations in simulated track and intensity of the cyclones. The variations in track and intensity of the cyclones are also sensitive to the choice of the MP schemes used in the model. However the variations are small compared to CP scheme variations.

Similar to track prediction, different schemes simulated different intensities for the same cyclone. Hence, we studied in detail the dependency of intensity on cyclone structure. Initially, we simulated the surface energy flux and its effect on intensity of cyclone. The Surface energy flux and wind speed are maximum at the eyewall region and minimum at the eye of the cyclone. However, the surface energy flux depends on the temperature difference and specific humidity. Later, we studied the dependency of intensity of cyclone on relative vorticity, divergence. The maximum surface wind depends on divergence field and minimum sea level pressure depends on the relative vorticity field. Further, we studied the vertical structure of the cyclones using vertical cross-section of wind speed, temperature, specific humidity and potential vorticity. The maximum wind is observed in the lower levels for all the cyclones and minimum wind is observed at the eye of the cyclone (width of the eye). The specific humidity is maximum at the eyewall region and it decreases towards the eye of the cyclone. The minimum wind and warmer temperatures are observed at the eye of the cyclone compared to eyewall regions for all the cyclones. Potential vorticity is maximum at the eye of the cyclone and decreases as we move away from the cyclone center in both sides in all the
cyclones. However, the potential vorticity is maximum in upper levels for some cyclones and in lower levels for other cyclones. We studied the dependency of potential vorticity on wind speed using vertically integrated potential vorticity (1°×1° box average) and wind speed (1°×1° and 2°×2° box averages) around the cyclone center. The vertical variation in wind speed is governed by potential vorticity from eye of the cyclone to eyewall region. Further the specific humidity depends on hydrometeor mixing ratio. Hydrometeor mixing ratio depends on the choice of MP scheme used in the model. FERR scheme simulated higher cloud ice between 950 and 350 hPa, THOMP scheme simulated higher snow between 500 and 150 hPa, LIN scheme shows higher rain water and cloud ice between 950 & 550 and 350 & 100 hPa and WSM6 shows higher graupel mixing ratio between 550 and 350 hPa.

6.2. Future Prospects:

1. As high-resolution WRF-ARW become increasingly instrumental in evaluations of tropical cyclones in current and future climate conditions, many questions remain to be addressed very near future.
   - Will the Cyclone hit the coast and where and when?
   - What will be its intensity?
   - What will be the cumulative damage?

2. Sensitive experiments will be performed to achieve greater accuracy of tropical cyclone track and intensity prediction, especially in the short range (48 -72 hr in advance), by maximizing the use of non-conventional data, mesoscale analysis, use of synthetic data for vortex specification, and the physical parameterization in non-hydrostatic environment at higher model resolution.

3. Role of Ocean parameters for enhanced cyclogenesis, intensification/weakening and frequent recurving tracks.

4. Role of atmospheric parameters for enhanced cyclogenesis, intensification/weakening and straight & recurving tracks.

5. A study will be carried out using coastal (Chennai, SHAR & Visakhapatnam) Doppler Weather Radar (DWR), satellite (Megha-Tropiques, SSM/I, TMI, AMSR QuikSCAT, INSAT, TRMM, and etc) products and buoys data for better...
understanding and characterization of physical processes leading to genesis, intensification/weakening and tracks of cyclonic disturbances over NIO.

6. A detail investigation will be carried out on the formation and intensification of secondary eyewall of the tropical cyclones in NIO.