4.1 Introduction

The problem of determination of initial conditions for a forecast model is very important and complex, and has become a science in itself (Daley 1998). Advance data assimilation in meteorological context refers principally to combining observations with a numerical model to produce first a better estimate of the atmospheric state, and then a prediction (Chock and Carmichd 2000, p. 165). In recent years, increasing research efforts and computer resources are devoted to the development of data assimilation techniques. In last two decades, however, data sparseness has been less of a problem as with advancement in the space technology and remote sensing (Chen 2007), today large number of sensor are available to provide enough information coverage over oceans. This development brought challenges to successfully incorporate the maximum available information from various satellite sensors to the model first guess to obtain best initial condition. The studies are needed to understand the individual as well as combined impact of available data sets on the simulations of various weather events. In this chapter we have assimilated various satellite observations to understand their impact on the simulation of North Indian ocean tropical cyclone. The cyclone studied are Orrisa Super cyclone and cyclone Gonu discussed in the following section. The various satellite observations used for assimilation are discussed in section 4.4. An experiment carried out to study the impact of SSM/I, QuikSCAT, and Meteosat wind assimilation is discussed in section 4.5. In section 4.6, combined impact of surface wind from QuikSCAT and multilevel wind from Meteosat is studied. Finally, in section 4.7 the impact of SSM/I preceplitable water vapor assimilation is studied. The results are discussed and summarized in section 4.8.

4.2 Tropical cyclone cases considered for the experiments

(a) Orissa Super Cyclone (October 1999)

The track of Orissa Super cyclone is shown in Figure-4.1. The Orissa Super cyclone, is the most intense cyclonic storm experienced over Bay of Bengal for the last 114 years since the false point cyclone of 1885 (Singh et al. 2008). The storm achieved minimum
central sea level pressure of 912 hPa and associated maximum sustained wind of 75.6 m/s. The details of Orissa super cyclone are discussed in Appendix-I.

(b) Cyclone Gonu (June 2007)

The track of cyclone Gonu is shown in Figure-4.2. Cyclone Gonu was the strongest tropical cyclone on record in the Arabian Sea. Gonu developed from a persistent area of convection in the eastern Arabian Sea on 1 June 2007, and made landfall at 0000 UTC 6 June 2007. The synoptic overview of cyclone Gonu is discussed in Appendix-I.
4.3 Assimilation Methodology and Experimental Details

The three dimensional variational data assimilation experiments were conducted by minimizing the cost function. The 3DVar method (Barker et al. 2004) is based on minimization of a cost function defined as (Ide et al. 1997):

\[ J(x) = J_b(x) + J_o(x) = \frac{1}{2}(x - x^b)^T B^{-1} (x - x^b) + \frac{1}{2}(y - y^o)^T (E + F)^{-1} (y - y^o). \]  

(4.1)

Where \( x \), analysis variables vector (n-dimensional), \( x^b \) the background variables vector (n-dimensional), \( y^o \) the observation vector (m-dimensional), \( B \) the background error covariances matrix (n x n), and \( R \) the observation error covariances matrix (m x m). In (4.1), the analyses \( x = x^a \) represents the a posteriori maximum likelihood (minimum variance) estimate of the true state of the atmosphere given two sources (\( x^b \) and \( y^o \)) of
data. The analyses fit to this data are weighted by estimates of their errors (B, R). The cost function (4.1) assumes that observation and background error covariance are described using Gaussian probability density functions with zero mean error.

The configuration of the WRF 3DVar system is based on an incremental formulation producing a multivariate incremental (Courtier et al. 1994) analysis in the WRF model space. The incremental cost function minimization is performed in a preconditioned control variables space. The preconditioned control variables are the stream function, velocity potential, unbalanced pressure and relative humidity. The background covariance matrix B is estimated in grid space by what has become known as the NMC method (Parrish and Derber 1992). The statistics are estimated with the differences of 24 and 48-hour GFS forecasts with T170 resolution valid at the same time for 357 cases distributed over a period of one year. A detailed description of the 3DVar system can be found in Barker et al. (2004).

In the WRF 3DVar, all observation errors are assumed to be uncorrelated in space and time. Since observation errors are assumed uncorrelated, the matrix E is simple diagonal with SSM/I and QuikSCAT observation error variances as elements. In this study, these variances are taken as constant in space and time. The variances for SSM/I wind speed and total precipitable water are assigned as 2.52 m² s⁻² and 22 mm², respectively. The variances for u and v component of QuikSCAT wind vector are 1.42 m² s⁻². These variances are defined by NCEP/NCAR based on the comparison of the QuikSCAT and SSM/I observations with ships and buoys data. The similar values of the variances in the SSM/I and QuikSCAT observations are used in earlier studies (Chen et al. 2004; Chen et al. 2007). However, the choice of the variances for minimization processes is always a challenge, and more studies are required to adequately define the variances in cyclone environment.

The domains of study for Orissa Super cyclone and cyclone Gonu are shown in Figure-4.1 and 4.2. For Orissa Super cyclone (Figure-4.1) outer domain is set from 74E-106E and -1N-30.3N and the inner domain extends from 8.5N-23N and 80.5E-98.3E. For cyclone Gonu (Figure-4.2) the outer domain extends from 46E-80E and 3.5N-35N, and
inner domain extends from 54.36E-75E and 10N-29.5N. In both cases the resolution of outer domain is 30 Km and of inner domain is 10 Km, with 28 vertical levels. The NCEP analysis (1 deg. resolution) is used for the model boundary conditions.

In each individual experiment for Orissa Super cyclone, the satellite observations are assimilated to the first guess at 1200 UTC 26 October 1999 using 3DVar, and 72 hour WRF simulation is carried out from 1200 UTC 26 October 1999 to 1200 UTC 29 October 1999. Instead of directly using NCEP analysis of 1200 UTC 26 October 1999 as first guess, a 6 hour WRF simulation from (0600 UTC to 1200 UTC, 26 October 1999) is integrated to provide 3DVar 1st guess at 1200 UTC 26 October 1999. This 6 hour forecast was used as 1st guess due to two reasons. First, we were not sure whether the NCEP analysis used as the initial state contained the satellite observations we are assimilating through 3DVar assimilation system. The 6 hour forecast eliminates these possibilities and provided an ideal test-bed for assessing the impact of satellite observations. Second, during 6 hour integration the coarser resolution NCEP analysis is expected to adjust to higher resolution environment of WRF, creating dynamically balanced field for assimilation experiments. The NCEP analysis has been used to provide 6 hourly boundary conditions. The initial condition is obtained by assimilating satellite observation available within +/- 1.5 hour window near 1200 UTC 26 June 1999. The process of assimilation using WRF 3DVar system is shown in Flowchart-1. The assimilation is done only for the outer domain. The initial condition for inner domain is obtained by interpolating data from outer domain.

Flowchart-4.1: Methodology of assimilation.
Similarly for cyclone Gonu, in each individual experiment a 72 hour simulation is done.

**Table-4.1: A brief summary of various assimilation experiments.**

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Name of Experiment</th>
<th>Data assimilated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CTL</td>
<td>Radiosonde</td>
</tr>
<tr>
<td>2</td>
<td>QS</td>
<td>Radiosonde + QuikSCAT wind</td>
</tr>
<tr>
<td>3</td>
<td>SSW</td>
<td>Radiosonde + SSM/I wind</td>
</tr>
<tr>
<td>4</td>
<td>MSW</td>
<td>Radiosonde + Meteosat AMVs</td>
</tr>
<tr>
<td>5</td>
<td>QMW</td>
<td>Radiosonde + QuikSCAT Wind + Meteosat AMVs</td>
</tr>
<tr>
<td>6</td>
<td>SWV</td>
<td>Radiosonde + SSM/I Water Vapor</td>
</tr>
</tbody>
</table>

from 0000 UTC 03 June 2007 to 0000 UTC 06 June 2007. For assimilation the first guess is obtained by carrying 6 hour WRF simulation from 1800 UTC 02 June 2007. The NCEP analysis has been used to provide 6 hourly boundary conditions. The initial condition is obtained by assimilating satellite observation available within +/- 1.5 hour window near 0000 UTC 03 June 2007. In both the cyclone cases, the observations were assimilated to the outer domain only. The initial condition for inner domain is obtained by interpolating data from outer domain. Table-4.1 summaries the various experiments carried out in this chapter for cyclone Gonu and Orissa Super cyclone, following the above discussed assimilation methodology. Various satellite observations used in the present study is discussed in the following section.

### 4.4 Satellite Observations

**(a) QuikSCAT Wind**

The NASA Quik Scatterometer (QuikSCAT) was launched in June 1999. It circles Earth at an altitude of 800 kilometers once every 101 minutes. The SeaWinds instrument on QuikSCAT is active microwave radar designed to measure the electromagnetic backscatter from the wind roughened ocean surface. The SeaWinds instrument uses a rotating dish antenna with two spot beams that conically sweep, producing a circular pattern on the surface. The antenna radiates microwave pulses at a frequency of 13.4
GHz. The antenna spins at a rate of 18 rpm, scanning two pencil-beam footprint paths at incidence angles of 46° (H-pol) and 54° (V-pol). The instrument collects data over ocean, land, and ice in a continuous, 1,800 km wide band centred on the spacecraft nadir ground track, covering 90% of Earth’s surface each day.

