SIMULATING THE TROPICAL CYCLONE 'HUDHUD' USING SKILL SCORES OF WRF MODEL

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree
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CANDIDATE DECLARATION

I hereby declare that the work, that is being presented in this dissertation is an authentic and genuine display of my work done and results obtained in due period of June 2014 – April 2015 under the joint supervision of Dr. Kamal Jain, Professor, Department of Civil Engineering, Indian Institute of Technology- Roorkee, Roorkee and Dr. Someshwar Das, Scientist-G/Project Director, India Meteorological Department, New Delhi.

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CERTIFICATE

This is to certify that the above mentioned statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

The North India Ocean Basin which homes the Bay of Bengal and the Arabian Sea is said to be relatively calm zone when assessed on the basis of frequency of cyclones occurrence. But, when the statistics about severity and damages are considered the scenario is absolute the opposite. Major cyclones of North Indian Ocean that incepted in the year 2014 were VSCS Hudhud and VSCS Nilofar.

In this study the present Cyclone Mitigation Framework of the country is analyzed to understand the scope of disaster management in domain of cyclones. The work also includes post event numerical simulation of VSCS Hudhud using mesoscale modelling (WRF-ARW) for predicting most possible accurate course and life history. For the purpose of simulation, five set of initial conditions i.e. 00 UTC of 7th October, 8th October, 9th October, 10th October and 11th October of 2014 are selected to cover entire life span of event i.e. 7th – 14th October, 2014. Initial and boundary conditions are provided by GFS analysis field, sources being IMD-GFS and NCEP-GFS.

Verification of the results illustrates Direct Position Error (DPE) error to be in range of 49 Km-310 Km and Intensity error between 7.6 knots-16 knots. Performance of WRF-ARW was found skillful when NCEP- GFS was employed for initial and boundary condition.

.....Off course it's Family

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Ankur Srivastava

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ACRONYMS

AIR	All India Radio
AMV	Atmospheric Motion Vectors
ARW	Advance Research WRF
AWS	Automatic Weather Station
BAS	Bias Score
BMTPC	Building Materials and Technology Promotion Council
BOB	Bay of Bengal
CS	Cyclonic Storm
CWDS	Cyclone Warning Dissemination System
D	Depression
DD	Deep Depression
DPE	Direct Position Error
EWS	Early Warning System
FAR	False Alarm Rate
GFS	Global Forecast System
GMDSS	Global Maritime Distress Safety System
GPFS	General Parallel File System
GUI	Graphical User Interface
HR	Hit Ratio
IBC	Initial and Boundary Condition
IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
IVRS	Interactive Voice Response System
LMC	Last Mile Connectivity
MSLP	Minimum Sea Level Pressure
MSW	Maximum Sustained Wind
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction

NCL	NCAR Command Language
NCRMP	National Cyclone Risk Mitigation Project
NDMA	National Disaster Management Authority
NIO	North Indian Ocean
NWP	Numerical Weather Prediction
PMSS	Peak Most Storm Surge
POD	Probability of Detection
RMSE	Root Mean Square Error
SCS	Severe Cyclonic Storm
SDMC	SAARC Disaster Management Cell
SLP	Sea Level Pressure
SMRC	SAARC Meteorological Regional Centre
SOP	Standard Operation Procedure
TC	Tropical Cyclone
TS	Threat Score
USGS	United States Geological Survey
UTC	Universal Time Co-ordinates
VSCS	Very Severe Cyclonic Storm
WMO	World Meteorological Department
WPS	WRF Preprocessing System
WRF	Weather Research and Forecasting

1. INTRODUCTION

The 5400 km stretch coastline of mainland India is prone to some of the calamitous disaster events including storms, tsunamis, cyclones, flooding, tides, waterspouts, Nor'easters and storm surge. Tsunami and cyclones are comparatively more cataclysmic among the mentioned above. Although the North Indian Ocean (NIO) Basin generates about 7% of global total cyclone, their devastating effect and catastrophic sway in the region has drawn copious prominence and attention. In the previous 300 years, 21 of the 23 major cyclones causing fatalities greater than 10,000 incepted over the regions covering Indian subcontinent.

1.1 System Overview

1.1.1 Terminology

A "Cyclone" is a swirl in the aerosphere with high velocity gale surrounding the low pressure region in a counter-clockwise orientation in Northern Hemisphere and in opposite direction in the Southern Hemisphere. The terminology "Cyclone" was propagated by Henri Paddington, to whom the tropical storms in the North Indian Ocean (NIO) basin appeared like the coiled serpents of the Sea. "Cyclos" means coil of snake in Greek hence named 'Cyclones'. Cyclones are named as 'Hurricanes' over Atlantic Ocean and 'Typhoons' over Pacific Ocean.

Tropical cyclone (TC) can also be defined as a tropical meteorological system of low pressure area, in which winds whirl at speed exceeding 34 knots (62 kmph). In the process pressure increases outwards from the center. The margin of decrease in pressure at the middle position of system and the strength of the wind gives the intensity of the cyclones.

1.1.2 Classification

The categorization utilised by India Meteorological Department (IMD) for classification of low pressure disturbances in the Bay of Bengal and in the Arabian Sea is on the basis of the associated Maximum Sustained Wind (MSW) at the land surface level (Mohapatra, 2014). As depicted by Table 1, the low pressure system with intensity level of depression and greater are coined as cyclonic disturbances.

Type of disturbance	Associated MSW
1. Low Pressure	Not exceeding 17 knots (<31 kmph)
2. Depression	17 to 27 knots (31-49 kmph)
3. Deep Depression	28 to 33 knots (50-61 kmph)
4. Cyclonic Storm	34 to 47 knots (62-88 kmph)
5. Severe Cyclonic Storm	48 to 63 knots (89-117 kmph)
6. Very Severe Cyclonic Storm	64 to 119 knots (118-221 kmph)
7. Super Cyclonic Storm	120 knots and above (≥222 kmph)

Table 1: Classification of low pressure systems over NIO (Source: Mohapatra, 2014)

1.1.3 Structure

A mature cyclone is vicious whirl in the troposphere with diameter ranging 100 to 700 miles and 7 to 10 miles in elevation. Gale of 100 to 150 mph or more whirl around the middle of intense low pressure area with 40 hPa to 120 hPa less than the mean sea level pressure. A full-fledged cyclone is inclusive of 4 primary integrant i.e., Eye, Wall cloud region, Rain bands and Exterior cyclone area.

'Eye' is the picturesque component of a full- grown cyclone that incepts in the middle, having diameter of about 8 to 30 miles and is generally a balmy domain with vaguely nil rain. The eye is surrounded by region of maximum winds, which is a thick wall of clouds. This is the most menacing part of cyclonic storm. In the rain band region winds persist whirling round the middle with depreciating wind pace, off the centre. The outer storm area is afar 150 miles from the middle. Here, the wind can still be termed as gale, but its tempo diminishes outside at considerable lower pace.

Figure 1.1: Schematic representation of a cyclone

1.2 System Impacts

TCs play a considerable part in diverting global and domain specific water cycle by intensifying the shallow level coincidence that contribute the unconfined troposphere by a rising flux of unsteady air that conducts moisture towards land from the oceans (Raymond 1995). This mechanism in turn is responsible for numerous cyclone related hazards i.e., violent wind, heavy rains, high seas, storm surge and other marine impact. Storm surge is the prime reason of desolation from TCs in which high- speed winds leads to massive piling of Sea water resulting sudden inundation and flooding of coastal regions.

1.2.1 Antecedent Aftermath

Dube et al. (2013) remarks that the Bay of Bengal has experienced more than 75% of total TC's causing human deaths of 5000 or more in last 300 years. According to SAARC Meteorological Research Centre (SMRC) and SAARC Disaster Management Cell (SDMC) report on cyclones, from the total 602,907 fatalities caused by 22 menace cyclones globally since 1951, the NIO reckoned for 550,500 (92%) in which Bay of Bengal was accounted 540,400 (89.4%). Table 2 reveals about Cyclonic disturbances that have caused 1000 plus fatalities since 1951. Out of the mentioned list, Bhola Cyclone and Gorky Cyclone that devastated Bangladesh in 1970 and 1991 recorded causalities greater than 0.1 million (about 300,000 in Cyclone Bhola and about 131,000 in Cyclone Gorky). The reasons for mammoth figure of deaths was dense throng habitation in the region.

Basin	Cyclone	Year	Countries	Deaths
North Indian Ocean	Cyclone	1963	East Pakistan	22,000
	Cyclone	1965	East Pakistan	17,000
	Cyclone	1965	East Pakistan	30,000
	Cyclone	1965	Karachi, Pakistan	10,000
	Cyclone Bhola	1970	East Pakistan	300,000
	Cyclone	1985	Bangladesh	10,000
	Cyclone Gorky	1991	Bangladesh	131,000
	Cyclone	1971	Orissa, India	10,000
	Cyclone	1977	Andhra, India	20,000
	Cyclone	1996	Andhra, India	1,000
	Cyclone	1998	Gujarat, India	1,000
	Cyclone	1999	Orissa, India	9,500
West Atlantic	Hurricane Flora	1963	Cuba, Haiti	8,000
	Hurricane Inez	1966	Mexico	2,000
	Hurricane Fifi	1974	Central America	5,000
	Hurricane David	1969	Central America	2,608
	Hurricane Mitch	1998	Central America	11,000
	Hurricane Katrina	2005	USA	1,836
East & South Pacific	Typhoon Iris	1955	Fujian, China	2,334
	Typhoon Sarah	1959	Japan, South Korea	2,000
	Typhoon Vera	1959	Japan	4,466
	Baguious Thelma	1991	Philippines	3,000

Table 2: Cyclonic Disturbances that have caused 1000 plus fatalities since 1950 (Source: SMRC)

1.2.2 Vulnerability

Broad-scale assessment of citizenry at risk suggests an estimate of about 320 million citizens, accounting to 1/3rd of India's populace, living in 13 coastline states & Union Territories including 84 districts, are endangered to cyclone induced hazards (Mohapatra, IMD). 4 states (T.N., A.P., W.B. and Orissa) & 1 Union Territory (Pondicherry) on the eastern coastline and 1 state on the western coast (Gujrat) are excessively prone to cyclonic disasters (NDMA, 2008). These statistics renders TCs as a colossal natural threat to the country. Figure

1.2 depicts Cyclone Hazard Prone Districts Map of India. Details of vulnerability profile of India with respect to cyclones is elaborately discussed in section 3.2- Vulnerability Assessment.

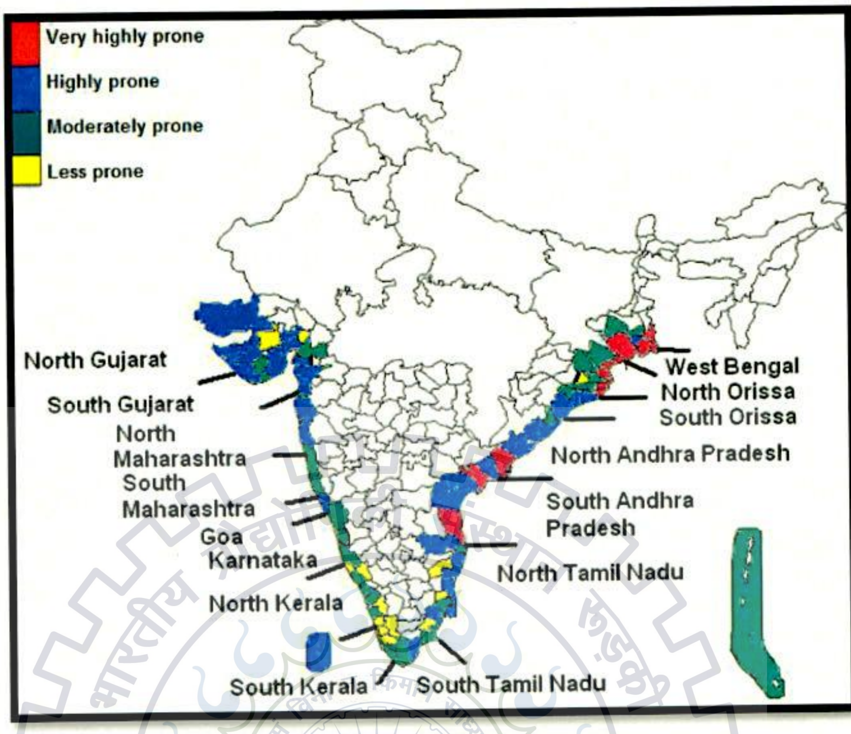


Figure 1.2: Cyclone Hazard Prone Districts Map of India (Source: NDMA, 2010)

1.3 System Alleviation

Among various disaster events, cyclone is one that dispenses 3- 4 days for preparedness activities. Mitigation of cyclone disasters depends upon several factors including, hazard analysis, vulnerability analysis, preparedness, planning and precise and effective early warning. Cyclone Warning System utilises data from observation sources like Automatic Weather Stations (AWS), Satellites, Radars, Numerical Weather Prediction (NWP) models and modern communication modes. Early warning system for Tropical Cyclone comprises of monitoring and prediction, warning concerned authorities, warning inception, presentation & dissemination and Cooperation with agencies responsible for disaster management.