The accuracy of the measured ocean surface wind reaches 2 ms⁻¹ in speed and 20° in direction for winds of 3-20 ms⁻¹ and 10% for winds of 20-30 ms⁻¹ (Shirtliffe 1999), where help from independent information (e.g., numerical models) is needed to remove the ambiguity in the direction determination. Rainfall can greatly affect the accuracy of the scatterometer wind measurements (Weissman et al 2002; Hoffman et al 2005). Light winds can be overestimated by excess backscatter from the hydrometers as they fall and because they roughen the sea surface. QuikSCAT SeaWinds level 2B wind vectors derived from Wentz and Smith (1999) at ~25 Km resolution over ocean region. For Orissa super cyclone (Figure-4.3-a) case, the QuikSCAT swath was available on 1154 UTC 26 October 1999. For cyclone Gonu (Figure-4.3-b), the QuikSCAT observation was available on 0118 UTC 3 June 2007. Before assimilating the data, a quality check is applied to remove the data in raining conditions.

Figure-4.3: a) QuikSCAT 10-meter wind observation on 1154 UTC 26 October 1999. b) QuikSCAT 10-meter wind observation on 0118 UTC 3 June 2007.
The SSM/I (Hollinger et al 1989) is a conical scanning, 4-frequency, linearly polarized, 7-channel passive microwave radiometer. The first SSM/I instrument was launched aboard the Defense Meteorological Satellite Program (DMSP) of the United States Navy in June 1987. This polar-orbiting satellite has a period of about 102 min. The instrument has a nearconstant incidence angle of 53°, a mean altitude of approximately 830 km, and a swath width of about 1400 km. Like QuikSCAT, the SSM/I data are available under both clear and cloudy oceanic conditions but can be contaminated by light as well as heavy precipitation.

The SSM/I instrument consists of seven radiometers sharing a common feed horn. Dual-polarization measurements are made at 19.35, 37.0, and 85.5 GHz, and a single vertical polarization measurement is made at 22.235 GHz. Earth observations are made during a 102.48 segment of each scan, corresponding to a 1400 km swath on the Earth’s surface.

Complete coverage of the Earth is provided every 2 or 3 days, except for small patches near the poles. Using these observations, it is possible to retrieve three important geophysical parameters over the oceans. These parameters are the near-surface wind speed, the columnar water vapor, and the columnar cloud liquid water. The physical basis for these retrievals is the absorption and scattering of microwaves by water in the atmosphere and the roughening of the ocean surface by wind stress, which changes its emission and reflection properties.

Satellite measures the surface roughness; the property of the wind that is most directly measured is the stress. This is converted to a wind speed assuming that the boundary layer over the ocean is neutrally stable. The Wentz (1997) algorithm was chosen by NASA for the production of the Scanning Multi-channel Microwave Radiometer (SSMR)-SSM/I Pathfinder data set, which will be a 20 year time series of geophysical parameters broadly available to the research community. The data collected and processed to date are available via the internet (http://www.ssmi.com) in the form of maps of geophysical parameters on a 0.258 grid.

The retrieved total precipitable water (TPW) and sea surface winds from DMSP-F13, F14 satellites are used for assimilation. For the present study SSM/I observations are
Figure-4.4: SSM/I 10-meter wind (shaded) and total precipitable water vapor (contour) observations on a) 1137 UTC 26 October 1999. b) 0112 UTC 3 June 2007. Available at 1137 UTC 26 October 1999 and 0112 UTC 3 June 2007, exactly over initial position of cyclone Figure-4.4.

(c) Meteosat Atmospheric Motion Wind (AMV)

Atmospheric Wind vectors from Meteosat image data are extracted routinely by European Organization for Exploitation of Meteorological Satellites (EUMETSAT). Since 1997 the EUMETSAT has been providing an enhanced AMV dataset at 90-min temporal sampling. The scheme is based on the tracking of clouds in all three spectral channels of Meteosat image data, using sequences of consecutive images (Schmetz et al 1993). Meteosat wind extraction is based on the recognition of displacement of patterns between successive images and uses consecutive sequences of images in half hourly intervals. All three spectral channels of Meteosat are used to measure displacements. The IR and WV channels are used in combination with externally supplied temperature and humidity forecast data for height assignment of the displacement vectors. Height assignment of IR and VIS displacement vectors relies basically on cloud top temperature measurement from the IR channel, with a semi-transparency correction for cirrus cloud tracers based on WV channel information. For WV displacement vectors, current operations use the same height assignment scheme as for IR winds. Since this leads to
satisfactory results only for height levels above 400 hPa, only those WV winds are selected for dissemination.

It is inherent to this scheme that redundant wind measurements are produced by observing the movement of the same tracer in different spectral channels. In most of these cases, high level winds from the WV channel and low level winds from the VIS channel are better than the corresponding winds from the IR channel. The internal quality control scheme performs a selection so that only the wind vectors with better quality mark are disseminated to users.

![Figure-4.5](image-url)

**Figure-4.5**: Meteosat-7 Cloud motion wind of cyclone Gonu (2223 UTC 2 June 2007), grided to 0.5 degree, black vectors represent 900-350 hPa and grey vectors represent 350-100 hPa.

For Orissa Super cyclone the Meteosat AMV product available at 1302 UTC of 26 October 1999 is used. Figure-4.5 shows the AMVs from Meteosat-7 of 0032 UTC 3 June 2007, used for cyclone Gonu.
4.5 Impact of satellite winds (QuikSCAT, SSM/I, and Meteosat) assimilation.

In case of tropical cyclones, the better representation of wind field in the initial condition at surface as well as upper level is very important. Air-Sea interactions including heat, momentum and moisture fluxes play a vital role in the formation and intensification of the tropical cyclones (Kuo and Lownam 1990; Kuo et al. 1991; Miller et al. 1992; Singh et al. 2004). The Near surface winds play a dominant role in air-sea interactions processes (Liu 1988; Geernaert 1990; Chou et al. 2003; Bao et al. 2000; Singh et al. 2006). Fortunately, several satellites have observed the near surface winds over the ocean during last two decade, such as the NASA Scatterometer (NSCAT), Geosat altimeter, Quick Scatterometer (QuikSCAT), Special Sensor Microwave Imager (SSM/I), European Space Agency ERS 1 and 2 (Isakessen and Stoffelene 2000; Leidner et al 2003).

The scatterometer provide both surface wind speed and direction, which significantly increases the tropical cyclone forecaster’s knowledge of tropical cyclone formation and surface wind structure. Global coverage of scatterometer data has been routinely available (Tomassini et al 1998) to forecasters and researchers since 1991 from the European Remote Sensing Satellite 1 (ERS-1) and European Remote Sensing Satellite 2 (ERS-2). However, ERS satellites often did not provide adequate coverage (Andrews et al 1998; Rufenach 1998) of tropical cyclones due to narrow swath (~500 Km) of these satellites. This situation changed following the launch of Quick scatterometer (QuikSCAT) satellite in 1999, with its sea wind instrument offering near-continuous daily coverage of over 90 % of the tropical oceans with a wide swath of 1800 Km. Ebuchi et al (2002) found that the wind speed and direction observed by QuikSCAT agree well with the buoy data. The root-mean-squared differences of the wind speed and direction for the standard wind data products are 1.01 m/s and 23° respectively. Boutin and Etcheto (1996) found that SSM/I retrieved wind speeds are underestimated by more than 1 m/s with respect to ship measurements at high latitudes. However, when compared with ERS-1, SSM/I winds are overestimated by 0.5 m/s over regions where the
atmospheric water vapor content is high. It has also been found that SSM/I winds derived from Wentz’s algorithm (Wentz 1997) are systematically overestimated in regions of higher water vapor content (Halpern 1993; Waliser and Gautier 1993; Boutin and Etcheto 1996). A neural network algorithm, which takes into account the nonlinear relationship between wind speeds and brightness temperatures, has also been used to derive the SSM/I winds and has produced promising results (Stogryn et al. 1994; Krasnopolsky et al. 1995; Yu et al. 1997).

Most studies of satellite-observed low-level winds have concentrated on data comparisons. Few focus on the use of data assimilation techniques to improve analysis and model simulations (Phalippou 1996; Yu et al. 1997; Zou and Xiao 2000; Lidner et al. 2003; Chen et al. 2004; Isaksen and Stoffelen 2000; Isaksen and Janssen 2004). Isaksen and Stoffelen (2000) showed a positive impact of assimilating ERS scatterometer wind data on tropical cyclone analysis and forecast using four-dimensional variational data assimilation technique (4DVAR). Chen et al. (2004) used 3DVAR to assess the impact of assimilating retrieved SSM/I products for Hurricane Danny (in 1997) simulations. They found very promising improvement in simulation of storm intensity, but little improvement for the simulated storm track. Chen et al. (2006) and Singh et al. (2007) shows that assimilation of QuikSCAT and SSM/I surface wind data improves the initial condition and gives better forecast of tropical cyclones. But, the QuikSCAT gives much better improvement as it consist both wind speed and direction information. Zang (2007) studied the rapid weakening of hurricane Lili using multi satellite data and four-dimensional data assimilation technique. He mentioned that the assimilation of QuikSCAT wind data improve not only the initial surface wind, but also the temperature at the lower levels. The increase of the surface cyclonic wind speed strengthens the convergence, initial stronger updrafts and releasing more latent heat. The above studies also mentioned that the inclusion of QuikSCAT data gives good improvement in track, but is not enough to improve the intensity prediction.

The AMVs are produced from all operational geostationary satellites and have been since the 1960s (Fujita 1968; Hubert and Whitney 1971). Common techniques in use today are described by Velden et al. (1997, 1998). The atmospheric motion winds are available
from GMS, GOES, and Meteosat satellite. The north Indian Ocean region is covered by Meteosat-5 and Meteosat-7. The proper specification and analysis of tropospheric wind is a prerequisite to accurate numerical model forecast (Valden et. al. 2005). Conventional upper air wind observations over oceanic region are sparse, and weather reconnaissance aircraft data are also not available. The AMV data are perhaps the most comprehensive regular source of atmospheric observations over oceanic regions. The assimilation of upper level atmospheric wind can improve the upper level divergence in tropical cyclones. Also, the improvement in the upper level steering flow can improve the track of cyclone. Zuo and Xiao (2000) assimilated the atmospheric wind data from GOES-8 to study the Hurricane Felix. They found that the initial hurricane vertical velocity structure is improved and become realistic. Also, the track and intensity of hurricane are improved slightly after assimilation of GOSE-8 satellite winds. Xaio et al. (2002) studied the impact of GMS-5 and GOES-9 satellite derived winds on the prediction of an extra tropical cyclone. He found that the assimilation has improved the track and intensity prediction slightly and, also suggested that the numerical model plays an equal and some times more important role than the initial conditions for prediction.