1.4 Limitations

The real time generated cyclone forecasts are not perfect. It is a necessity to promote individual research efforts apart from the facilities provided by national services for subsequent improvement in prediction quality. But at present, the resources for relevant experimentation i.e. High Power Computational Facility, Operational Scripts etc., in cyclone management are limited and confined to certain close domains only. Most of software involved in systematic generation and development of cyclone forecast are proprietary and generally costly for individual usage. Although consistent efforts are made by certain international organisations to provide a transparent platform for amateurs, still a wide gap exist to be stocked by compact and ready to use utilities. Accessibility of subsequent database for conducting relevant research and investigation for cyclones is generally limited which act as potential inconvenience for conducting standalone investigational experiments. Three dimensional visualisation technology for cyclone products is still in its flourishing juncture and the products of national services have yet to transmute to make themselves compatible with the same.

1.5 Objectives

As apparent from earlier discussions, tropical cyclones are prevalent disaster phenomenon in Indian subcontinent, therefore keeping in view the necessity of effective diminution schemes for cyclones the initial aim of study is stated to assess the cyclone management practices in the country. Further efforts are made in developing 'independent' methodologies and technologies to investigate and foster accurate and timely forecast for the purpose of wider amateur participation in Cyclone Management. Thus prime intension can be developing a standalone Cyclone Prediction System by using open source and freely available software and synthesis of indigenous algorithms for product generation and verification. As sheer need is felt for amalgamation of three dimensional visualisation technology with cyclone products third need is three dimensional interactive visualisation of cyclone products. Thus problem statement is compiled as

'Assessment of the existing Cyclone Mitigation Framework in the country and thereby developing a standalone Cyclone Prediction System by utilising open source and freely available source codes and synthesising indigenous algorithms for product generation and verification along with three dimensional interactive visualization'

For the purpose developing an independent and cyclone forecasting system, Weather Research and Forecasting (WRF) model program is proposed which is an open source and freely available NWP program. Simulation of VSCS Hudhud would replicated using WRF and results are to be verified to analyse model performance. Data to be used as initial and boundary conditions are IMD-GFS and NCEP-GFS. As NCEP-GFS is shared and readily available on NCEP's network, efforts would be made to evaluate its utility and usability in forecast generation along with its IMD counterpart. Indigenous algorithms for utilities are developed for product synthesis with intension of public sharing. Further freely available VAPOR software package is to be used for the development of three dimensional visualisation product.

Thus the objectives of the study are defined as follows:

1. **Assessment of the existing Cyclone Mitigation Framework in the country.**
2. **Developing independent Cyclone Prediction System using an open source and freely available WRF model program by replicating simulation of VSCS Hudhud for assessment of the model performance in case of two sources of initial and boundary condition i.e. NCEP-GFS and IMD-GFS along with forecast verification and development of indigenous algorithms and utilities for product generation.**
3. **Three dimensional interactive visualisation of cyclone products using freely available VAPOR software package.**

2. LITERATURE REVIEW

2.1 Cyclone Impacts and Management

There are many literature that highlight the statistics pertaining to the "vandalization" cyclones have constrained over mores and living standards of coastal communities.

A "Cyclone" is a swirl in the troposphere with high gale circulating around a surrounding a region of low pressure in anticlockwise direction in Northern Hemisphere and in opposite direction in the Southern Hemisphere (IMD Standard Operation Procedure, 2013).

Tropical Cyclone deliver a substantial role in controlling global and domain specific water cycle by intensifying the shallow level coincidence that contribute the unconfined troposphere by a rising flux of unsteady air that conducts moisture towards land from the oceans (Raymond 1995).

Dube et al. (2013) reported that Bay of Bengal is home to some of very calamitous Tropical Cyclones reportedly over 75% of total TC's causing human deaths of 5000 or more in last 300 years.

According to SAARC Meteorological Research Centre (SMRC) and SAARC Disaster Management Cell (SDMC), major share of fatalities since 1950 were accounted to cyclones incepting in the North Indian Ocean.

"NDMA Guidelines" entitled "Management of Cyclones 2008" provides a quintessential and a lucid overview about the current situation, government initiatives, Broad scale assessment. National Cyclone Risk Mitigation Project (NCRMP) and standards related with cyclone mitigation. Broad-scale assessment of the vulnerable communities reckons that an approximate 320 million citizens, accounting to 1/3rd of India's populace, living in 13 coastline states & Union Territories including 84 districts, are prone to cyclone induced hazards.

BMTPC (Building Materials and Technology Promotion Council), GoI, 2006 provided a Vulnerability Atlas of India where 84 districts were depicted prone to Cyclone Hazards.

Mohapatra and Mandal (2009) tried to upgrade existing vulnerability maps of cyclone. According to the text the districts adjoining the Arabian Sea and Bay of Bengal, Coastline districts recognised by BMTPC, districts classified for issuing cyclone warning by India Meteorological Department and districts having close proximity to seas without abut were taken into consideration.

Bhatia et al. (2013) delineated the recent advances in observational support from space-based systems for tropical cyclones where features like analysis of cloud imagery data for location and intensity estimation of Tropical Cyclones, atmospheric Motion Vectors (AMVs) derived from satellite data and their use for cyclone tracking and use of microwave data for tropical cyclone analysis were extensively outlined.

Mohapatra et al. (2014) provided an exhaustive elucidation over the Early Warning Services for Cyclone Management where a detailed narration of existing Standard Operation Procedure in practice at India Meteorological Department was covered. It also expounded all aspects commencing from Warning Generation to its subsequent Dissemination at aspirated levels.

The "Standard Operation Procedure" literature issued by "Cyclone Warning Division" explicated aspects like "Cyclone Hazards, Observational Aspects of Cyclone Warning System, Monitoring and Prediction Technique used, Bulletins and Warnings and Post Cyclone Action".

2.2 WRF Simulation of Tropical Cyclones

Weather Research and Forecasting (WRF) Model is a product of cooperative alliance, primarily designed by the NCAR. It is pliable, modern atmospheric and weather simulation system, mobile and methodical on available parallel computational platform, productive for use in a wide spectrum of utilities with scales amounting from meters to thousands of kilometers and includes operational Numerical Weather Prediction, forecasting advancement, and integrated-model utilization. The model can also be set as either a one-way, two way nesting, or a moving nest model. These options allow the WRF-ARW model to be versatile for both research and operational purpose (Skamarock et al., 2008). The components of WRF Model are WRF Pre-processing System (WPS), WRF-ARW solver and codes and WRF Post processing. WPS is used for interpolation topographical and meteorological data for real data simulation. The final analysis is processed into gridded forecasts by the WRF-ARW dynamics solver. WRF Post processing is used for post processing the WRF outputs.

Weisman et al. (1997) suggested that in case of multiple nesting case the finer model resolution allows for the simulations to detect a majority of mesoscale features within the inner domains.

Cavallo et al. (2010) and Shi et al. (2010) reported that simulation by NWP models are imperfect and therefore they need to be ceaselessly updated and redefined as new errors are detected, capabilities added, or parameterizations are implemented.

Chen et al. (2011) explicated based upon user need and computation expense, WRF users either parameterized urban surface processes or ran a sub-grid scale, multiple layered urban canopy model to describe heat exchanges and their interaction with the atmospheric boundary layer.

Michalakes et al. (2010) and Janjic et al. (2010) stated that following the forecast generated by WRF-ARW dynamics solver, the data can then be output to meteorological packages such as the NCAR Command Language (NCL) or some other visualization packages for post processing.

Das et al. (2008) examined performance of four mesoscale model viz. MM5, ETA, RSM and WRF and found that WRF produced superlative degree of forecast for the observations in the day-1 forecast but recommendation included usage of ensemble technique rather than relying on any single model for forecast generation.

Gopalalkrishnan et al. (2012) remarked that higher resolution domain produced better intensity and structure results of the cyclones.

Srivastava et al. (2015) studied "Performance of WRF-ARW Model on the Track and Intensity Prediction of VSCS Hudhud over BoB System" and concluded that Average track error was in range of 49 km-340 km and in terms of prediction of intensity, apex value of average intensity error was less than 25 knots and 17 hPa.

Srinivas et al. (2011) found from 65 sensitivity experiments that for five severe tropical cyclones over Bay of Bengal, the combination of Kain-Fritch (KF) convection, Yonsei University planetary boundary layer, NOAH land surface schemes and LIN explicit microphysics provided best simulation for track and intensity prediction".

2.3 Impact of initial conditions on WRF Model performance

Pielke et al. (2006) worked on a new paradigm for parameterizations in numerical weather prediction and other atmospheric models and suggested that "even a small error in initial condition may contribute large error in subsequent forecast as the accuracy of boundary conditions also play important role because the atmospheric waves and distribution generated at the boundary can rapidly propagate throughout the domain".

Majewski (1997) illustrated that the forecast skill of the model is influenced by large scale flow advected from the boundary.

Mandal and Singh (2014) commented on the impact of initial and boundary conditions on mesoscale simulation of Bay of Bengal cyclones using WRF-ARW model. In the study seven land falling BoB cyclones were simulated which included three Severe Cyclonic Storms and four Very Severe Cyclonic Storms that crossed Bangladesh, Myanmar and Eastern Coast of India. In the first simulation FNL was used to provide initial and boundary condition and in the second GFS data was utilised. It was concluded that track and intensity forecast was better in case of GFS initial and boundary condition and the mean error in landfall location were 90 Km and 198 Km respectively in GFS and FNL simulation.

3. CYCLONE MITIGATION FRAMEWORK IN INDIA

The catastrophic effects of cyclone cannot be avoided but only can be reduced. An efficient Cyclone Mitigation Scheme requires strides as Hazard Assessment, Vulnerability Assessment, Early Warning System, Community-Preparedness and Structural Mitigation. On the basis of experience gathered from past cyclones intercepted globally and the advances in field of cyclone mitigation following framework (Figure 3.1) can be proposed for preparedness and risk mitigation.

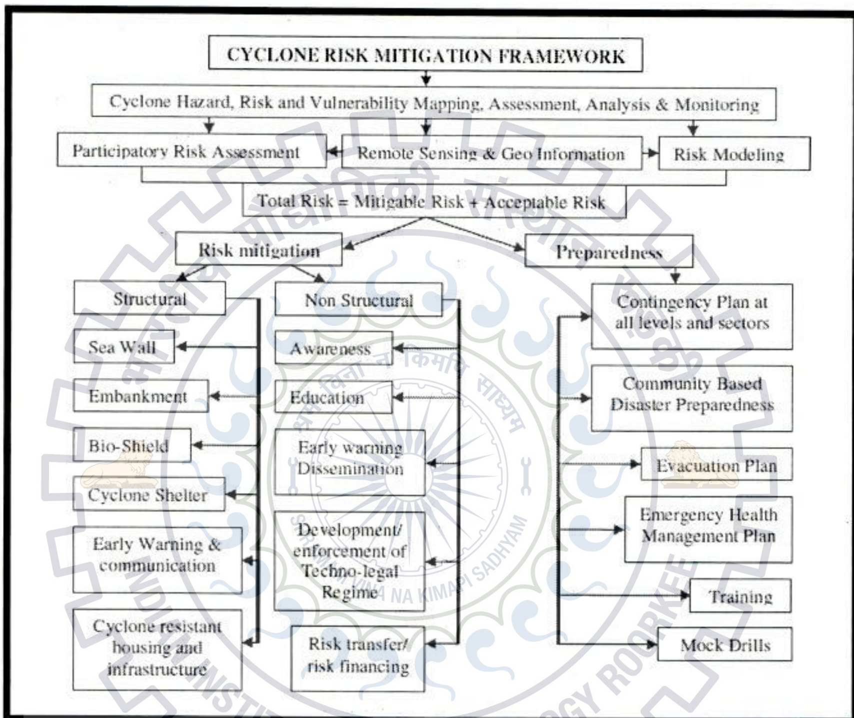


Figure 3.1: Cyclone Mitigation Framework

3.1 Hazard Assessment

The initial and exclusively intricate task in cyclone mitigation is hazard mapping and incessant monitoring of susceptible domains. It is essential to manifest such a knowledge-database so that a sane and prudently efficacious blueprint of Cyclone Risk Mitigation can be procured.