In the present study, our purpose is to assess the impact of assimilation of surface and upper level satellite winds on the simulation of north Indian Ocean tropical cyclones. The cyclones studied are the Orissa super cyclone (October 1999, bay of Bengal) and tropical cyclone Gonu (June 2007, Arabian Sea). The special thing about these cyclone cases is that they are the most intense cyclone occurred in the history their respective basins. We have assimilated the winds from the QuikSCAT, SSM/I, and Meteosat satellites. The experiments were carried out to assess their individual as well as combined impact on the simulation of both the cyclones. The WRF model and 3D-VAR technique (chapter-2, section-2.2) are used for this study.

4.5.1 Wind assimilation Experiments

The four sets of experiments (Table-4.1) were carried out for Orissa Super cyclone are CTL, QS, MSW, and SSW. CTL is the control experiment carried out for comparing the performance of assimilation experiments. In CTL experiment only radiosonde data (provided by University of Wyoming) has been assimilated. The locations of radiosonde
stations are shown in Figure-4.1. In QS experiment wind vectors and wind speed observations of 1154 UTC 26 October 1999 from QuikSCAT (Figure-4.3-a) and radiosonde observations were assimilated to the first guess at 1200 UTC 26 October 1999. In MSW experiment AMVs derived from Meteosat of 1302 UTC 26 October 1999 and radiosonde observations were assimilated. In the forth experiment SSW we have assimilated radiosonde data, and SSM/I winds of 1137 UTC 26 October 1999 (Figure-4.4-a). The assimilation methodology is discussed in section 4.3.

The four sets of experiments (Table-4.1) are carried out for cyclone Gonu. CTL is the control experiment carried out for comparing the performance of other assimilation experiments of Gonu. In CTL experiment only radiosonde data is assimilated. The locations of radiosonde stations are shown in Figure-4.2. In QS experiment radiosonde data and wind vectors and wind speed an observation of 0118 UTC 3 June from QuikSCAT Satellite was assimilated (Figure-4.3-b). In MSW experiment the radiosonde data and AMVs (Figure-4.5) derived from Meteosat at 0032 UTC 3 June 2007 was assimilated. In the forth experiment SSW we have assimilated radiosonde data, SSM/I winds 0112 UTC.

4.5.2 Initial Conditions

1) Orissa Super Cyclone-

The observations are assimilated into the initial conditions by minimizing the cost function that is the measure of the distance between observed and first guess derived surface winds. In order to see the agreement between QuikSCAT observation (O) and first guess (B) wind, we have compared these two products. Comparison shows that the two products differ significantly with the RMSE of 2.95 m/s. The RMSE (2.0 m/s) of the QS analysis (A) and QuikSCAT observation (O) is less than the RMSE of observation and first guess. Similarly, for SSW analysis the RMSE between analysis and SSM/I wind observation is 2.85 m/s. Which is less than the RMSE (3.11 m/s) between first guess and SSM/I wind observation. In MSW experiment, the RMSE between Meteosat AMVs observation and first guess is very high of the order 7.29 m/s and 5.1 m/s in u and v
components respectively. The RMSE between the Meteosat wind observation and the MSW analysis reduced to 3.42 m/s and 2.1 m/s in u and v components respectively.

**Table-4.2:** The summary of different initial conditions for Orissa Super cyclone

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Vortex Position</th>
<th>Error in Vortex Position (Km)</th>
<th>max. wind at 900 hPa (m/s)</th>
<th>Correlation coefficient (SSMI vs Analysis 950 hPa) wind</th>
<th>BIAS (SSMI-Analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>93.9E,15N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTL</td>
<td>93.62E,13.78N</td>
<td>139.18</td>
<td>19.34</td>
<td>0.31</td>
<td>1.15</td>
</tr>
<tr>
<td>QS</td>
<td>93.62E,14.11N</td>
<td>103.74</td>
<td>26</td>
<td>0.59</td>
<td>0.90</td>
</tr>
<tr>
<td>SSW</td>
<td>93.57E,13.74N</td>
<td>143.57</td>
<td>19</td>
<td>0.78</td>
<td>-1.75</td>
</tr>
<tr>
<td>MSW</td>
<td>93.68E,13.71N</td>
<td>145.51</td>
<td>20</td>
<td>0.32</td>
<td>1.87</td>
</tr>
<tr>
<td>QMW</td>
<td>93.53E,13.77N</td>
<td>142.82</td>
<td>21.9</td>
<td>0.54</td>
<td>1.39</td>
</tr>
<tr>
<td>SWV</td>
<td>93.67E,13.74N</td>
<td>141.2</td>
<td>18.75</td>
<td>0.48</td>
<td>1.45</td>
</tr>
</tbody>
</table>

The winds at 950 hPa of all the initial conditions (1200 UTC) compared with the common observation i.e. SSM/I surface wind observation (1137 UTC) to get the impact of respective observation assimilation on the surface wind field. The RMSE of surface winds in the CTL, QS, SSW, and MSW analysis are 4.1 m/s, 3.2 m/s, 2.85 m/s, 4.5 m/s respectively. The assimilation of QuikSCAT and SSM/I surface wind has improved the analysis over CTL analysis. But, the assimilation of Meteosat AMVs has increased the error in surface wind of MSW analysis. The correlation coefficients for the wind in CTL, QS, SSW, and MSW analysis are 0.31, 0.59, 0.78, and 0.32 respectively. The bias (observation-analysis) of wind in CTL, QS, SSW, and MSW analysis are 1.15 m/s, 0.90 m/s, -1.75 m/s, and 1.87 m/s respectively. The poor correlation of CTL analysis wind is improved after the assimilation of QuikSCAT wind. The SSW analysis show very good correlation with observations, but the analysis is under estimated. There is not much impact of Meteosat AMVs on the surface wind in the MSW analysis, and shows high positive bias. The QS analysis remains best among all.
Figure-4.6: 950 hPa wind field valid at 1200 UTC 26 October 1999 for, a) CTL b) QS c) SSW d) MSW.

Figure-4.6 shows the circulation pattern and wind magnitude at 950 hPa in the initial condition of experiment CTL, QS, SSW, and MSW experiments. Table-4.2 summaries the vortex position errors, and surface maximum wind magnitude at 950 hPa in the initial conditions. The observed JTWC best track position of vortex at 1200 UTC 26 October was (93.9N, 15.0E). The error of vortex position in the initial condition of CTL, QS, SSW, and MSW are 139.1 Km, 103.7 Km, 143.5 Km, and 145.5 Km respectively. The QuikSCAT surface wind assimilation has improved the position of vortex in the QS
analysis. Where, the assimilation of SSM/I surface wind and Meteosat AMVs has negative impact on the vortex position in the respective analysis.

The observed surface maximum wind at 1200 UTC 26 October 1999 was 22.5 m/s. The maximum surface wind in the initial condition of CTL, QS, SSW, and MSW are 19.34 m/s, 26 m/s, 19 m/s and 20 m/s respectively. The under estimated intensity in CTL analysis has been overestimated in the QS analysis. Where the intensity is again reduced by assimilation of SSM/I wind. The Meteosat AMVs assimilation has shown very good improvement in the intensity in MSW analysis.

2) Gonu-

Comparison of QuikSCAT observation (O) and first guess (B) wind shows that the RMSE between QuikSCAT observed surface wind and first guess wind is 2.81 m/s. The RMSE (1.26 m/s) of the QS analysis (A) and QuikSCAT observation (O) is less than the RMSE of observation and first guess. Similarly, in SSW analysis the RMSE between analysis and SSM/I wind observation is 2.8 m/s. Which is slightly less than the RMSE of 3.1 m/s between first guess and SSM/I wind observation. In MSW experiment, the RMSE between Meteosat AMVs observation and first guess is very high of the order 8.76 m/s and 7.62 m/s in u and v component respectively. The RMSE between the Meteosat wind observation and the MSW analysis reduced to 3.35 m/s and 3.01 m/s in u and v component respectively.

The 950 hPa winds of all the initial conditions (0000 UTC) are compared with the SSMI surface wind observation (0112 UTC). The RMSE of surface winds in the CTL, QS, SSW, and MSW analysis are 3.44 m/s, 2.36 m/s, 2.8 m/s, and 5.1 m/s respectively. The QuikSCAT wind assimilation has reduced the RMSE significantly. The assimilation of Meteosat AMVs has negative impact on the surface winds. The correlation coefficients for the wind in CTL, QS, SSW, and MSW analysis are 0.65, 0.84, 0.87, and 0.24 respectively. The bias (observation-analysis) of surface wind in CTL, QS, SSW, and MSW analysis are -0.52 m/s, -0.03 m/s, -2.14 m/s, and -0.009 m/s respectively. The assimilation of QuikSCAT wind show very good impact on the correlation of surface wind in analysis with the SSM/I observation. The SSW analysis shows very good
correlation with observation, but model analysis wind is highly over estimated. Meteosat AMVs has reduced the correlation in the MSW analysis, but the bias is improved.

Table-4.3: The summary of different initial conditions for cyclone Gonu.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Vortex Position</th>
<th>Error in Vortex Position</th>
<th>max. wind (m/s) at 900 hPa</th>
<th>Correlation coefficient (SSMI-Analysis950 hPa) wind</th>
<th>BIAS (SSMI - Analysis)</th>
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<tbody>
<tr>
<td>Observed</td>
<td>67.40N,16.10E</td>
<td></td>
<td>27.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTL</td>
<td>66.75E,15.34 N</td>
<td>111.20 Km</td>
<td>22.62</td>
<td>0.65</td>
<td>-0.52</td>
</tr>
<tr>
<td>QS</td>
<td>66.98E,16.02N</td>
<td>47.54 Km</td>
<td>23.69</td>
<td>0.84</td>
<td>-0.03</td>
</tr>
<tr>
<td>SSW</td>
<td>67.19E,16.52N</td>
<td>52.55 Km</td>
<td>20.78</td>
<td>0.87</td>
<td>-2.14</td>
</tr>
<tr>
<td>MSW</td>
<td>66.80E,15.40N</td>
<td>102.51 Km</td>
<td>25.70</td>
<td>0.24</td>
<td>-0.60</td>
</tr>
<tr>
<td>QMW</td>
<td>66.97E,16.09N</td>
<td>47.82 Km</td>
<td>25.49</td>
<td>0.81</td>
<td>-0.009</td>
</tr>
<tr>
<td>SWV</td>
<td>66.49E,15.44N</td>
<td>123.50 Km</td>
<td>19.78</td>
<td>0.577</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Figure-4.7 shows the circulation pattern and wind magnitude at 950 hPa in the initial conditions of experiment CTL, QS, MSW, and QMW. Table-4.3 summaries the vortex position errors, and surface maximum wind magnitude at 950 hPa in the initial conditions. The observed position of vortex on 0000 UTC 3 June 2007 was (67.40N, 16.10E). The error of vortex position in the initial condition of CTL, QS, SSW, and MSW are 111.20 Km, 47.54 Km, 52.55 Km, and 102.5 Km respectively. The assimilation of QuikSCAT and SSM/I wind have improved the position of vortex in the QS and SSW analysis respectively. Where, the assimilation of Meteosat AMVs has small improvement in the vortex position.

The observed (JTWC) surface maximum wind at 0000 UTC 3 June 2007 was 27.5 m/s. The surface maximum wind underestimated in all the analysis for Gonu. The maximum surface wind in the initial condition of CTL, QS, SSW, and MSW are 22.6 m/s, 23.6 m/s, 20.78 m/s, and 25.4 m/s respectively. The SSM/I wind assimilation shows negative impact on the intensity in SSW analysis. The Meteosat AMV has shown better improvement in the intensity than QuikSCAT wind assimilation.
Figure-4.7: 950 hPa wind field valid at 0000 UTC 3 June 2007 for, a) CTL b) QS c) SSW d) MSW.

4.5.3 Simulated Tracks

1) Orissa Super Cyclone

The 72 hour (1200 UTC 26 October - 1200 UTC 29 October, 1999) observed and simulated tracks for all set of experiments carried out for Orissa Super cyclone (CTL, QS, SSW, and MSW) are shown in Figure-4.8-a. The errors of vortex position in the initial condition of different experiment are shown in Table-4.2. Figure-4.8-b shows the
comparison of daily mean track errors for all the experiments of Orissa super cyclone. In CTL analysis, the error of vortex position was 138.9 Km. For the 1\textsuperscript{st} and 2\textsuperscript{nd} day mean track error is 136.9 Km and 131.9 Km respectively (Figure-4.8-b). After first 36 hour simulated cyclone started moving eastward where the observed movement was northeastward (Figure-4.8-a). This caused a large mean track error of 344.7 Km in the 3\textsuperscript{rd} day simulation of CTL. The CTL experiment could not predict the landfall of Orissa super cyclone.

In QS experiment, the position error of vortex in the initial condition is reduced to 95 Km. Improvement in the initial vortex position gave positive impact on track simulation. For the 1\textsuperscript{st} day forecast mean error is 124.7 Km. On 2\textsuperscript{nd} day the mean track error reduced to 61.7 Km. On third day it increased to 155.8 Km. Though mean track error is large on third day in QS, but it is significantly smaller than the control simulation. QS could not simulate the landfall of Orissa Super cyclone.

![Figure-4.8-a: 72-h simulated tracks of Orissa Super cyclone (from 1200 UTC 26 October 1999) in CTL, QS, SSW, and MSW experiment.](image-url)
In SSW experiment, the high error of vortex position in analysis increased the mean track error of 1st day simulation to 184.8 Km. This error is higher than CTL experiment. However, the error reduced considerably for 2nd and 3rd day simulations to 110.3Km, 129.6 Km respectively. The improvement of track simulated for 3rd day SSW simulation was less as compared to QS experiment. Similar to QS and CTL, the SSW experiment could not simulate the landfall of Orissa Super cyclone.

In MSW experiment, the position error of vortex in the initial condition is 144.1 Km. Despite of this large vortex position error, MSW has reduced the track errors in prediction. The mean track error of 1st, 2nd, and 3rd 24 hour simulation in MSW are 91.1 Km, 139.3 Km and 103.7 Km respectively. For the 1st and 3rd day simulation, MSW has performed better than QS. The best feature of MSW experiment is that, unlike CTL, QS, and SSW it has predicted the landfall of Orissa Super cyclone with good accuracy. The error in landfall position is 92 Km and the error in landfall timing is 0 hours.

2) Gomu-

The 72 hour (0000 UTC 3 June 2007 - 0000 UTC 6 June 2007) observed and simulated tracks for all set of experiments (CTL, QS, SSW, and MSW) are shown in Figure-4.9-a.

Figure-4.8-b: Daily mean of track prediction errors in different experiments for Orissa Super cyclone.
The errors in the initial position of vortex in the initial conditions of different experiment are shown in Table-4.3. Figure-4.9-b shows the comparison of daily mean track errors for all the experiments of cyclone Gonu. In CTL analysis the vortex position error is 111.20 Km. For 1st and 2nd day mean track errors are 92.27 Km and 63.5 Km respectively. Afterwards the cyclone moved south-westward in CTL simulation, while the actual movement was north-westward. This has caused a large positional error at the end of 3rd day integration. The mean track error for 3rd day is 162.60 Km. CTL simulation could not predict the landfall of Gonu.

In QS analysis the position error of vortex is 47.5 Km. The 1st day mean error in track is 103.5 Km. Here, onward Gonu showed slight northward motion and the mean error of

![Diagram](image.png)

**Figure-4.9-a:** 72-h simulated tracks of cyclone Gonu (from 0000 UTC 3 Jun 2007) in CTL, QS, SSW, and MSW experiment.
2nd day of integration reduced to 42.6 Km. On 3rd day the position and movement of simulated cyclone coincided with the observed track. The mean error for 3rd day simulation is 75.01 Km. The cyclone made landfall on 0000 UTC 6 June 2007, with 11 Km error in position and 00 hour error in landfall-time. QS Experiment has simulated the track with much better accuracy than CTL.

In SSW analysis the vortex position error reduced to 52.55 Km. For the 1st day mean error of SSW was smallest of all i.e. 65.9 Km. On 2nd and 3rd day the cyclone moved very fast and the track remained south of the observation (Figure-4.9-a). This has increased mean errors of 2nd and 3rd day to 128.2 Km and 265 Km respectively. The SSW has predicted landfall 12 hours earlier i.e. on 1200 UTC, 5 June 2007 at 59.12 E, 21.56 N with 222.3 Km error in position.

In MSW initial condition the position error of vortex is 101.2 Km. For 1st day cyclone moved slower than observed and caused high mean error of 225 Km. On 2nd and 3rd day the mean error reduced to 198.09 Km and 156.06 Km., but shown some northward movement. This northward movement was continued through out the integration. At the end of 3rd day i.e. on 0000 UTC 6 June 2007, cyclone remain 140.84 Km north of Oman.
(Figure-4.9-a) without making landfall. The Meteosat AMVs have shown negative impact on the track simulation of Gonu.

### 4.5.4 Simulated Intensity

#### 1) Orissa Super Cyclone-

The Figure-4.10-a shows the time series of the low level (900 hPa) maximum sustained wind predicted by CTL, QS, SSW, and MSW experiments. Figure-4.11-a shows the comparison of RMSE of 1"rd, 2"nd, and 3"rd day maximum surface wind prediction in all experiments of Orissa super cyclone. In CTL analysis, the intensity of Orissa Super cyclone is 19.34 m/s, where the observed (JTWC) intensity is 22.5 m/s. The intensity remained under predicted up to 1"st 30 hours. After 36 hours cyclone intensified rapidly and reached 75.3 m/s on 28 October 1200 UTC, where the observed intensity achieved the peak of 70 m/s at 1800 UTC 28 October. In CTL, RMSE of intensity for 1"st, 2"nd, and 3"rd day of simulation are 8.5 m/s, 7.6 m/s, 8.1 m/s respectively.

In QS analysis, the intensity of cyclone is 26 m/s. QS over predicted the intensity for 2"nd day simulation. On 1"st and 3"rd day it was closer to the observation. In QS RMSE of intensity prediction for the 1"st, 2"nd, and 3"rd day of simulation are 5.06 m/s, 12.30 m/s, and 5.35 m/s respectively.

In SSW analysis, the intensity of cyclone is 19 m/s. The RMSE of intensity prediction for the 1"st day is highest among all experiments i.e. 12.8 m/s. The intensity remained under predicted as compared to all the experiment up to 36 hours. On 2"nd and 3"rd day the RMSE are 9.3 m/s and 5.48 m/s. The peak intensity of 71.2 m/s is achieved at 1200 UTC 28 October.