The calamitous prospective of cyclone is elucidated by damage it unleashes on the life and life-line infrastructures of the prone span. Such kind of sporadic weather conditions predominantly occurs in accordance with low pressure disturbances that are readily evident over distinct parts in the region. A cyclonic storm is accompanied by multiple hazards resulting grim situations and enormous diminution of life and property. Types of vandalism relevant to a tropical cyclone are inclusive of flooding of coastal areas, erosion of beaches, loss of soil fertility, damage to structures, loss of power and communication, potential injuries and causalities, detriment of crops, vegetation, contamination of water supply system, land subsidence and flooding of inland area. Causative factors for mentioned damages are violent wind, storm surge, rain and high sea. These factors are analysed and explicated as follows:

3.1.1 Winds

Winds damage residential buildings, power houses, communication towers, infirmaries, ration warehouses, bridges, conduits and vegetation owing to their violent velocities. The intensity of category five cyclonic storm is more than 285 kmph. The damage extent due to wind covers larger area than rainfall and storm surge. The effect of the cyclone eye passage of directly over a region is entirely dissimilar from that does not hit the place directly. The region lying in course of the eye passage experience frequent changes in wind direction that results in torque imposition.

The torque developed can twist the building structures leading to basement failure. It causes uprooting of vegetation cover. Rest of the region bears unidirectional winds due to which leeward side is somewhat protected from action of direct winds. Violent winds also result in roof failures where roofing systems are revealed to sturdy lifting forces as shown in Figure 3.2(a). Absence of roofing structure leads to damage of walls either due to percolation of water or owing to lack of support mechanism which was initially provided by the roofing systems.

(a) (b)

Figure 3.2: Damage due to winds during VSCS Hudhud (a) Damaged roof of Vishakhapatnam Airport (b) The collapsed telephone tower near Visakhapatnam (Source: IMD, 2014)

As evident from Figure 3.2 (b) communication medium suffers immensely from damaging actions of winds.

It is observed that wind with speed of 44 m/s disrupts telephone lines connection and causes misalignment of microwave towers. This affects local telephone and cellular services. Wind speed more than 52 m/s demolishes microwave and radio towers including large antennas and satellite communication dishes. Winds hinders rescue and logistics attempts as roadways are blocked with uprooted trees, power poles and lines, and debris falling on roads and blocking them. Table 3 reveals wind speed intensity along with damage expected and action suggested.

Intensity	Damage expected	Action Suggested
Deep Depression 50 – 61 kmph (28-33 knots)	Minor damage to loose and unsecured structures	Fishermen advised not to venture into the open seas.
Cyclonic Storm 62 – 87 kmph (34-47 knots)	Damage to thatched huts. Breaking of tree branches causing minor damage to power and communication lines	Total suspension of fishing operations
Severe Cyclonic Storm 88-117 kmph (48-63 knots)	Extensive damage to thatched roofs and huts. Minor damage to power and communication lines due to uprooting of large avenue trees. Flooding of escape routes.	Total suspension of fishing operations. Coastal hutment dwellers to be moved to safer places. People in affected areas to remain indoors.
Very Severe Cyclonic Storm 118-167 kmph (64-90 knots)	Extensive damage to kutcha houses. Partial disruption of power and communication line. Minor disruption of rail and road traffic. Potential threat from flying debris. Flooding of escape routes.	Total suspension of fishing operations. Mobilise evacuation from coastal areas. Judicious regulation of rail and road traffic. People in affected areas to remain indoors.
Very Severe Cyclonic Storm 168-221 kmph (91-119 knots)	Extensive damage to kutcha houses. Some damage to old buildings. Large-scale disruption of power and communication lines. Disruption of rail and road traffic due to extensive flooding. Potential threat from flying debris.	Total suspension of fishing operations. Extensive evacuation from coastal areas. Diversion or suspension of rail and road traffic. People in affected areas to remain indoors.
Super Cyclone 222 kmph and more (120 knots and more)	Extensive structural damage to residential and industrial buildings. Total disruption of communication and power supply. Extensive damage to bridges causing large-scale disruption of rail and road traffic. Large-scale flooding and inundation of sea water. Air full of flying debris.	Total suspension of fishing operations. Large-scale evacuation of coastal population. Total suspension of rail and road traffic in vulnerable areas. People in affected areas to remain indoors.

Table 3: Wind speed along with associated Damage and Action Suggested (Source: IMD, 2013)

3.1.2 Rainfall

Cyclonic Rainfall are widespread and generally very heavy, which results in release of excessive proportions of water within very minute span of time leading to flood like situations. Mohapatra et al. (2013) states that it can rain more than 300 mm in 24 hours during cyclones. Rains are worst nemesis for victims who became homeless in initial cyclonic activity and for the people involved in the rescue and relief operations. Rainfall disrupts and damages the life line infrastructures like water distribution, rail road connectivity and flood induced wrecks power transmission grids and communication systems.

Figure 3.3: Snapshot from Odisha (then Orissa) Super Cyclone, October 1999 (Source: IMD, 2013)

Rainfall induces widespread soil erosion as the water percolates down which causes it's softening and thereby making it vulnerable to withering. This adds to fragility of embankments and similar structure. Figure 3.3 provides a snapshot of flood situation which was induced by very heavy rainfall during Odisha (then Orissa) Super Cyclone.

3.1.3 Storm Surge

Storm Surge is an intrinsic cataclysmic costal phenomenon of cyclones. The catastrophic intensity depends on associated storm surge amplitude during landfall time of cyclone, characteristics of coast, phase of tides and vulnerability of area and community.

Figure 3.4: Impact of storm surge caused by VSCS 'Nargis' (Source: IMD, 2013)

Inception of storm surge is a result of interaction between high speed air, land and sea. When cyclone reaches the coast the "on- shore wind" propels the sea water towards the coast, as a result sea level rises, which finally materializes as storm surge. Storm surge is in indirect correlation with the depth of sea water and advances to its maximum height on the coast at the landfall point. The depth varies from 5 meters along the West Bengal- north Odisha coast to about 500 meters at about 20 degrees in north central Bay. This is quite a considerable area of shallow continental shelf which leads to exponential amplification of storm surges during any cyclonic activity. Figure 3.4 shows the impact of storm surge caused by VSCS Nargis. Astronomical tides are another cause for rise in sea level. The Probable Maximum Storm Surge (PMSS) values for east and west coasts of India are deciphered by the Figure 3.5.

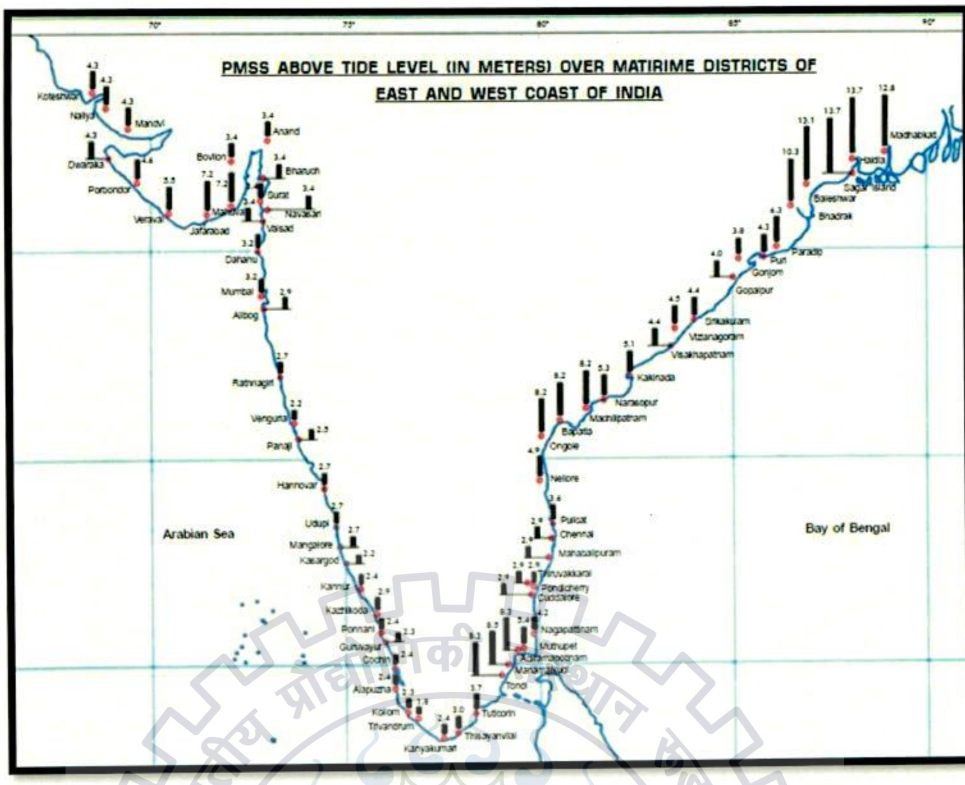


Figure 3.5: Probable maximum storm surge (PMSS) above tide levels (In metres) over maritime districts of east and west coasts of India (Source: IMD, 2013)

3.1.4 Thalassic Influence

The strength of winds, sea condition and the wave height related with Satellite 'T' number for all classifications of cyclonic disturbance, are illustrated in Table 4. During the life span to cyclone, the sea condition becomes high to phenomenal with waves bouncing at a height of 6 meters and more.

S. N.	Intensity	Strength of wind(kmph/knots)	Satellite 'T' No.	Condition of Sea	Wave height (m)
1.	Depression	(i)(31- 40)/(17-21) (ii)(41- 49)/(22-27)	1.5	Moderate Rough	1.25-2.5 2.5-4.0
2.	Deep Depression	(50–61)/(28-33)	2.0	Very Rough	4.0-6.0
3.	Cyclonic Storm	(62–87)/(34-47)	2.5-3.0	High	6.0-9.0
4.	Severe Cyclonic Storm	(88-117)/(48-63)	3.5	Very High	9.0-14.0
5.	Very Severe Cyclon-ic Storm	(i)(118-167)/(64-90) (ii)(168-221)/(91-119)	4.0-4.5 5.0–6.0	Phenomenal Phenomenal	Over 14.0
6.	Super Cyclonic Storm	(222/120 and more)	6.5 and more	Phenomenal	Over 14.0

Table 4: Thalassic influence of cyclonic disturbances (Source: IMD, 2013)

3.2 Vulnerability Analysis

The chronological data available for cyclones are constructively exploited for the zonation of regions culpable to cyclone hazards. Such zonation maps are accessible in digital format for regional as well as locale levels. The availability of map in digital format permits to integrate spatial data with variables that can enable swift and speedy assessment of possible vulnerabilities which would incept a suitable mitigation framework.

The Building Material Technology Promotion Council (BMTPC) have discerned the districts susceptible to hazard related to cyclones on the basis of their vicinity to the coasts. The compiled list by BMTPC have certain issues it have names of some inland districts of Northeast India which have actually never faced the obvious detriment of cyclones. Secondly, at the time of scripting of guidelines, the significance of cyclone frequency and intensity was subdued.

Mohapatra and Mandal (2009) published a report entitled "Cyclone Hazard Prone Districts of India: A Report" in which they tried to upgrade existing vulnerability maps of cyclone. According to the report districts adjoining the Arabian Sea and Bay of Bengal, Coastline districts recognised by BMTPC, districts classified for issuing cyclone warning by India Meteorological Department and districts having close proximity to seas without abut were taken into consideration. The results (Figure 3.6) provided a pragmatic overview of the extent of vulnerability of districts to the cyclone hazards, as it included the frequency and intensity information of cyclones and also counting other hazards susceptible of possible damage.