In MSW analysis, the intensity of cyclone is improved to 20 m/s. After first 12 hour of simulation, MSW has over-predicted the intensity up to 42 hours. After 42 hour, it has under predicted the intensity up to 72 hours. The peak intensity of 66.3 m/s was attained on 1800 UTC 28 October. In QS RMSE of intensity simulation on 1"st, 2"nd, and 3"rd day of simulation are 5.60 m/s, 9.80 m/s, and 7.91 m/s respectively. This shows that on 1"st day
the errors in QS and MSW are comparable and smaller than other experiments. On the other hand, SSW has performed worst in intensity prediction among all the experiments. For 2\textsuperscript{nd} day all the experiments have performed poorer than CTL. So, looking to the 1\textsuperscript{st} and 2\textsuperscript{nd} day performance the QS and MSW has performed better than other experiments for intensity prediction of Orissa Super Cyclone.

![Graph](image)

**Figure-4.10:** Time series of maximum sustained wind at 900 hPa predicted in different experiments. a) Orissa Super Cyclone. b) Cyclone Gonu.
Figure 4.11: Daily RMSE of intensity prediction errors in all experiments for a) Orissa Super cyclone b) cyclone Gonu.
2) Gonu-

The Figure-4.10-b shows the time series of the low level (900 hPa) maximum sustained wind predicted by CTL, QS, MSW, and QMW experiments. Figure-4.11-b shows the comparison of RMSE of 1st, 2nd, and 3rd day maximum surface wind prediction in all experiments of cyclone Gonu. In CTL experiment the intensity of Gonu in initial condition on 0000 UTC 3 June is 22.62 m/s, while in JTWC observation it is 27.5 m/s. In observations there was a gradual rise in intensity after 1200 UTC 3 June but CTL showed such rise on 0600 UTC 4 June, that is 18 hours past the actual timing of intensification. In CTL simulation cyclone was most intense on 1200 UTC 5 June with maximum surface wind of 78.03 m/s which is 24 hour delayed and 10 m/s greater than observed maximum surface wind. The RMSE of intensity prediction on 1st, 2nd, and 3rd day of integration for CTL are 18.31, 20.12, and 22.13 respectively.

Overall in assimilation experiments, there is a slight improvement in the intensity of Gonu in initial condition. As we have seen, the assimilation of Meteosat wind data gives best improvement in surface wind speed in initial condition. In QS experiment the wind increased for 1st 18 hours similar to the observed pattern of intensification, but caused sudden fall in maximum wind at 1800 UTC 3 June. After here the cyclone intensified continuously up to 1200 UTC 5 June and attained the peak intensity of 70.77 m/s, almost same as observed intensity (70 m/s) although the timing of the simulated peak intensity is delayed by 24 hours. RMSE of intensity in 1st, 2nd, and 3rd day integration for QS are 20.41 m/s, 23.96 m/s, and 20.29 m/s respectively. These errors are higher for 1st and 2nd day as compared to the CTL.

In SSW experiment, the intensity in analysis is 20.7 m/s. The intensity remained under-predicted for the 1st 48 hour. On 1st and 2nd day the RMSE of intensity prediction are 16.7 and 19.4 respectively. The peak intensity is achieved at 0600 UTC 5 June, with an under estimation of 5.4 m/s. On 3rd day the intensity prediction of SSW is best among all experiments, with RMSE of 10 m/s. On 3rd day all experiments have over-predicted the intensity. Where as, in SSW the intensity is decreased because of early interaction with land due to landfall.
In MSW experiment, the intensity prediction is accurate up to first 12 hours. Similar to QS, at 18 hour sudden fall in intensity (Figure-4.10-b) affected the further prediction. The corresponding central sea level pressure (CSLP) also shows the rise of 3 hPa. Further, the cyclone intensified continuously to 72.01 m/s wind at 1200 UTC 5 June and corresponding CSLP is 940.01 hPa. RMSE errors on 1st, 2nd, and 3rd day integration for MSW are 11.81 m/s, 16.60 m/s, and 22.39 m/s respectively. This shows the assimilation of Meteosat AMV's resulted in more positive impact on intensity prediction compared to QuikSCAT surface winds.

4.5.5 Simulated Rainfall

The model has heavily over-predicted rainfall in all the experiments for Gonu and Orissa Super cyclone. Figure-4.12 shows the 72 hour (1200 UTC 26 October to 1200 UTC 29 October) accumulated rainfall of Orissa Super cyclone from TRMM 3B-42 product, CTL, QS, SSW, and MSW. The observed maximum rainfall from TRMM in this case is 39.5 cm. The CTL predicted very heavy rainfall of 92.5 cm. The experiment QS and SSW has improved rainfall prediction to maximum value 66.8 cm and 79 cm. In MSW experiment, the maximum accumulated rainfall is 56.4 cm, which is better than QS and SSW.

Figure-4.13 shows the 72 hour (0000 UTC 3 June to 0000 UTC 6 June) accumulated rainfall of cyclone Gonu from TRMM 3B-42 product, CTL, QS, SSW, and MSW. The performance of assimilation experiments is better than control simulation in Orissa Super cyclone case. Where as, in cyclone Gonu case except SSW, all assimilation experiments performed poorer. The TRMM 3B-42 observation shows the maximum value of 72 hour accumulated rainfall is 29.4 m/s. In control simulation, maximum rainfall is 59.9 cm. In QS, SSW, and MSW the accumulated rainfall amount increased to 68.6 cm, 53.6 cm, and 70.3 cm respectively.
Figure-4.12: Total accumulated rainfall (72 hour, 1200 UTC 26\textsuperscript{th} October to 1200 UTC 29\textsuperscript{th} October, 1999) simulation in different experiments of Orissa Super cyclone; a) TRMM 3B42 b) CTL c) QS d) SSW e) MSW.
Figure-4.13: Total accumulated rainfall (72 hour, 0000 UTC 3rd June to 0000 UTC 6th June, 2007) simulation in different experiments of cyclone Gonu; a) TRMM 3B42 b) CTL c) QS d) SSW e) MSW.
Discussion: The QuikSCAT wind shows consistent positive impact on track simulation for both the cyclone cases. The SSM/I winds have shown improvement in track of Orissa Super cyclone. For cyclone Gonu the SSM/I winds has reduced accuracy below control experiment. Impact of Meteosat AMVs on the track simulation is exactly opposite in the two cyclones. It performed extremely well in case of Orissa Super cyclone and remained best among all experiments. Where as, it performed worst in track prediction among all the experiment in case of cyclone Gonu. Though, the impact of Meteosat AMVs is not consistent, the results show that the cyclone track simulation is highly sensitive to the AMVs.

In all the experiments, Orissa Super cyclone and cyclone Gonu have nearly achieved the observed maximum intensity. But, the time of attaining maximum intensity is not correct in most of the experiments. The intensity remained under predicted in the initial phase of all the experiments, and after achieving maximum the intensity is over-predicted in decaying phase. The QuikSCAT winds assimilation has shown improvement in intensity prediction for Orissa Super cyclone. But, the performance of QS in intensity prediction is worst in case of cyclone Gonu. The SSM/I winds assimilation show poor intensity prediction in case of Orissa Super cyclone. The improvement in intensity prediction shown by assimilation of SSM/I winds in case of Gonu is because of the early landfall has reduced the intensity of cyclone due to land interaction and brought intensity towards observation, while other experiments have over predicted the intensity on 3rd day integration. So, this improvement shown by the SSM/I winds for cyclone Gonu is not appropriate. The assimilation of Meteosat AMVs made significant improvement in intensity prediction of Orissa Super cyclone and cyclone Gonu. The assimilation of Meteosat AMVs has improved the upper level divergence. This improvement gave result in the improvement in lower level convergence and hence the improvement in intensity prediction.

As compared to SSM/I the QuikSCAT winds assimilation show better potential for the improvement of track and intensity prediction. This may be due to the following reasons. First, the QuikSCAT measurements are slightly less sensitive to precipitation (particularly light precipitation) as compared to SSM/I measurements. As a result
QuikSCAT observations are available over large area of the cyclone than SSM/I (Figure-4.3 and Figure-4.4). Second, the QuikSCAT has additional information of wind direction. Meteosat AMVs show consistent positive impact on the intensity prediction.

The sudden fall of intensity is observed in QS and MSW experiment at few places (Figure-4.10-b) and this has reduced the performance in the intensity prediction. Especially for QS experiment in cyclone Gonu case the performance in intensity prediction is poorer than the control simulation for 1st 48 hours. It is found that this happened because of increase in vertical wind shear. This increase in the vertical wind shear leads to increase in the asymmetry of cyclone and hence reduced the divergence at upper level (Figure-4.14). The temperature distribution area at upper level is increased in experiment QS and MSW as compared to the CTL experiment (Figure-4.15). This asymmetry ultimately affected the track and intensity prediction of tropical cyclones. This may be the reason, why assimilation of Meteosat AMVs have performed very well in track prediction of Super cyclone but worst in case of cyclone Gonu. So these asymmetries should have reduced the intensity of cyclone Gonu in MSW experiment as compared to the CTL experiment at all other times. But, the increased amount of rainfall in experiments have produced extra heating in the upper level (Figure-4.15), this has increased the divergence at upper level and hence the intensity. But, the asymmetries have increased the errors in track prediction. This shows that the individual assimilation of QuikSCAT surface winds and Meteosat multilevel AMVs some times doesn't give improvements in vertical wind structure of atmosphere. Hence, in next experiment we have done combined assimilation of QuikSCAT surface winds and Meteosat AMVs.
Figure-4.14: Wind magnitude of cyclone (shaded) at 300 hPa and wind stream lines at 900 hPa of 1800 UTC 3 June 2007 a) CTL b) QS.
Figure-4.15: Wind magnitude of cyclone Gonu (shaded) at 300 hPa and wind stream lines at 900 hPa of 1800 UTC 3 June 2007 a) CTL b) QS.
4.6 Combined Impact of QuikSCAT and Meteosat Winds assimilation.

We have seen in previous section that QuikSCAT wind Meteosat AMVs performs better than SSM/I winds in cyclone prediction. We have also found that the individual assimilation of QuikSCAT surface winds and Meteosat AMVs of different atmospheric level does not give consistent improvement in wind structure of atmosphere. In this section we have studied the impact of combined assimilation of the surface wind from QuikSCAT and Meteosat AMVs of different levels. The methodology of the experiment is same as explained in section-4.3.

The simulations are carried out using WRF model and 3DVar assimilation technique. The two cyclones studied are Orissa Super cyclone and cyclone Gonu. The domains of study are similar to the domains described in previous experiments. In this experiment (QMW) the data sets assimilated are radiosonde data, QuikSCAT winds, and Meteosat AMVs (Table-4.1). The other experimental details are similar to described in section-4.3. The results of experiment are compared with the observations and CTL experiment in the following section.

4.6.1 Initial Conditions

1) Orissa Super Cyclone-

Figure-4.16 shows the circulation pattern and wind magnitude at 950 hPa in the initial condition of CTL, and QMW experiments. Table-4.2 summaries the vortex position errors, and surface maximum wind magnitude at 950 hPa in initial conditions. The observed position of vortex at 1200 UTC 26 October 1999 was (93.9N, 15.0E). The vortex position error in the initial condition of CTL and QMW are 139.1 Km and 142.8 Km respectively. The combined assimilation of QuikSCAT wind and Meteosat AMVs has negative impact on the vortex position in analysis. The observed surface maximum wind at 1200 UTC 26 October 1999 was 22.5 m/s.
The maximum surface wind in the initial condition of CTL and QMW are 19.34 m/s and 21.9 m/s respectively. Combine impact of surface wind and AMVs have brought the intensity very close to the observation in the QMW analysis.

The winds at 950 hPa of all the initial conditions (1200 UTC) compared with the common observation i.e. SSM/I surface wind observation (1137 UTC) to estimate the impact of respective observation’s assimilation on the surface wind fields in the different analysis. The RMSE of surface winds in the CTL and QMW analysis are 3.44 m/s and 2.5 m/s respectively. The combined assimilation of Meteosat and QuikSCAT winds has reduced the RMSE in QMW analysis as compared to the CTL analysis. The correlation coefficients for the wind in CTL and QMW analysis with SSM/I observation are 0.31 and 0.54 respectively. The bias (observation-analysis) of wind in CTL and QMW analysis are 1.15 m/s and 1.39 m/s respectively. The combined impact of the QuikSCAT wind and Meteosat wind improved the surface wind field in model analysis of QMW experiment.
Figure-4.17 shows the circulation pattern and wind magnitude at 950 hPa in the initial conditions of experiment CTL and QMW. Table-4.3 summaries the vortex position errors, and surface maximum wind magnitude at 950 hPa in the initial conditions. The observed position of vortex on 0000 UTC 3 June 2007 was (67.40 N, 16.10 E). The error of vortex position in the initial condition of CTL and QMW are 111.20 Km and 47.8 Km respectively. The combined assimilation of Meteosat and QuikSCAT winds has improved the position of vortex in the initial condition.

Figure-4.17: 950 hPa wind field valid at 0000 UTC 03 June 2007 for, a) CTL b) QMW.

The observed surface maximum wind at 0000 UTC 3 June 2007 is 27.5 m/s. The maximum surface wind in the initial condition of CTL and QMW are 22.6 m/s and 25.7 m/s respectively. Combined impact of surface and upper level winds has brought the intensity very close to the observation in the QMW analysis. The winds at 950 hPa of all the initial conditions (1200 UTC) are compared with the common observation i.e. SSM/I surface wind observation (0112 UTC) to get the impact of respective observations assimilation on the surface wind field. The RMSE of surface winds in the CTL is 4.1 m/s, combined assimilation of winds in QMW analysis has reduced it to 3.7 m/s
respectively. The correlation coefficients for the wind in CTL and QMW analysis are 0.65 and 0.81 respectively. The bias (observation-analysis) of surface wind in CTL and QMW analysis are -0.52 m/s and -0.60 m/s respectively.

4.6.2 Simulated Tracks

1) Orissa Super Cyclone-

The JTWC observed and simulated tracks (CTL, QMW experiment) of Orissa Super cyclone are shown in Figure-4.18-a. In QMW experiment, the combine effect of both data sets have increased the error to 141.8 Km. Similar to MSW, the track errors reduced in subsequent simulation dramatically (Figure-4.18-b). The mean errors of 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd} day track simulation in QMW are 82.4 Km, 50.8 Km, and 41.2 Km respectively (Figure-4.18-c). For CTL experiment the 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd} day mean track errors are 136.9 Km, 131.9 Km, and 344.7 Km respectively. QMW has very accurately simulated the landfall of Orissa super cyclone with an error of 29.4 Km in position and 00 hour in the timing. The errors of track in QMW experiment are found to be least among all the experiments for Orissa Super cyclone. The improvements shown by individual assimilation of QuikSCAT and Meteosat wind has enhanced in combined assimilation.

2) Gonu:

The observed and simulated tracks (CTL, QMW experiment) of cyclone Gonu are shown in Figure-4.19-a. In QMW initial condition the vortex position error is 47.70 Km. The mean error of 1\textsuperscript{st} day track is 153.10 Km. On 2\textsuperscript{nd} day the mean error reduced to 90.37 Km. Up to here the track is in good agreement with the observations, but on third day the cyclone showed slight northward movement. At the end of 3rd day integration, error increased to 145 Km (Figure-4.19-b). In CTL experiment mean track error for 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd} day simulation are 92.27 Km, 63.5 Km, and 162.60 Km respectively (Figure-4.19-c). The cyclone remained north of the Oman, 145 Km away from landfall point on 0000 UTC 6 June 2007. The combine assimilation has improved the accuracy as compared to the MSW experiment, but the errors are higher than CTL experiment for 1\textsuperscript{st} and 2\textsuperscript{nd} day. The errors in 1\textsuperscript{st} and 2\textsuperscript{nd} day are due to slow motion predicted by QMW
Figure 4.18: a) 72-h simulated tracks of Orissa Super cyclone (from 1200 UTC 26 October 1999) in CTL and QMW experiment. b) Time series of errors in track simulation. c) Daily mean of track prediction errors in all experiments for Orissa Super cyclone.
Figure-4.19: a) 72-h simulated tracks of cyclone Gonu (from 0000 UTC 03 June 2007) in CTL and QMW experiment. b) Time series of errors in track simulation. c) Daily mean of track prediction errors in all experiments for Orissa Super cyclone.
experiment. The performance of QMW in track prediction remained less accurate than QS.

4.6.3 Simulated Intensity

1) Orisa Super cyclone

Figure-4.20-a shows the time series of intensity observed and simulated in CTL and QMW experiments. In QMW analysis, the intensity of cyclone is 21.9 m/s, very close to observation. However, the intensity remained under predicted on 1st and 2nd day simulation (Figure-4.20-b).

Figure-4.20: a) Time series of maximum sustained wind at 900 hPa of Orissa super cyclone predicted in CTL and QMW. b) Daily RMSE of intensity prediction
The RMSE of intensity for 1st and 2nd day of simulation are 11.20 m/s and 11.20 m/s respectively. The intensity increased drastically on 3rd day and attained the peak of 75.86 m/s on 0000 UTC 29 October. The intensity predictions on 3rd day remain very close to the observation with RMSE of 3.28 m/s. In CTL experiment RMSE of intensity for 1st, 2nd, and 3rd day of simulation are 8.5 m/s, 7.6 m/s, and 8.1 m/s respectively. The intensity prediction of QMW is poorer for 1st and 2nd day than CTL experiment.

**Figure-4.21:** a) Time series of maximum sustained wind at 900 hPa of cyclone Gonu predicted in CTL and QMW. b) Daily RMSE of intensity prediction.
2) Gonu

Figure-4.21-a shows the time series of observed intensity and simulated intensity for CTL and QMW experiments. In QMW experiment, the intensity increased continuously with time and attained 65 m/s wind on 1200 UTC 4 June, when the observed intensity reached to its maximum i.e. 70 m/s (Figure-4.21-b). No other experiment have attended this much accuracy in intensity prediction. The cyclone intensified further to 73.48 m/s on 1200 UTC 5 June and corresponding CSLP is 939.14 hPa. RMSE of intensity on 1st, 2nd, and 3rd day of integration for QMW are 14.47 m/s, 14.58 m/s, and 22.33 m/s respectively. The RMSE of intensity prediction on 1st, 2nd, and 3rd day of integration for CTL are 18.31 m/s, 20.12 m/s, and 22.13 m/s respectively. The performance of QMW in intensity prediction is better than CTL and QS, and it is comparable to the MSW.

4.6.4 Simulated Rainfall

Figure-4.22 shows the 72 hour (1200 UTC 26 October to 1200 UTC 29 October) accumulated rainfall of Orissa Super cyclone from TRMM 3B42 product, and CTL and QMW simulations. The observed maximum rainfall from TRMM in this case is 39.5 cm. The CTL predicted very heavy rainfall with maximum of 92.5 cm. The QMW has improved the rainfall prediction, and reduced the maximum value to 55.4 cm. This improvement is much better than the QS and MSW.