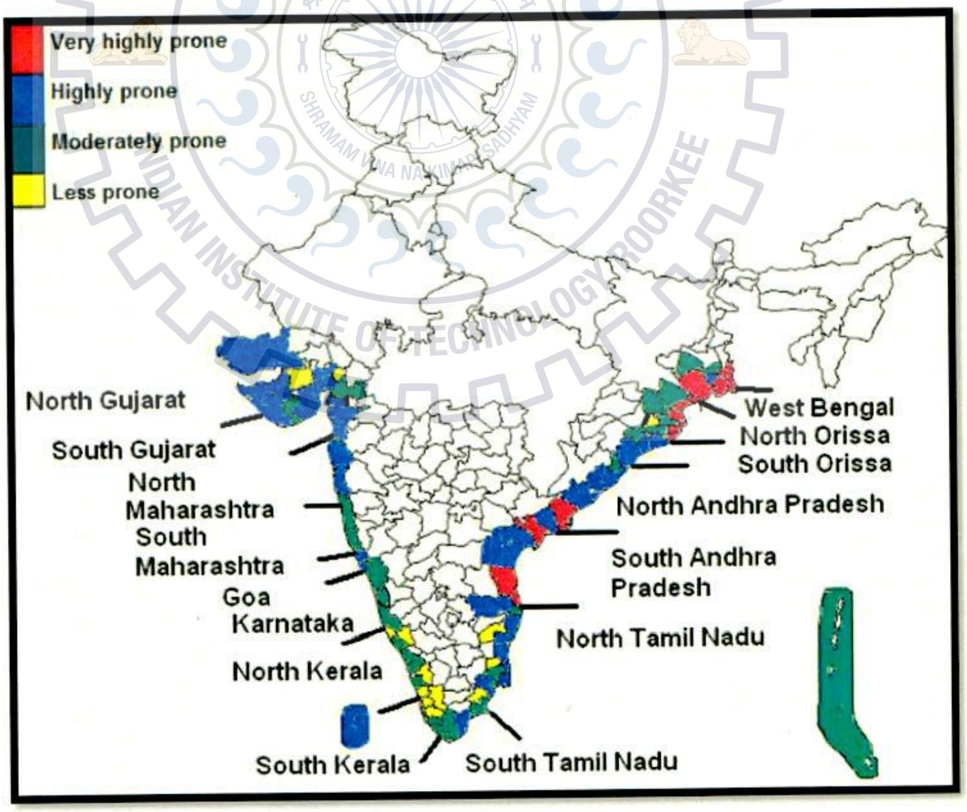


Figure 3.6: Cyclone hazard prone districts of India (Source: NDMA 2010)

3.3 Early Warning System

The fabrication of Early Warning for cyclones and its efficient dispersal to the probable stakeholders is an integral mitigation procedure to ascertain that forfeiture of life and property is minimal during cyclone onset duration. Recent advancement in technologies have enhanced the operational ability of Early Warning Systems (EWS) in exponential terms. Presently, we have DWR systems using which we can now monitor and track the possible sources of cyclonic disturbances accurately and concerned authorities and immediate stakeholders can warned well in advance with margin of 2-3 days. Warning will not only decipher the intensity of the system but also the characteristics like landfall time and location.

On the basis of inundation level forecasts generated by storm surge numerical prediction models, vulnerable regions can be identified and population can be evacuated accordingly. There are numerous occasions when EWS have saved lives of citizens dwelling in coastal regions. Still the existing Operational Procedure and Warning system needs to be upgraded as certain inaccurate responses by EWS at few instances have considerable reduced population's faith over warning issued for coastal communities.

A productive EWS must include components like efficient prediction- monitoring system and effective warning generation- circulating systems. The entire early warning system of cyclone can be shown as in Figure 3.7.

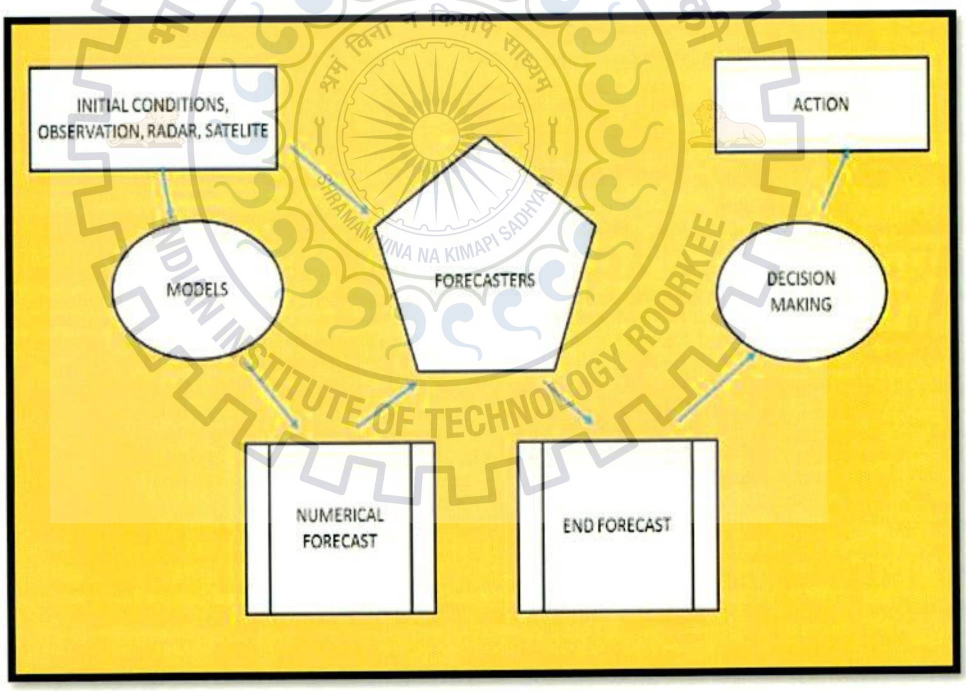


Figure 3.7: Early Warning system of cyclone over NIO

3.3.1 Prediction and Monitoring

It is important to correctly determine the location and intensity of the cyclone as initial error in location and intensity can lead to increase in error in forecast location and intensity (Mohanty et al., 2010). Cyclones in the NIO Basin are observed utilising land, ocean and space based observational systems that is inclusive of standard meteorological observations, observations from buoys, coastline radars and satellites. The cyclogenesis information i.e. location and time are determined with satellite observations. When systems comes closer to the coast and within radar's range, radar used to monitor followed by satellite observation. Ultimately at the instant system lies next to coastal boundaries priority sequence of data is costal observation followed by radar and satellite.

3.3.1 (a) *Procedure for Monitoring of Cyclone*

Procedure for monitoring is inclusive of monitoring of genesis of cyclone and determination of centre and intensity of cyclone. Genesis parameters are computed as:

1. Sea Surface Temperature, depth of 26 degree Celsius isotherm and ocean thermal energy.
2. Conditional instability through deep and moist atmospheric layer.
3. Pre-existing disturbance.
4. Environmental Condition.
5. NWP and dynamical- statistical model forecast for genesis.

Based on synoptic, statistical, dynamical-statistical and NWP models guidance, a consensus decision is taken to give actual information about genesis of depression.

3.3.1 (b) *Locating Centre and Determining Intensity*

Determining cyclone's eye coordinates and probable intensity is on the basis of Synoptic technique, Satellite observations and Radar Observations. Observations gathered are assigned with a priority based on vicinity of the system from the coast.

In Synoptic Technique the centroid of the wind distribution at surface level marks the centre of cyclonic system. While considering pressure field, the location of Minimum Sea Level Pressure (MSLP) is assumed to be centre position. The Synoptic technique has a limitation over the open sea as there sufficient observations are not available. Coastal Automatic Weather Stations (AWS) are very useful in such cases as they render hourly data on operational basis (Bhatia et al., 2008). For calculating the intensity, Maximum Sustained Winds is taken into account along with number of closed isobars with an interlude of 2 hectopascal (hPa).

Using the Satellite facility, centre is defined by locating low cloud lines (IMD, 2003). After the intensification of cyclones, centre is determined from banding feature using logarithmic spiral. Intensity classification using satellite is on the basis of Dvorak's technique. Intensity is represented by T numbers which is based on Pattern Recognition technique and CI numbers which is related to wind speed of cyclones.

Usage of Radar for location of eye can be done by finding the geometrical centre of the echo free area and the intensity can be obtained from Doppler Weather Radars (Raghavan, 2013).

3.3.1 (c) *Prediction of characteristics of Cyclones*

Characteristics of cyclones which are predicted include Track, Intensity (in terms of Maximum Sustained Winds), Radius of Maximum Wind, Heavy Rainfall, Gale wind at time of landfall and storm surge.

3.3.2 Warning Organisations in India

According to Standard Operation Procedure maintained by Cyclone Warning Division the design of a TC warning system in IMD takes into consideration of the prevailing state of the meteorological science, the available technological means of communication, the built-up environment such as dwellings, socio-economic conditions, appropriateness of protective actions as well as the expectations of the society. To escalate the value and efficaciousness of Tropical Cyclone Warning, blueprints are devised in accordance with forecast delineation, stimulating efficient methodologies, cooperation and coordination with disaster management agencies, warning products generation, presentation & dissemination. Some of the warning bulletins issued by IMD include Tropical Weather Outlook, Tropical Cyclone Advisories, Tropical Cyclone Advisories for Civil Aviation, Global Maritime Distress Safety System (GMDSS), Bulletin for India coasts, Sea Area Bulletin, Coastal Weather Bulletins, All India Radio (AIR) Bulletins, Registered and designated warnees Bulletin, Press Bulletins, Aviation Warnings, Bulletins for Indian Navy etc.

3.3.3 Warning generation

According to National Disaster Management (NDMA) Guidelines for Management of Cyclones a four-stage cyclone warning system was introduced in IMD to replace precursory dual-stage warning system:

First, a special bulletin called Pre-Cyclone Watch is issued containing early potential indications about the development of a cyclonic disturbance in the NIO region, its possible development into a cyclone and adverse weather that specific areas of the coastal belt are likely to experience. Additional warnings in respect of fisheries and ports are issued to enable the respective authorities to take necessary precautionary steps.

At the second stage, a Cyclone Alert message is issued 48 hours prior to the expected time of commencement of adverse weather over the specific coastal areas.

A Cyclone Warning is issued 24 hours in advance of the cyclone's landfall in order to cover the devastating impact of cyclones over inland areas.

Finally, a Post Landfall Outlook is issued 12 hours before the landfall and continues till such time as cyclone force gusty winds are expected to prevail over the interior areas.

Generation of customised warning at central level is accomplished by participation of operational agencies, research scientists, and CRC including media personnel in the preparation of sector specific multi-lingual cyclone warning.

3.3.4 Warning Dissemination

According to Standard Operation Procedure maintained by Cyclone Warning Division procedures implemented for Warning Dissemination includes Cyclone warnings to be disseminated to various users through telephone, tele-fax, VHF/HFRT, satellite based cyclone warning dissemination system (CWDS), Police Wireless, AFTN (Aviation), Internet (e-mail), Websites, Radio/TV network, Mobile Phones, Interactive Voice Response System (IVRS) and SMSs. These advisories are put in the website, www.imd.gov.in of IMD. In IVRS the requests for weather information and forecasts from general public are automatically answered. As telephonic communication often breaks down during cyclones, the warnings meant for the Chief Secretary and Collectors of coastal districts are passed on to these officials through police W/T channels, FAX or by telephone to ensure that the warnings reach these officials quickly to enable them to take precautionary measures promptly. In addition, as a part of State Level Disaster Management Plan, VHF set is installed at ACWC, Mumbai and CWC, Bhubaneswar for quick communication to State Control Room. IMD has specially designed receivers known as Cyclone Warning Dissemination System (CWDS) within the vulnerable coastal areas for transmission of warnings to the concerned officials and people using broadcast capacity of INSAT satellite which is a direct broadcast service of cyclone warning in the regional languages meant for the areas affected or likely to be affected by the cyclone.

3.4 Pre-Impact Preparedness

Pre-Impact preparedness in case of cyclones includes Contingency Planning at all levels, Community Preparedness, Evacuation Plan, Emergency Health Management Plan, Training and Mock drills.

3.4.1 Contingency Plans

Contingency Plans are necessity to plan and act in a coordinated way to avoid any pandemonium situation not only between the crisis responders but also amidst stakeholders. An efficient Contingency Plan must provide a lucid portrayal of the duties and responsibilities of associated organisations, mentioning precise modulus operandi to be enacted. It should also contain list of processes to be followed in course of carrying out afore said duties and responsibilities. The necessary equipment, devices and gadgets should be in working condition. Contingency plan must contain details about ways to conduct evacuation mock-drills and EMP.

3.4.2 Capacity Development

Capacity development is a reasonable technique to reduce the proneness of the population residing in the vulnerable regions. The local people follow certain indigenous capacity which are readily exist in their traditional systems which were procured on the basis of experience and through cultural inheritance. But often these capacities appears to be obsolete owing to numerous anthropogenic reasons. These capacities are needed to be reformed in accordance with recent advances in technology. Such capacities can be framed through regular interactions and periodic mutual pedagogy. Training programmes are needed to rational and pragmatic so that the responders and stakeholders are knowledgeable and up to date about their individual liability in the course of the disaster.

3.4.3 Community Based Disaster Preparedness

Communities are the ultimate stakeholders in any disaster predicament. Despite of having an effective response mechanism there would certain amount of duration between the impact of cyclone and the subsequent response by concerned agencies. If the local population is sufficiently trained to control the situation in that span of time, lot of fatalities and other losses can be prevented. Therefore the community should be trained to assess their own risk through participatory risk assessment process, develop their own contingency plans and set up their own teams for evacuation, search and rescue, emergency shelter and first aid.

3.4.3 Awareness and Education

Awareness is a generalised procedures for cyclone mitigation when come compared with capacity building and community preparedness which are specific and locale. Awareness provide knowledge related to risks, vulnerabilities of cyclones and the preventive, mitigative and preparedness measures that can be taken at the government, community, household and individual level. Media render an important role in this task due to its reach at grassroots. Cyclone education is rather a formal obligation that needs to be extensively propelled in the existing education system.

3.5 Structural Mitigation

Structural mitigation measures in generally refer to capital investment on physical constructions or other development works, which include engineering measures and construction of hazard resistant and protective structures and other protective infrastructure (SRMC, 2009). Structural mitigation for cyclones include building Sea Walls and Embankments, Bio-Shield, Cyclone Shelters and Cyclone Resistant Housing.

3.5.1 Sea Walls and Embankments

In cyclone structural mitigation sea walls and saline water embankments are most efficacious structures. Sea walls are built using reinforced concrete to prevent surges and at times soil erosion. PMSS is taken into account to determine height of the sea walls. Due to heavy expenditure incurred in building sea walls, it can't be a pragmatic and exclusive solution for cyclone mitigation but still suggested for assets like city or ports. Saline water embankments are recommended for rural dwellings were we have agricultural fields so as to avoid ingression of saline water of seas. Embankments are built with earth or stone masonry. Efficiency of embankment is limited in comparison with sea walls but it is quite cost effective. Choking of sea water have led to damaging of mangroves, so embankment are chosen for spots where vegetation are not efficient enough to abstain intrusion of saline water into vicinity of population dwellings.

3.5.2 Bio- Shield

Bio shield generally include mangroves, casuarinas salicornia, laucaena, atriplex, palms, bamboo and other tree species and halophytes and other shrub species that inhabit lower tidal zones. These biological structures abstain the storm surges, trap sediments and avoid soil erosion. They also act as a barrier to the ferocious winds and thereby preventing perishable livestock, vegetation and crops. Also these bio-shields decelerate moisture evaporation and transpiration from soils and plants respectively.

Instead of providing many benefits, bio-shields themselves are on edge of existence due constant anthropogenic thrust from costal population. Hefty efforts are needed to be implied for subsequent rejuvenation of these biological shields in the coastal areas.

3.5.3 Cyclone Shelters

Cyclone Shelters are built at spots which easily accessible to the masses. Structural capacity of such building includes ability to withstand violent high speed winds. Such structures are built over pillars and high platforms to avoid surges and inundation arising from any cyclonic activity. The capacity of accommodation of shelter homes are generally few hundreds to thousands. Throughout the year in normal seasons these shelter houses are used for community purposes like schools and hospitals and during time of crisis it is used for shelter as well as warehouses for accumulating relief materials.

3.5.4 Cyclone Resistant Housing

Cyclone Resistant Housing involves adherence to certain standard codes for construction purposes. The design specifics should involves traits like minimal required maintenance and ability to cope with wretched weather situations.

4. SYSTEM DESCRIPTION: VSCS 'HUDHUD'

The VSCS Hudhud incepted from a low pressure area over Tenasserim coast on 6th October 2014. The system escalated into Depression (D) at early hours of 7th October. It advanced west-north-westwards where it further developed into a Cyclonic Storm (CS) on 8th October and passed Andaman Island in period of 0800 and 0900 hours of Indian Standard Time.

Further the system transpired towards Bay of Bengal in south-eastern direction and advanced west-north-westwards. Intensification into a Severe Cyclonic Storm (SCS) happened in the morning of 9th October and into a Very Severe Cyclonic Storm (VSCS) in the afternoon of 10th October.

Moving north-westwards it reached to its pinnacle intensity in the early morning of 12th with a MSW of 110 mph over the West-Central Bay of Bengal off Andhra Pradesh coastline.

The system passed northern region of Andhra Pradesh coastline over Visakhapatnam in period of 1230 and 1330 hours Indian Standard Time of 12th October with similar speed of wind.

After landfall, it continued moving north-westwards and weaken continuously into SCS in the evening and further into a CS in the midnight. It then, debilitated into a Deep Depression (D) in the early morning of 13th and into a depression in the evening of 13th.

After that, the system advanced northward and decayed into a low pressure region over eastern part of Uttar Pradesh in the evening of 14th October 2014.

The exclusive traits of Hudhud are:

1. VSCS Hudhud is the said to be the first cyclone after 1986 that has crossed Vishakhapatnam coastline.
2. At landfall the estimated MSW value was about 100 Knots.
3. Landfall date was same as that of VSCS Phailin i.e. 12th October 2014.
4. The evaluated central minimum sea level pressure was 951 hPa with depreciation in pressure was about 55 hPa in the middle in comparison with that of surrounding.
5. It induced enormous downpour over Northern region of Andhra Pradesh and Southern parts of Odisha. Maximum 24 hour cumulative rainfall of 38 cm ending at 0830 hrs IST of 13 October was reported from Gantyada (District Vizianagaram) in Andhra Pradesh.
6. Maximum of storm surge of 1.4 meters above the astronomical tide has been reported by the tide gauge at Visakhapatnam.
7. Maximum 24 hour rainfall recorded was of 39 cm ending at 0800 hrs IST of 13 October at Gantyada (District Vizianagaram) in Andhra Pradesh.
8. IMD predicted the characteristics of Hudhud skilfully with 88 km Direct Position Error.

4.1 Observed Track

The observed track is depicted in Figure 4.1.

Figure 4.1: Observed track of VSCS HUDHUD during 7th-14th Oct. 2014. (Source, MoI)

4.2 Best Track Parameters

The best track parameters of VSCS 'HUDHUD' are depicted in Table 5.

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade *
07-10-2014	0300	11.5/95.0	1.5	1004	25	3	D
	0600	11.7/94.8	1.5	1004	25	3	D
	1200	12.0/94.0	2.0	1000	30	5	DD
	1800	12.0/93.5	2.0	1000	30	5	DD
08-10-2014	0000	12.2/93.0	2.0	1000	30	5	DD
	0300	12.3/92.9	2.5	998	35	7	CS
	The system crossed Andaman & Nicobar island near Long island (near lat. 12.4^{0}N and long. 92.9^{0}E) between 0300-0400 UTC						
	0600	12.5/92.5	2.5	996	40	8	CS
	0900	12.7/91.7	2.5	996	40	8	CS
	1200	12.8/91.0	2.5	996	40	8	CS
	1500	13.0/90.5	2.5	996	40	8	CS
	1800	13.2/90.2	3.0	994	45	9	CS
	2100	13.5/89.6	3.0	992	45	10	CS
09-10-2014	0000	13.7/89.2	3.0	990	45	12	CS
	0300	13.8/89.0	3.5	988	55	16	SCS
	0600	13.9/88.8	3.5	988	55	16	SCS
	0900	14.0/88.6	3.5	988	55	16	SCS
	1200	14.1/88.4	3.5	988	55	16	SCS
	1500	14.1/88.1	3.5	988	55	16	SCS
	1800	14.1/87.9	3.5	988	55	16	SCS
	2100	14.3/87.7	3.5	988	60	16	SCS
10-10-2014	0000	14.4/87.6	3.5	988	60	16	SCS
	0300	14.7/87.2	3.5	988	60	16	SCS

	0600	14.8/87.0	3.5	986	60	18	SCS
	0900	15.0/86.8	4.0	984	65	22	VSCS
	1200	15.2/86.7	4.0	982	70	26	VSCS
	1500	15.4/86.5	4.0	980	75	28	VSCS
	1800	15.5/86.4	4.0	978	75	30	VSCS
	2100	15.7/86.1	4.0	974	75	30	VSCS
11-10-2014	0000	15.9/85.7	4.0	970	75	30	VSCS
	0300	16.0/85.4	4.5	968	80	34	VSCS
	0600	16.1/85.1	5.0	966	90	40	VSCS
	0900	16.1/85.0	5.0	964	90	42	VSCS
	1200	16.2/84.8	5.0	962	95	44	VSCS
	1500	16.2/84.8	5.0	960	95	46	VSCS
	1800	16.4/84.7	5.0	954	100	50	VSCS
	2100	16.7/84.4	5.0	952	100	52	VSCS
12-10-2014	0000	17.2/84.2	5.0	950	100	54	VSCS
	0300	17.4/83.8	5.0	950	100	54	VSCS
	0600	17.6/83.4	5.0	950	100	54	VSCS
	The System crossed Andhra Pradesh coast over Visakhapatnam (near lat. 17.7^{0}N and long.83.3^{0}E between 0630-0730 UTC						
	0900	17.8/83.0	-	960	90	42	VSCS
	1200	18.0/82.7	-	982	60	20	SCS
	1500	18.3/82.5	-	986	45	15	CS
	1800	18.7/82.3	-	987	40	14	CS
	2100	18.7/82.3	-	988	40	13	CS
13-10-2014	0000	19.5/81.5	-	994	30	8	DD
	0300	20.5/81.5	-	996	30	6	DD
	0600	20.7/81.5	-	998	30	5	DD
	1200	21.3/81.5	-	998	25	4	D
	1800	22.3/81.5	-	1000	25	4	D
14-10-2014	0000	24.8/81.5	-	1000	25	4	D
	0300	25.1/81.6	-	1000	20	3	D
	0600	25.6/81.7	-	1000	20	3	D
	0900	26.3/81.8	-	1000	20	3	D
	1200	Weakened into a well marked low pressure area over East Uttar Pradesh and neighbourhood.					

Table 5: Best fit track co-ordinates and other specification of the "Very Severe Cyclonic Storm HUDHUD" over the BoB during 07-14 October, 2014 (Source: IMD, 2014)

*

D = Depression

DD = Deep Depression

CS = Cyclonic Storm

SCS = Severe Cyclonic Storm

VSCS = Very Severe Cyclonic Storm

4.3 Estimated Central Pressure

The hourly MSLP as recorded by Visakhapatnam is shown in Fig.3a which clearly indicates that the pressure fell gradually from 11th onwards and fall became rapid from the early morning of 12th Oct. As a result, 24-hour pressure fall ending at 0600 UTC of 12th was 45 hPa and the lowest pressure was 950.3 hPa as recorded at 0700 UTC over Visakhapatnam (time of landfall). Thereafter the pressure rose sharply as the VSCS crossed coast and filled in due to increase in surface pressure and cut off from moisture supply.

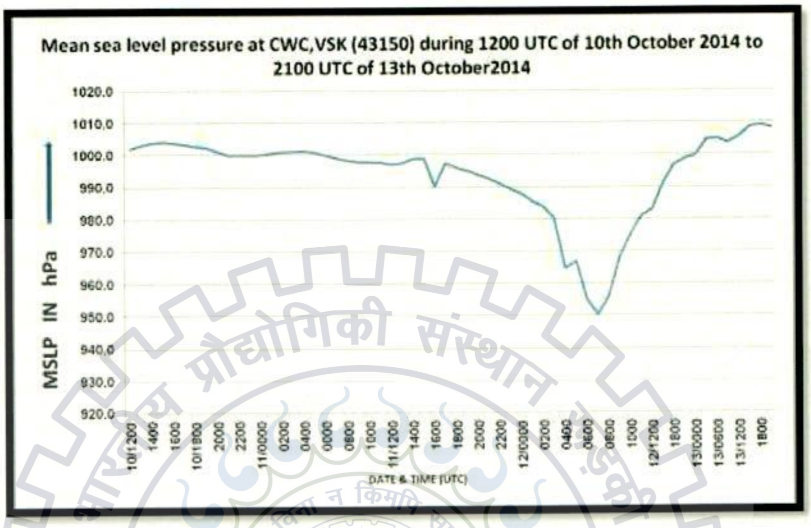


Figure 4.2: Hourly MSLP recorded at Visakhapatnam during 10-12th Oct. 2014 (Source: IMD, 2014)

4.4 Estimated Maximum Sustained Wind

Estimated Wind Speed as reported by Visakhapatnam Observatory for period from 1200 UTC of 10th October 2014 to 2100 UTC of 13th October is shown in Figure 4.3

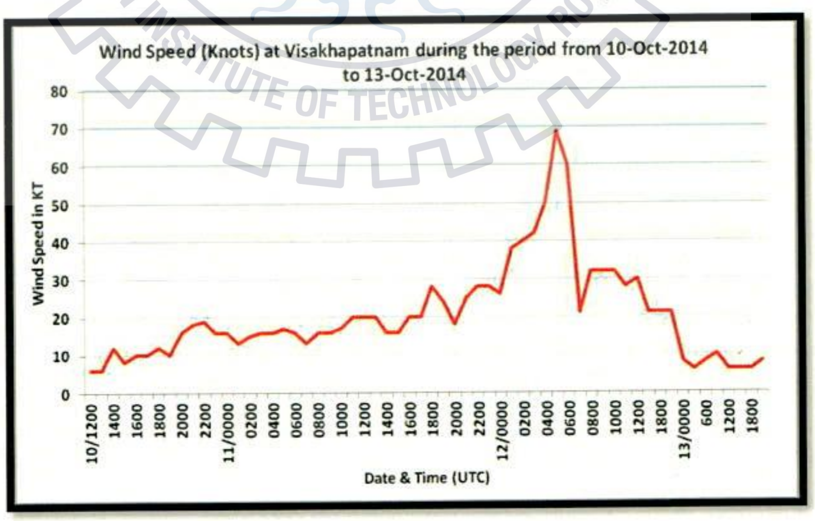


Figure 4.3: Hourly wind speed reported by Visakhapatnam Observatory during the period from 1200 UTC of 10th October 2014 to 2100 UTC of 13th October 2014. (Source: IMD, 2014)

4.5 Satellite Observation

Satellite imagery for VSCS Hudhud using INSAT- 3D is illustrated in Figure 4.4.