Figure-4.23 shows the 72 hour (0000 UTC 3 June to 0000 UTC 6 June) accumulated rainfall of cyclone Gonu. The TRMM 3B42 observation shows that the maximum value of 72 hour accumulated rainfall is 29.4 cm. In control simulation, maximum rainfall is 59.9 cm. The performance of QMW in rainfall prediction is poorer than the CTL. The maximum value of accumulated rainfall amount increased to 69.0 cm. The combined assimilation of wind could not improve the rainfall in case of cyclone Gonu.

Discussion: The combined assimilation of winds shows consistent improvement in intensity in the analysis for both cyclone cases. But, it shows uncertainty in fixing the
Figure-4.22: Total accumulated rainfall (72 hour, 1200 UTC 26\textsuperscript{th} October to 1200 UTC 29\textsuperscript{th} October, 1999) simulation in different experiments of Orissa Super cyclone; a) TRMM 3B42 b) CTL c) QMW.
Figure 4.23: Total accumulated rainfall (72 hour, 0000 UTC 3\textsuperscript{rd} June to 0000 UTC 6\textsuperscript{th} June, 2007) simulation in different experiments of cyclone Gonu; a) TRMM 3B42 b) CTL c) QMW.
position of vortex. This uncertainty may be due to Meteosat winds, as we have seen in the MSW experiments in previous section. Because of the lack of surface wind information, Meteosat wind can’t always improve the surface vortex position, but the improvement in surface wind magnitude of MSW analysis is because of improvement in the divergence at upper levels. The analysis of Gonu in QMW experiment shows that the Meteosat upper level winds assimilation has stronger impact on the surface vortex field compared to the QuikSCAT surface winds.

We have assimilated the QuikSCAT winds and Meteosat AMVs with the expectation that it will improve the atmospheric wind field at surface as well as at upper levels in the analysis. But, we found that the combined assimilation of winds has improved the track and intensity some times but some times it has negative impact also. The combined assimilation of surface and multilevel winds showed significant improvement in intensity prediction than their individual impact. The Meteosat AMVs are found to be more significant in intensity prediction. The uncertainty of Meteosat AMVs impact in track prediction can be due to the error of height assignment associated with the AMVs. We found that the assimilation Meteosat AMVs has stronger influence on the surface wind and vortex position of cyclone compared to the QuikSCAT winds assimilation in the analysis. The results showed that the Meteosat wind remain dominant in all the results. The track and intensity are more sensitive to the upper level winds than the surface winds.

This sensitivity shown by track simulation of tropical cyclones to the Meteosat AMVs assimilation may because of the following reasons. Divergence term can play an important role in determining the vorticity tendency and tropical cyclone motion has been identified the maximum local change in relative vorticity as the future position of the cyclone (Chan 1984). The observational studies by Geoge and Grray (1976), Brand et al. (1981), and Chan and Gray (1982) reported that, divergence term is one important factor which causes the cyclone to move in slightly different manner (both in speed and direction) with respect to its surrounding flow. Thus, any change in the divergence representation in analysis can result in to an entirely different track. The Meteosat AMVs assimilation has impact on the divergence at upper level. One has to be very careful
while assimilating Meteosat AMVs, as it has large errors associated with direction and height.

4.7 Impact of SSM/I water vapor assimilation.

It is well known now that atmospheric moisture is crucial to the evolution of severe weather systems because of its potential to release large amounts of latent heat (Xiao et al. 2002; Chen et al. 2004). Therefore, uncertainties in the initial condition of humidity field in numerical weather prediction models could have a significant impact on weather forecasts. These uncertainties can be reduced through the use of accurate humidity observations in model initialization. The conventional observational network of the World Meteorological Organization (WMO) (e.g., upper air radiosonde and surface stations) provides moisture observations, but these are mostly distributed over land with soundings usually available only twice a day. This is insufficient to sample the rapidly evolving environment of marine weather systems, such as tropical cyclones, adequately. Non-conventional observations, such as satellite data, on the other hand, can provide spatially dense information with high frequency. Satellite measurements of water vapor could be a useful source of additional humidity information in analyses over oceans, where the conventional measurements (radiosonde and meteorological station) are very sparse. There are several satellite instruments that measure atmospheric moisture including the Advanced Microwave Sounding Unit (AMSO-B), humidity sounder (English et al. 1994; Rosenkranz 2001), the High-resolution Infrared Radiation Sounder (HIRS) (McNally and Vesperini 1996; Derber and Wu 1998; Engelen and Stephens 1999; Escoffier et al. 2001), Special Sensor Microwave/Imager (SSM/I), and Moderate Resolution Imaging Spectrometer (MODIS).

In the present study, our purpose is to assess the impact of assimilation total precipitable water vapour from SSM/I (TPW) on the simulation of north Indian Ocean tropical cyclones. The cyclones studied are the Orissa super cyclone (October 1999, bay of Bengal) and tropical cyclone Gonu (June 2007, Arabian Sea) (discussed in section 4.2). The SSM/I TPW observation description is given in section 4.4.2. The SSM/I TPW
observations are available for Orissa Super cyclone on 1137 UTC 26 October 1999 and for cyclone Gonu on 0112 UTC 3 June 2007 (Figure-4.24).

Figure-4.24: The SSM/I total precipitable water vapor observation of a) 1137 UTC 26 October 1999 and b) 0112 UTC 3 June 2007

The domains of study were similar to the domains described in previous section (Figure-4.1 and 4.2). In this experiment (SWV) the data sets assimilated (Table-4.1) are radiosonde and SSM/I TPW (Figure-4.24) observations. The other experimental details are similar as described in section-4.4.2. The results of experiment were compared with the observations and CTL experiment in the following section.

4.7.1 Initial Conditions

I) Orissa Super Cyclone-

In order to see the agreement between SSM/I TPW observation (O) and first guess (B) TPW, we have compared these two products. Comparison showed that the two products differ significantly with the RMSE of 0.3 gm/cm². The RMSE (0.06 gm/cm²) of the SSW analysis (A) and SSM/I TPW observation (O) is less than the RMSE of observation and first guess. The correlation coefficients for the wind in CTL and SWV analysis with
SSM/I observation are 0.31 and 0.48 respectively. The bias (observation-analysis) of wind in CTL and SWV analysis were 1.15 m/s and 1.45 m/s respectively. The relative humidity has decreased in the SWV analysis near cyclonic circulations and center, at almost all the levels. The relative humidity of 700 hPa and 850 hPa in CTL and SWV analysis are shown in Figure-4.25.

Figure-4.25: Relative humidity for Orissa Super cyclone in analysis. (a) CTL (700 hPa), (b) SWV (700 hPa), (c) CTL (850 hPa), and (d) SWV (850 hPa).
Figure-4.26: 950 hPa wind field valid at 1200 UTC 26 October 1999 for, a) CTL b) SWV analysis.

Figure-4.26: 950 hPa wind field valid at 1200 UTC 26 October 1999 for, a) CTL b) SWV analysis.
Figure-4.26 shows the circulation pattern and wind magnitude at 950 hPa in the initial condition of CTL, and SWV experiments. The wind circulation patterns in SWV analysis remain almost same as in CTL analysis. Table-4.2 summaries the vortex position errors, and surface maximum wind magnitude at 950 hPa in the initial conditions. The error of vortex position in the CTL analysis is 139.18 Km. The vortex position error is slightly increased in SWV analysis to 141.2 Km. The intensity in CTL analysis is 19.34 m/s, where as the observed intensity at initial time is 22.5 m/s. The assimilation of TPW in SWV has increased the error by reducing intensity to 18.75 m/s. The wind circulation pattern of CTL and SWV analysis (Figure-4.26) were almost similar.

2) Cyclone Gonu

Figure-4.27 shows the circulation pattern and wind magnitude at 950 hPa in the initial condition of CTL, and SWV experiments. The error of vortex position in the CTL analysis is 110.7 Km (Table-4.3). The assimilation of SSM/I TPW increased the vortex position to 123.5 Km. The intensity in CTL analysis is 22.6 m/s, where the observed intensity is 27.5 m/s. The SWV has reduced intensity to 21.1 m/s.

Comparison of SSM/I TPW and TPW from first guess shows that the two products differ significantly with the RMSE of 0.35 gm/cm². The RMSE (0.02 gm/cm²) of the SSW analysis (A) and SSM/I TPW observation (O) was less than the RMSE of observation and first guess. The correlation coefficients for the surface wind in CTL and SWV analysis with SSM/I observation are 0.65 and 0.57 respectively. The bias (observation-analysis) of surface winds in CTL and SWV analysis with SSM/I winds are 0.52 m/s and 0.40 m/s respectively. The assimilation of SSM/I TPW reduced accuracy of the wind field in the SWV analysis. The relative humidity is reduced at almost all the levels in the SWV analysis near cyclonic circulations and center. The relative humidity of 700 hPa and 850 hPa in CTL and SWV analysis are shown in Figure-4.28. This reduced humidity at the center of cyclonic circulation in the SWV analysis may be the reason for weakening of intensity in SWV analysis for both the cyclone cases. The drying at mid-tropospheric level can increase the evaporation of liquid water in and around cumulonimbus clouds. This could lead to the reduction in intensity of cyclone.
Figure-4.27: 950 hPa wind field valid at 0000 UTC 3 June 2007 for, a) CTL b) SWV analysis.
Figure-4.28: Relative humidity for cyclone Gonu in analysis. (a) CTL (700 hPa), (b) SWV (700 hPa), (c) CTL (850 hPa), and (d) SWV (850 hPa).
4.7.2 Simulated Track

1) Orissa Super Cyclone:

The observed and simulated tracks (CTL, SWV experiment) of Orissa Super cyclone are shown in Figure-4.29-a. The vortex position error is increased in the SWV analysis. For the 1\textsuperscript{st} and 2\textsuperscript{nd} day simulation, the mean track error of SWV and CTL were comparable (Figure-4.29-c). On 1\textsuperscript{st} and 2\textsuperscript{nd} day mean track errors of CTL experiment are 136.9 Km and 131.5 Km respectively. For SWV experiment the 1\textsuperscript{st} and 2\textsuperscript{nd} day mean track error are 136.7 Km and 132.9 Km respectively. On third day SWV simulation shows improvement in track as compared to CTL experiment (Figure-4.29). For 3\textsuperscript{rd} day, the mean track errors of CTL and SWV experiments are 344.7 Km and 154.1 Km. The SWV experiment could not predicted the landfall of Orissa Super cyclone (Figure-4.29-a).