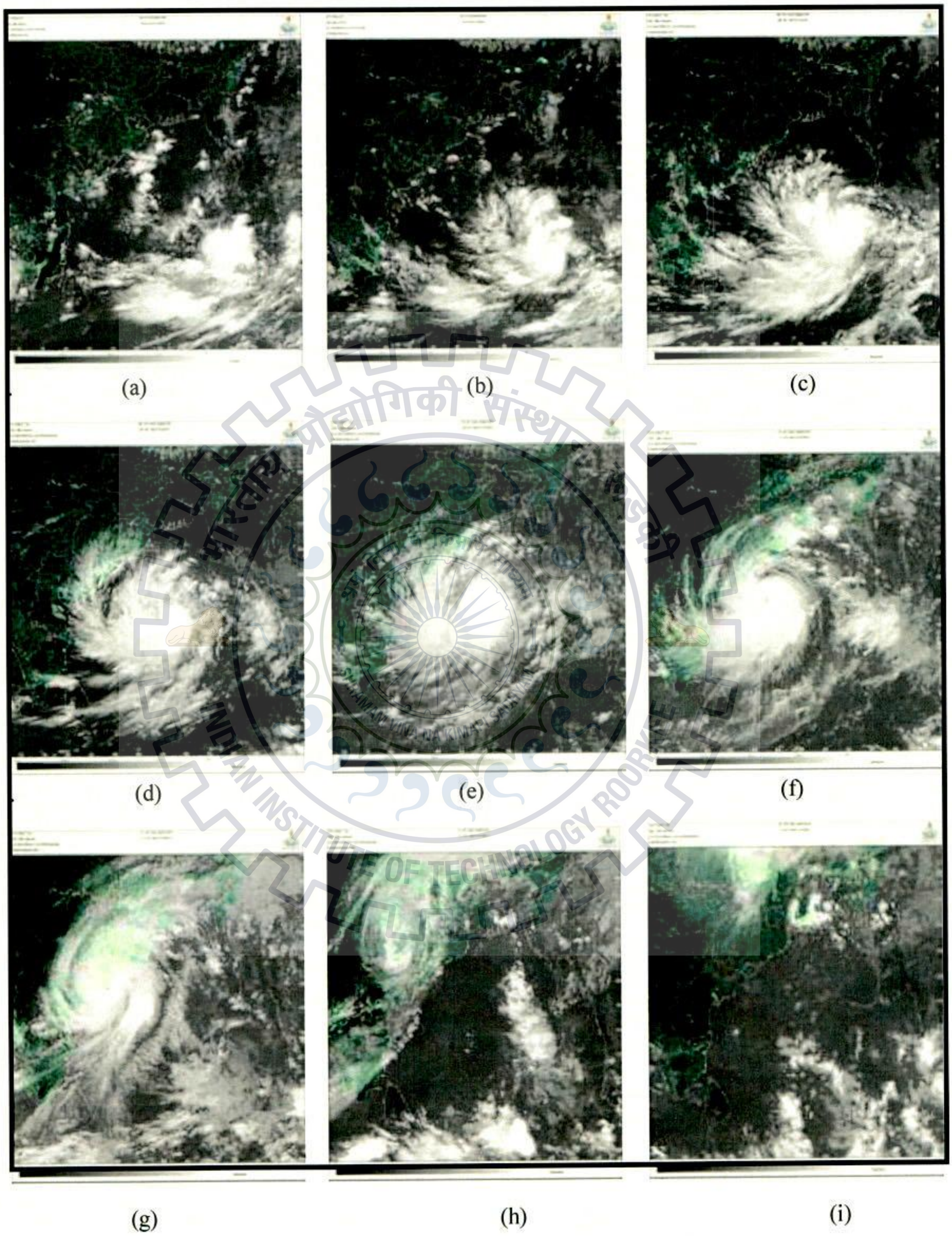


Figure 4.4: Typical INSAT-3D IR imageries for 0600 UTC for (a) 6th Oct. (b) 7th Oct. (c) 8th Oct (d) 9th Oct. (e) 10th Oct. (f) 11th Oct. (g) 12th Oct. (h) 13th Oct. (i) 14th Oct. (Source: IMD, SATMET Division)

4.6 Radar Observation

Observation based on Visakhapatnam RADAR for 0000 UTC to 1500 UTC of 11th October 2014 are illustrated in Figure 4.5.

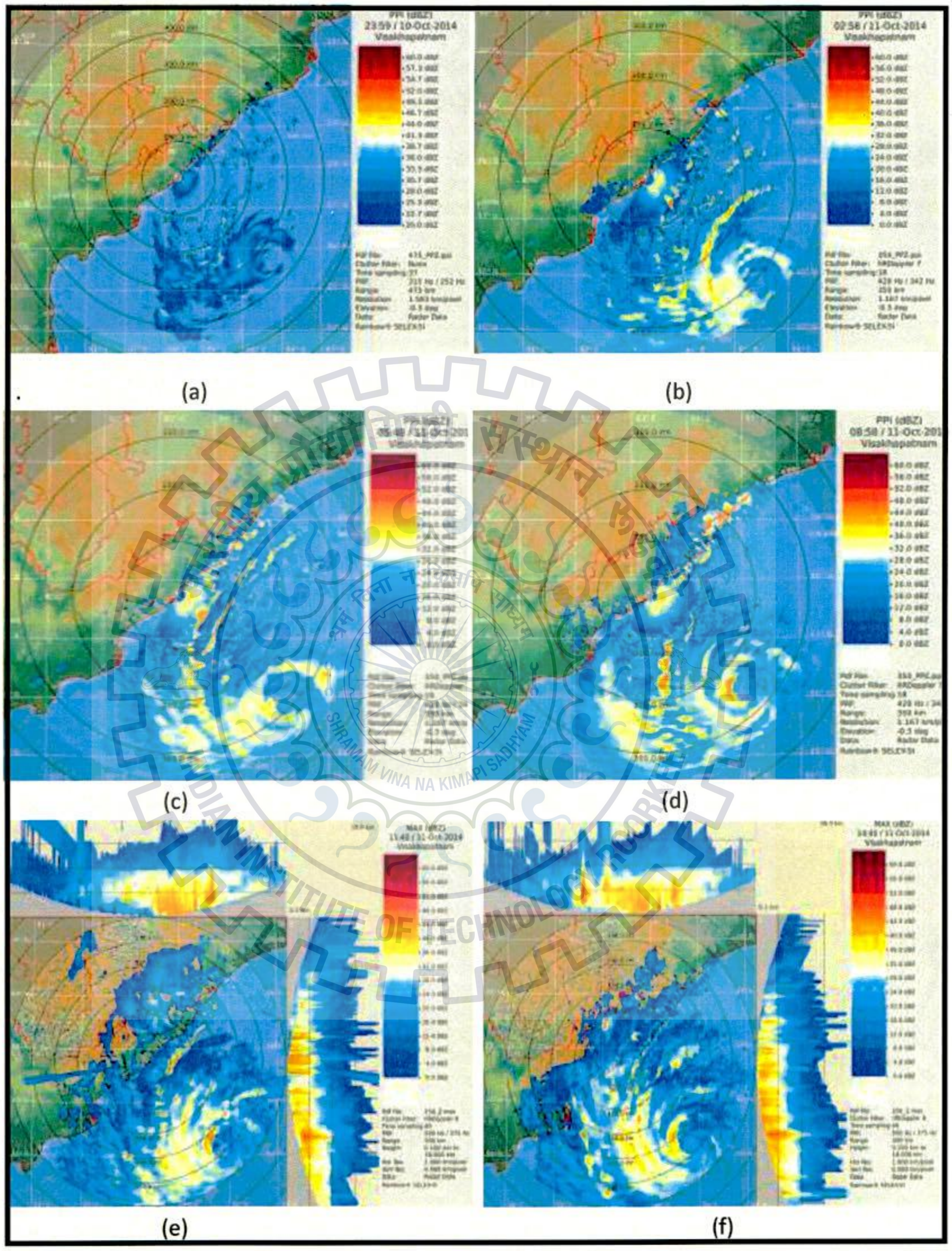


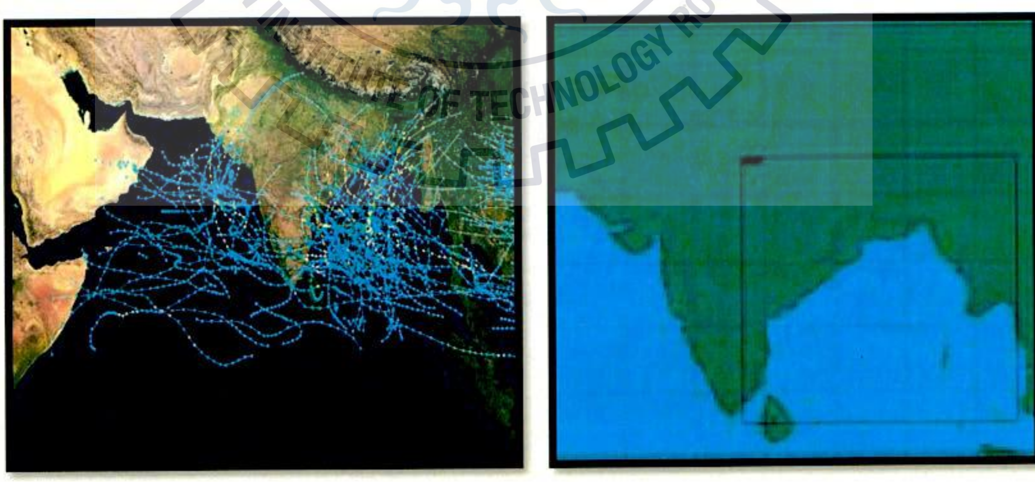
Figure 4.5: Visakhapatnam RADAR imageries depicting Max Z based on (a) 0000 UTC (b) 0300 UTC (c) 0600 UTC (d) 0900 UTC (e)1500 UTC of 11th October 2014 (Source: IMD, Radar Division)

5. DATA AND RESEARCH METHODOLOGY

In the current years mesoscale models are substantially utilised for simulation of various phases of tropical cyclones Numerous numerical research have been performed over the Bay of Bengal system using cloud- scale models to examine model performance in accordance with resolution, initial conditions, data assimilation etc. e.g. Srinivas et al., 2007,2012; Osuri et al., 2011, 2012; Mohanty et al., 2010. Pielke et al. 2006 experimentally determined the need to study the impact of initial condition is essential for accurate prediction. In the present study VSCS 'Hudhud' is simulated using WRF model on the basis of various initial conditions and source of initial condition. Forecast of considered TC's characteristics is generated followed by diagnostics and subsequent verification. Here, ARW is initialised with analysis data of IMD's Global Forecasting System (IMD-GFS) and "National Centers for Environmental Prediction" GFS (NCEP-GFS).

5.1 Study Domain

The domain considered for study is the Bay of Bengal of North Indian Ocean (NIO) basin. NIO basin is comprehensible from Figure 5.1. NIO basin is bifurcated in 2 regions i.e. the Bay of Bengal and the Arabian Sea, with the Bay of Bengal witnessing 7-8 times the activity than the latter. The NIO is considered to be relatively stagnant when compared with other basin, with 5-7 cyclones on per annum basis. There are 2 peak season of cyclonic activity in the basin, one in April –June before onset of monsoon and second in October-November. Although the North Indian Ocean (NIO) Basin generates about 7% of global total cyclone, their devastating effect and catastrophic sway in the region has drawn copious prominence and attention. Model simulations were made over two domains. Domain 1 (do1) covered entire national boundary of India and Domain 2 (do2) was restricted to the Bay of Bengal system. The horizontal resolution of the parent domain was set at 27 km and for nested domain 9 km.



(a) (b)

Figure 5.1: The NIO basin (a) Tracks of all TCs in the NIO from 1980 to 2005 (b) Nested Domain (do2)

5.2 Model Specifics

5.2.1 Weather Research Forecasting Model

The version of WRF model used is WRF-3.6.1. Weather Research and Forecasting (WRF) Model is a product of cooperative alliance, primarily designed by the NCAR. It is pliable, modern atmospheric and weather simulation system, mobile and methodical on available parallel computational platform, productive for use in a wide spectrum of utilities with scales amounting from meters to thousands of kilo-meters and includes operational Numerical Weather Prediction, forecasting advancement, and integrated-model utilization. The model can also be set as either a one-way, two way nesting, or a moving nest model. These options allow the WRF-ARW model to be versatile for both research and operational purpose (Skamarock et al., 2008). These options allow the WRF-ARW model to be versatile for both research and operational purpose.

5.2.2 Components

The components of WRF Model include (Figure 5.2):

1. WRF Pre-processing System (WPS)
2. WRF-ARW solver and codes
3. WRF Post processing

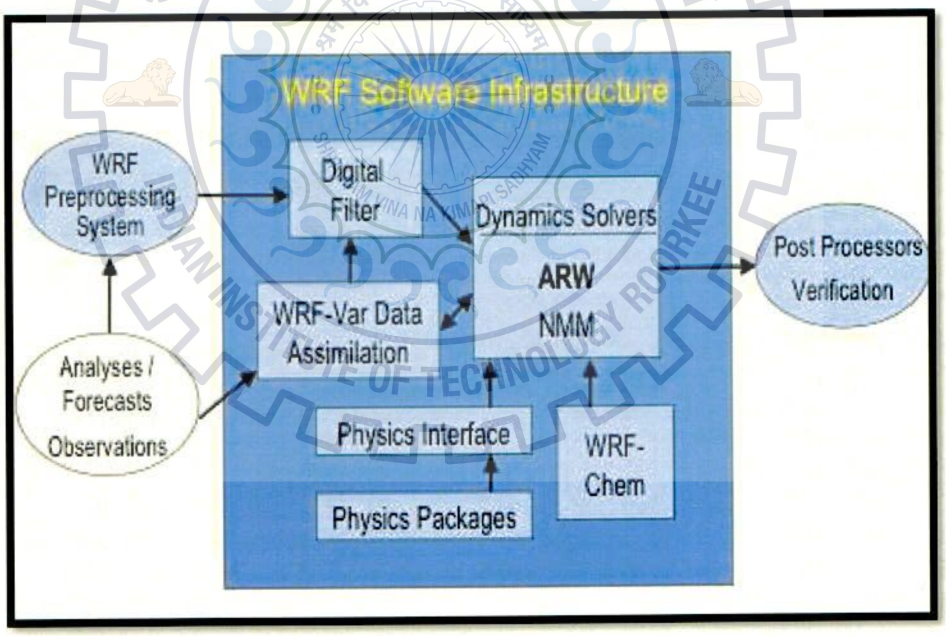


Figure 5.2: Components of WRF Model Skamarock *et al.* (2008).

1. WRF Pre-processing System (WPS)

WPS is used to interpolate terrestrial data and meteorological data for real data simulation. Following utilities are exploited in WPS for the preparation of inputs:

Geogrid: Defines simulation domain and ARW nested domains. It interpolates the static geographic data to the grids of the model domain. Some of the time Invariant terrestrial fields interpolated by Geogrid are Topography height, Land use categories, Soil type (top layer & bottom layer), Annual mean soil temperature, Monthly vegetation fraction, Monthly surface albedo.

Ungrib: It degribs or extracts the Grib format meteorological fields into intermediate format.

Metgrid: It interpolates the time varying meteorological data from another model obtained by Ungrib to the domain expounded by Geogrid horizontally. The various interpolation options available are 4-point bilinear, 16-point overlapping parabolic, 4-point average (simple or weighted), 16-point average (simple or weighted), Grid cell average, nearest neighbour, and Breadth.

2. WRF-ARW solver

The final analysis is processed into gridded forecasts by the WRF-ARW dynamics solver. The dynamic solver uses second and third order Runge-Kutta schemes to generate forecasts. Also during this stage, the physics parameterization schemes are applied to the analysis between time steps (Wang et al. 2011). After the WRF-ARW dynamics solver has generated forecasts, the data can then be output to meteorological packages such as the NCAR Command Language (NCL) or the Read/Interpolate/Plot (RIP4) data visualization packages (Michalakes et al. 2010; Janjic et al. 2010).

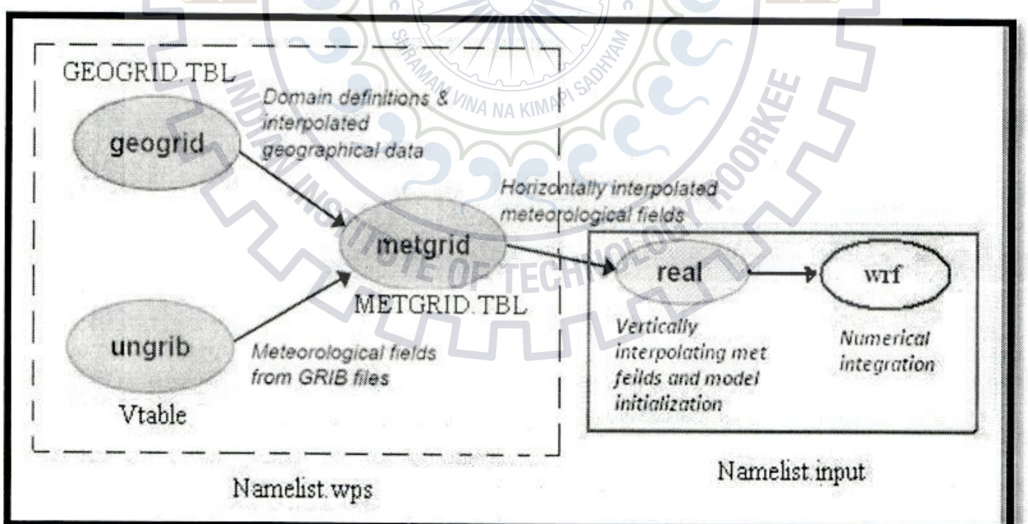


Figure 5.3: Summary of WRF Process Flow (Duda, 2010)

WRF- ARW Governing Equations: To determine the state of the atmosphere, the ARW dynamical solver "integrates compressible, non-hydrostatic Euler equations". "These equations are depicted in flux form using scalar variables with conservation properties" (Ooyama, 1990)

$\delta_t U + (\nabla \cdot \mathbf{V}u) - \delta x(p\delta_n\Phi) + \delta n(p\delta x\Phi) = Fu$ — Horizontal Momentum Equations

$\delta_t V + (\nabla \cdot \mathbf{V}v) - \delta y(p\delta_n\Phi) + \delta n(p\delta y\Phi) = Fv$

$\delta_t W + (\nabla \cdot \mathbf{V}w) - g(\delta_n p - \mu) = Fw$ .... Vertical Momentum Equation

$\delta_t \theta + (\nabla \cdot \mathbf{V}\theta) = F_\theta$ .... Thermodynamic Equation

$\delta_t \mu + (\nabla \cdot \mathbf{V}) = 0$ .... Continuity Equation

$\delta_t \Phi + \mu^{-1}[(\nabla \cdot \mathbf{V}\Phi) - gW] = 0$ .... Geopotential Height Equation

3. WRF Post processing

It is used for post processing the WRF outputs. There are a numerous tools available to visualize WRF-ARW model data. NetCDF format is quite portable and can be readily visualized by utilising most of the displaying tools. Supported post-processing software tools are NCL, RIP4, ARWpost, and VAPOR. VAPOR software package used for 3-dimensional visualization of WRF data. NCL and ARWpost are currently used by India Meteorological Department to display forecast in real time.

In the present study an NCAR Command Language (NCL) is used for the purpose. NCL, a product of the Computational & Information Systems Laboratory at the National Center for Atmospheric Research (NCAR) and sponsored by the National Science Foundation, is a free interpreted language designed specifically for scientific data processing and visualization.

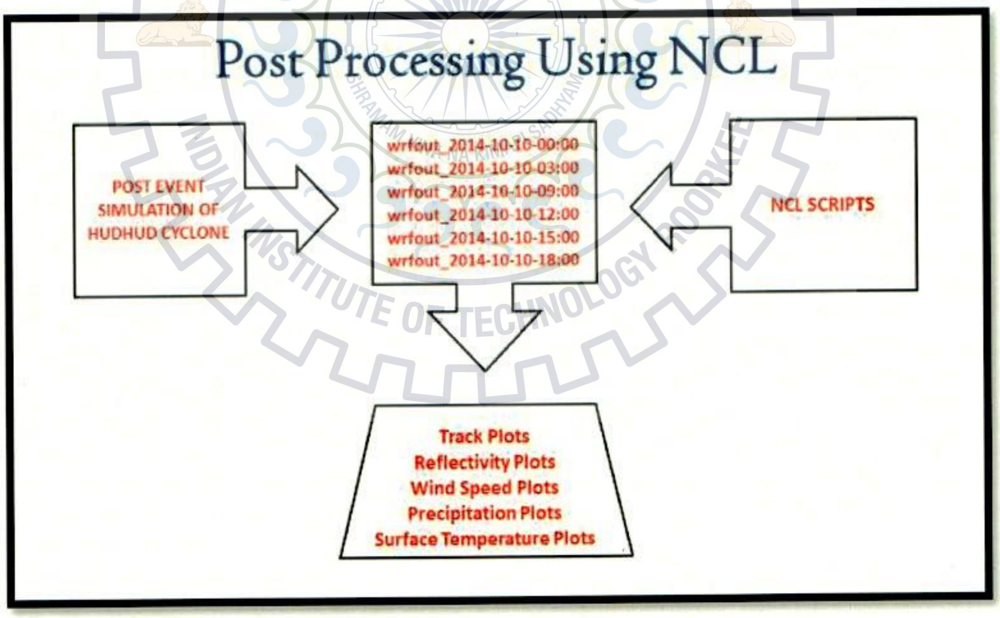


Figure 5.4: Post Processing Using NCL

5.2.4 Model Initialization

The United States Geological Survey (USGS) terrain topographical data of resolution 10' and 2' is used for pre-processing. The GFS analysis data having resolution of 0.25° is used for initialisation of ARW at a constant interval of 6 hours as initial and lateral boundary condition. Table 6 provides set of Initial Conditions used for simulation of VSCS Hudhud.

SOURCE	SIMULATION SEQUENCE	INITIAL CONDITION	LEAD TIME	FORECAST DATES
IMD- GFS	1	00 UTC of 7 October 2014	72	7th, 8th ,9th October
	2	00 UTC of 8 October 2014	72	8th, 9th ,10th October
	3	00 UTC of 9 October 2014	72	9th, 10th ,11th October
	4	00 UTC of 10 October 2014	72	10th, 11th ,12th October
	5	00 UTC of 11 October 2014	72	11th, 12th ,13th October
NCEP- GFS	6	00 UTC of 7 October 2014	72	7th, 8th ,9th October
	7	00 UTC of 8 October 2014	72	8th, 9th ,10th October
	8	00 UTC of 9 October 2014	72	9th, 10th ,11th October
	9	00 UTC of 10 October 2014	72	10th, 11th ,12th October
	10	00 UTC of 11 October 2014	72	11th, 12th ,13th October

Table 6: Initialisation Details

5.2.3 Experimental Setup

In this experiment two way WRF-ARW nesting is used for five set of experiment covering entire life-span of VSCS Hudhud (7th – 14th October 2014). The horizontal resolution of the parent domain is set at 27 km and for nested domain 9 km is set with 28 vertical levels.

DOMAIN DETAILS	
Map Projection points	Mercator
Reference Latitude of the domain	21.562
Reference Longitude of the domain	82.018
Number of domain	2
Number of vertical layers	28
Horizontal grid distance	27 Km and 9 Km
Time steps	90 seconds
e_we and e_sn	132, 226 and 134, 247
Nesting	Two way interactive
Resolution of Geographical data Nesting	10' and 2'

Table 7: Model Configuration Details

The model is integrated with 90 seconds time steps for the 72 hours simulation. Microphysics used is mp_physics = 3; "WRF single moment 3-class scheme with ice and snow process" suitable for mesoscale grid size. The cumulus parameterization (cu_physics) was taken as 2; Betts-Miller-Janjic scheme. Table 7 provides model configuration details.

5.2.6 Experimental Procedure

In the current experiments computer simulated NWP Program, WRF Model is executed using High Power Computing System (HPCS) at IITM-Pune. Version of WRF model program is WRF- 3.6.1 and HPCS involved is 'AADITYA Supercomputer'.