2) Cyclone Gonu

The JTWC observed and simulated tracks (CTL, SWV experiment) of cyclone Gonu are shown in Figure-4.30. The vortex position error is higher in the SWV analysis compared to CTL analysis. On 1\textsuperscript{st} day the mean track simulation error is higher in SWV than CTL i.e. 92.2 Km and 98.7 Km respectively (Figure-4.30-c). The SWV prediction improved for the 2\textsuperscript{nd} and 3\textsuperscript{rd} day (Figure-4.30-b). For CTL mean track prediction error for 1\textsuperscript{st} and 2\textsuperscript{nd} day were 62.5 Km and 162.6 Km respectively. For SWV experiment the error for 1\textsuperscript{st} and 2\textsuperscript{nd} day mean track prediction are 31.9 Km and 82.9 Km respectively. The SWV experiment has predicted the landfall of cyclone Gonu with better accuracy. The error in SWV simulated landfall position is 88.4 Km and the error in landfall time is 06 hour (early).

4.7.3 Simulated Intensity

1) Orissa Super Cyclone

The time series of observed intensity and simulated for CTL and SWV experiments are shown in Figure-4.31-a. The accuracy of intensity prediction of Orissa super cyclone has reduced after SSM/I TPW assimilation (Figure-4.31-b). The SWV has reduced the inten-
Figure 4.29: Orissa super cyclone: a) 72-h simulated tracks (from 1200 UTC 29 October 1999) in CTL, SWV experiment and observed track from JTWC. b) Time series of errors in track position. c) Daily mean of track prediction errors.
Figure 4.30: cyclone Gonu: 

a) 72-h simulated tracks (from 0000 UTC 3 Jun 2007) in CTL, SWV experiment and observed track from JTWC. 

b) Time series of errors in track position. 

c) Daily mean of track prediction errors.
Figure 4.31: a) Time series of maximum sustained wind at 900 hPa predicted in different experiments of cyclone Orissa Super cyclone. b) Daily RMSE of intensity prediction errors in all experiments for cyclone Orissa Super cyclone.
nsity for 1st 36 hours, which is already under predicted in the CTL experiment. SWV has attained the peak of maximum sustained wind of 76.3 m/s at 1800 UTC 28 October 1999. Where as, the observed peak intensity is 70 m/s. The CTL attained peak of wind intensity at 75.3 m/s. The RMSE of intensity prediction in CTL for 1st and 2nd day was 8 m/s and 7m/s respectively. The RMSE of intensity prediction was increased in SWV to 10.7 m/s 7.7 m/s. On 3rd day the RMSE of intensity are comparable in CTL and SWV i.e. 6.3 m/s and 6.5 m/s respectively.

2) Cyclone Gonu

The time series of observed intensity and simulated by CTL and SWV are shown in Figure-4.32-a. Similar to the Orissa Super cyclone, SWV performed poorer in intensity prediction for cyclone Gonu. Overall SWV has highly under predicted the intensity for 1st 54 hours, and attained peak intensity of 65.5 m/s, with an error of 4.5 m/s and 30 hours delay in timing (Figure-4.32-b). The RMSE of 1st, 2nd, and 3rd day intensity simulation in CTL are 18.3 m/s, 20.1 m/s, and 22.1 m/s respectively. The RMSE of 1st, 2nd, and 3rd day intensity simulation in SWV are 20.3 m/s, 36.0 m/s, and 17.1 m/s respectively. The RMSE in SWV are higher than CTL except for 3rd day (Figure-4.32-b).

4.7.4 Simulated Rainfall

Figure-4.33 shows the 72 hour (1200 UTC 26 October to 1200 UTC 29 October) accumulated rainfall of Orissa Super cyclone from TRMM 3B-42 product, CTL, SWV. The observed maximum amount of total accumulated rainfall from TRMM in this case was 39.5 cm. The CTL experiment predicted very heavy amount total accumulated rainfall, with maximum of 92.5 cm. The SWV has improved rainfall prediction to maximum value 79.3 cm. The assimilation of SSM/I TPW has improved the rainfall for Orissa super cyclone.

Figure-4.34 shows the 72 hour (0000 UTC 3 June to 0000 UTC 6 June) accumulated rainfall of cyclone Gonu. The TRMM 3B-42 observation shows the maximum value of 72 hour accumulated rainfall is 29.4 m/s. In control simulation, maximum of total accumulated rainfall is 59.9 cm. In SWV the accumulated rainfall amount increased to
75.7 cm respectively. The assimilation of SSM/I TPW has increased the error in rainfall for cyclone Gonu.

**Figure-4.32:** a) Time series of maximum sustained wind at 900 hPa predicted in CTL and SWV experiments of cyclone Gonu. b) Daily RMSE of intensity prediction errors in all experiments for cyclone Gonu.
Figure-4.33: Total accumulated rainfall (72 hour, 1200 UTC 26th October to 1200 UTC 29th October, 1999) simulation in different experiments of Orissa Super cyclone; a) TRMM 3B42 b) CTL c) SWV
Figure-4.34: Total accumulated rainfall (72 hour, 0000 UTC 3\textsuperscript{rd} June to 0000 UTC 6\textsuperscript{th} June, 2007) simulation in different experiments of cyclone Gonu; a) TRMM 3B42 b) CTL c) SWV
**Discussion:** The assimilation of SSM/I TPW observations gives negative impact on the vortex position and maximum sustained wind in the SWV analysis for both the cyclone cases. Despite of this increased vortex position error, the SSM/I TPW assimilation consistently showed significant improvement in the track prediction of both the cyclones. But, the assimilation of SSM/I TPW has shown the negative impact on intensity of both cyclones cases, in analysis and prediction. Chen et al. (2007) and Singh et al. (2007) got the similar results on assimilation of SSM/I TPW for intensity prediction of cyclones. This negative impact of TPW on intensity prediction in SSW experiments may be because of the drying of mid-tropospheric level (700 hPa, Figure-4.26 and 4.28) near cyclonic region. This drying has increased the evaporation of liquid water in the cloud, which has reduced the temperature of the region and has ultimately affected the intensification process. Further the decreased intensity at lower-troposphere (850 hPa, Figure-4.26 and 4.28) has reduced the supply of moisture from surface and as well as the rate of intensification process in the subsequent simulation.

### 4.8 Summary

In this chapter we have studied the impact of various satellite observations assimilation on the simulation of two Indian ocean tropical cyclones. The WRF model was used for the simulation of cyclones and a three dimensional variational assimilation technique was used for the data assimilation. The cyclones studied are Orissa Super cyclone formed over bay of Bengal in October 1999, and cyclone Gonu formed over Arabian sea in June 2007. The experiments include assimilation of, QuikSCAT winds, SSM/I winds, Meteosat AMVs, combined QuikSCAT and Meteosat winds, SSM/I TPW. These observations are assimilated along with the radiosonde observations. The performances of all experiments were compared with the control experiment in which only radiosonde observation was assimilated. The NCEP analysis was used for the boundary conditions and a 6 hour simulation using initial condition from NCEP analysis was used as first guess for assimilation. The results of different experiments can be summarized as follows:
i) The assimilation of surface winds from QuikSCAT and SSM/I improved the vortex position of cyclone in the initial condition, but the improvement by QuikSCAT is better than the SSM/I winds assimilation due to lack of wind direction information in SSM/I observations. The SSM/I winds show negative impact on the intensity in the initial condition. The QuikSCAT winds improve intensity in the initial condition. The assimilation of Meteosat AMVs shows small improvement in vortex position for cyclone Gonu, but it gives negative impact in case of Orissa super cyclone. Meteosat AMVs improve intensity in the initial condition, this improvement is better than that showed by QuikSCAT winds. The combined assimilation of QuikSCAT and Meteosat winds have negative impact on the vortex position in the analysis. The assimilation of SSM/I total precipitable water vapour has dried the environment near cyclonic circulation at all the levels. This caused the reduction of intensity of cyclone in the analysis. SSM/I TPW assimilation has underestimated the cyclone intensity in the analysis. SSM/I TPW have also reduced the accuracy of vortex position in the analysis.

ii) The QuikSCAT winds assimilation shows consistent positive impact on the track simulation of tropical cyclones. The SSM/I winds are found to be inconsistent in track improvement. In surface winds assimilation, the QuikSCAT wind performs better than SSM/I winds. The assimilation of Meteosat AMVs also shows uncertainty in the track simulation. The assimilation of SSM/I water vapour shown positive impact on the cyclone track simulation. The combined impact of QuikSCAT and Meteosat winds found to be beneficial for track prediction only when their individual assimilation also give positive improvement. Meteosat AMVs have shown consistent significant improvement in the intensity prediction of cyclone. The QuikSCAT winds do not show much promising result in intensity prediction. Where as the SSM/I winds and water vapour assimilation shows negative impact on the intensity prediction in their respective experiment. The combined assimilation of QuikSCAT and Meteosat winds shows positive impact on the intensity prediction. This shows that the QuikSCAT winds and SSM/I water vapour are the only observations, which have consistent positive impact on the track simulation. And the Meteosat AMVs is the only observation having consistent positive impact on intensity simulation.