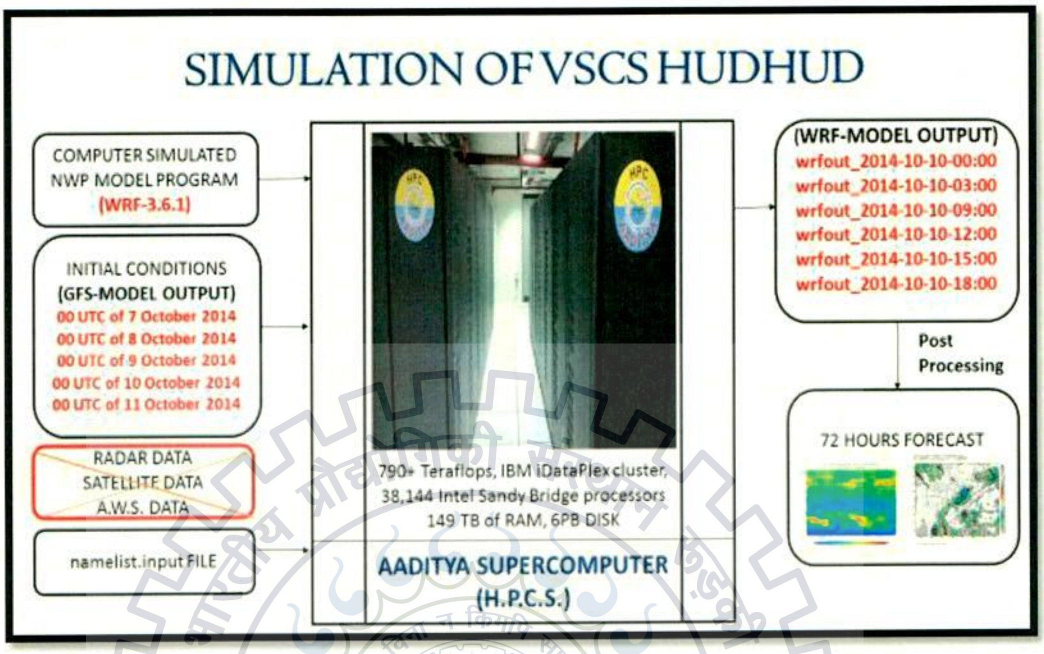


Figure 5.5: Flowchart of Experimental Procedure

ARW is initialised with relevant initial conditions which is basically GFS analysis data. Observations procured from Radar, Satellite and AWS are assimilated into the Model program. However in present study the assimilation process has been bypassed. Namelist file is compiled as per requirement. Details mentioned in Model Configuration Table (Table 5.2) is used in present experiment for Namelist file scripting. Output of the program execution are wrfout data files which are further post processed to obtain desirable forecast. Figure 5.5 illustrates flow sequence of the experiment.

5.3 Verification Method

Skill scores have been calculated to investigate and decipher the impact of initial condition over track and intensity prediction obtained by VSCS Hudhud simulation. Track error is obtained using Direct Position Error (DPE). Maximum Sustained Wind (MSW) and Central Sea Level Pressure (CSLP) are compared with observed values. To obtain DPE distance between two earth coordinates is evaluated. This computation is accomplished through the usage of Haversine Formula. The Haversine formula evaluates the great- circle distance between any 2 points on the sphere. The Haversine of the central angle between any two points on sphere is:

$$\text{haversin}\left(\frac{d}{r}\right) = \text{haversin}(\phi_2 - \phi_1) + \cos(\phi_1)\cos(\phi_2)\,\text{haversin}(\lambda_2 - \lambda_1)$$

Where,

- haversin is Haversine function
- d is the distance between the two points
- r is the radius of the sphere
- ϕ_1, ϕ_2 are latitude of point 1 and latitude of point 2
- λ_1, λ_2 are longitude of point 1 and longitude of point 2

L.H.S. has d/r which is the central angle calculated in radians assuming angles are measured in radians. Solve for 'd' by applying the inverse haversine (if available) or by using the arcsine (inverse sine) function:

$$d = r \operatorname{haversin}^{-1}(h) = 2r \arcsin\left(\sqrt{h}\right)$$

To use above formula in computer programming to evaluate distance 'd', the expression can be re-written as

$$d = R * c$$

Where,

- R is the radius of the Earth
- c = 2 * atan2(sqrt(a), sqrt(1-a))
- a = $(\sin(dlat/2))^2 + \cos(lat1) * \cos(lat2) * (\sin(dlon/2))^2$
- dlon = lon2 - lon1
- dlat = lat2 - lat1

6. RESULTS AND DISCUSSIONS

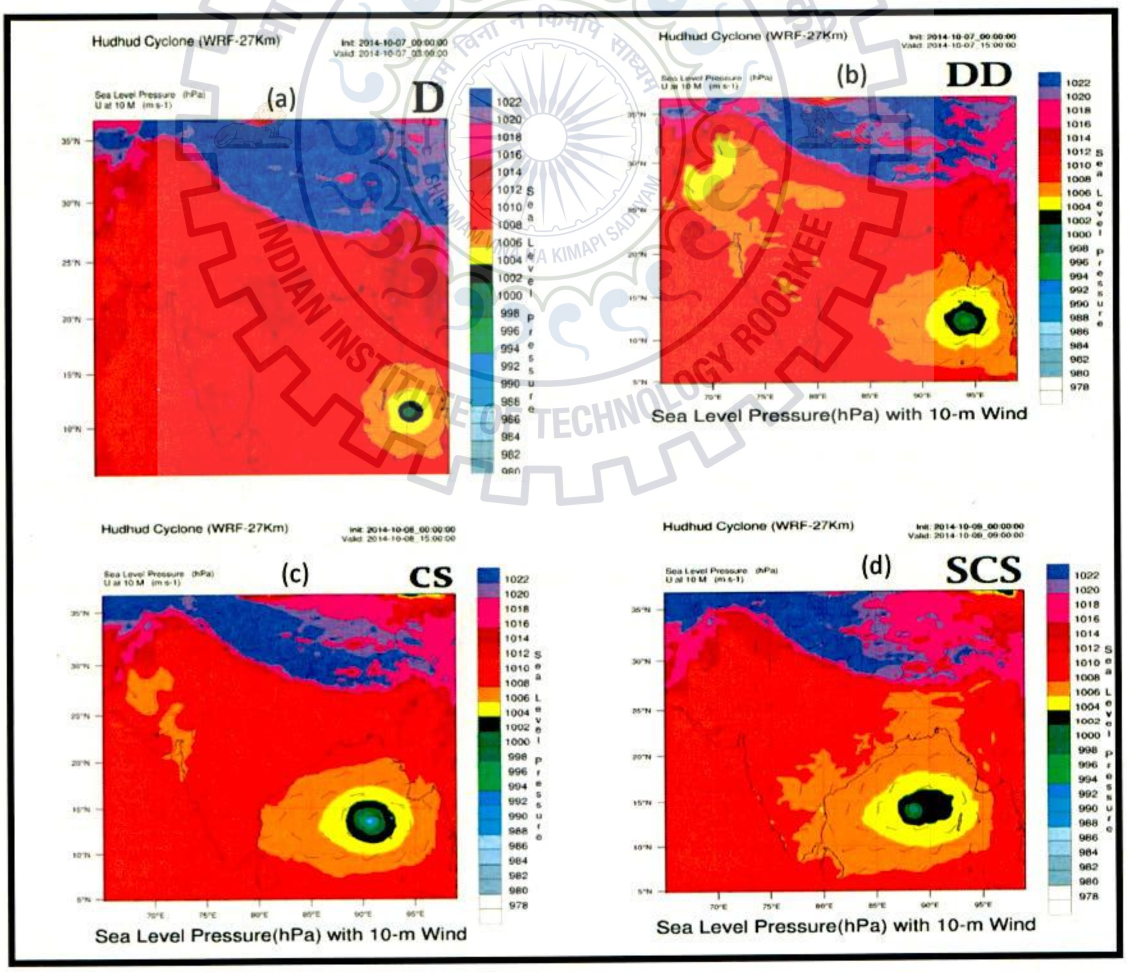
The prime impact of mesoscale WRF simulation of VSCS Hudhud is mainly based on track and intensity prediction of the storm inculcated during its lifespan of 8 days (7th to 14th October, 2014).

6.1 Cyclone Intensity Forecast

The WRF analysis based on 00 UTC of 7th October 2014 depicted Deep depression northwestwards of the Andaman Sea. It would eventually intensify into Cyclonic storm by 8th October, 2014 and Super Cyclonic Storm by 9th October. Model also predicted that system would eventually turn into Very Severe Cyclonic Storm by 10th October and landfall date could be 12th October.

6.1.1 Minimum Sea Level Pressure (MSLP)

Figure 6.1 depicts Sea Level Pressure (SLP) variation and 10 m wind during` intensification and decay of cyclone (based on IMD-GFS as initial condition). Trajectory of Minimum Sea Level Pressure marks the track of the cyclone. The system can be observed moving northwestwards.



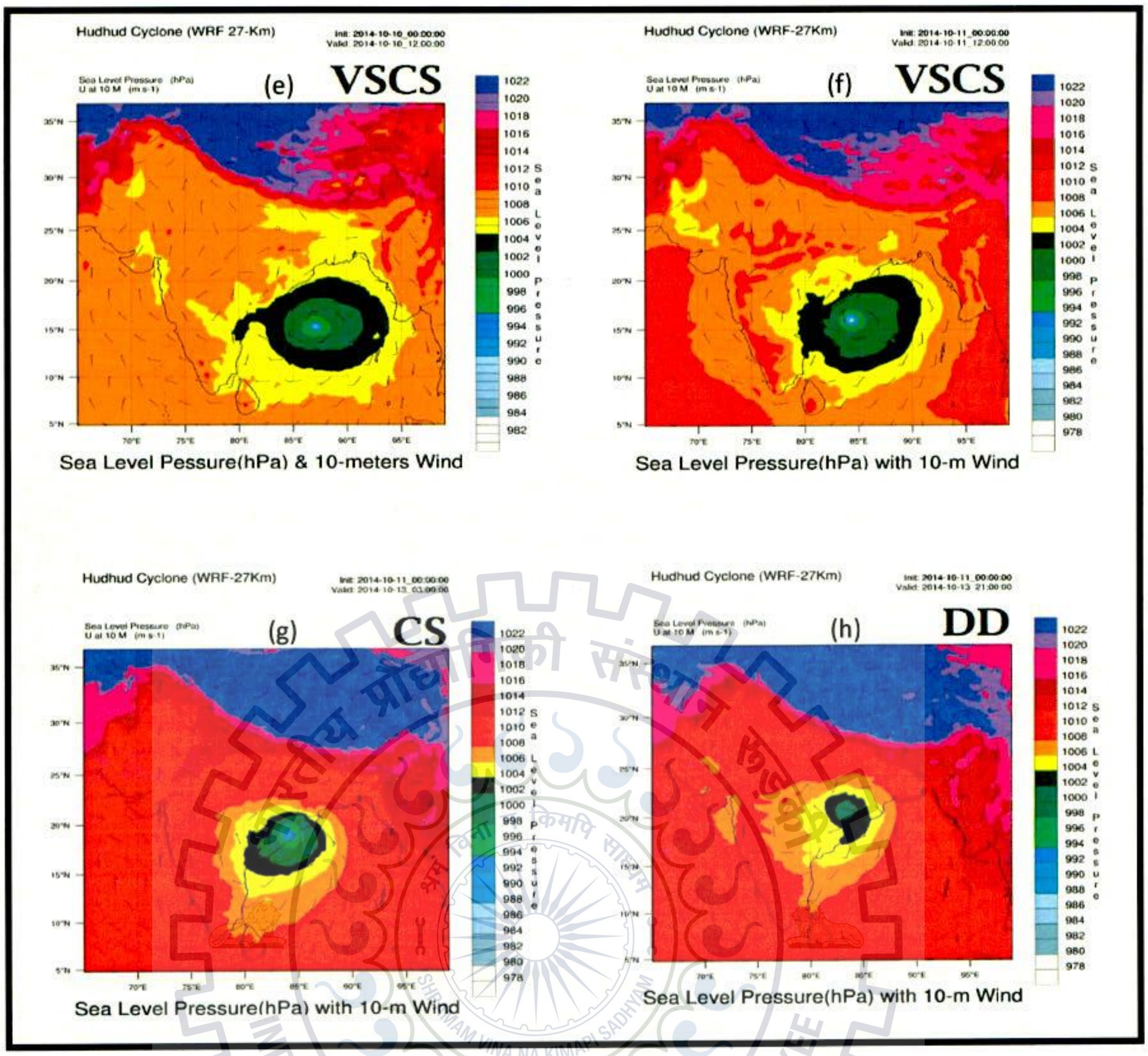
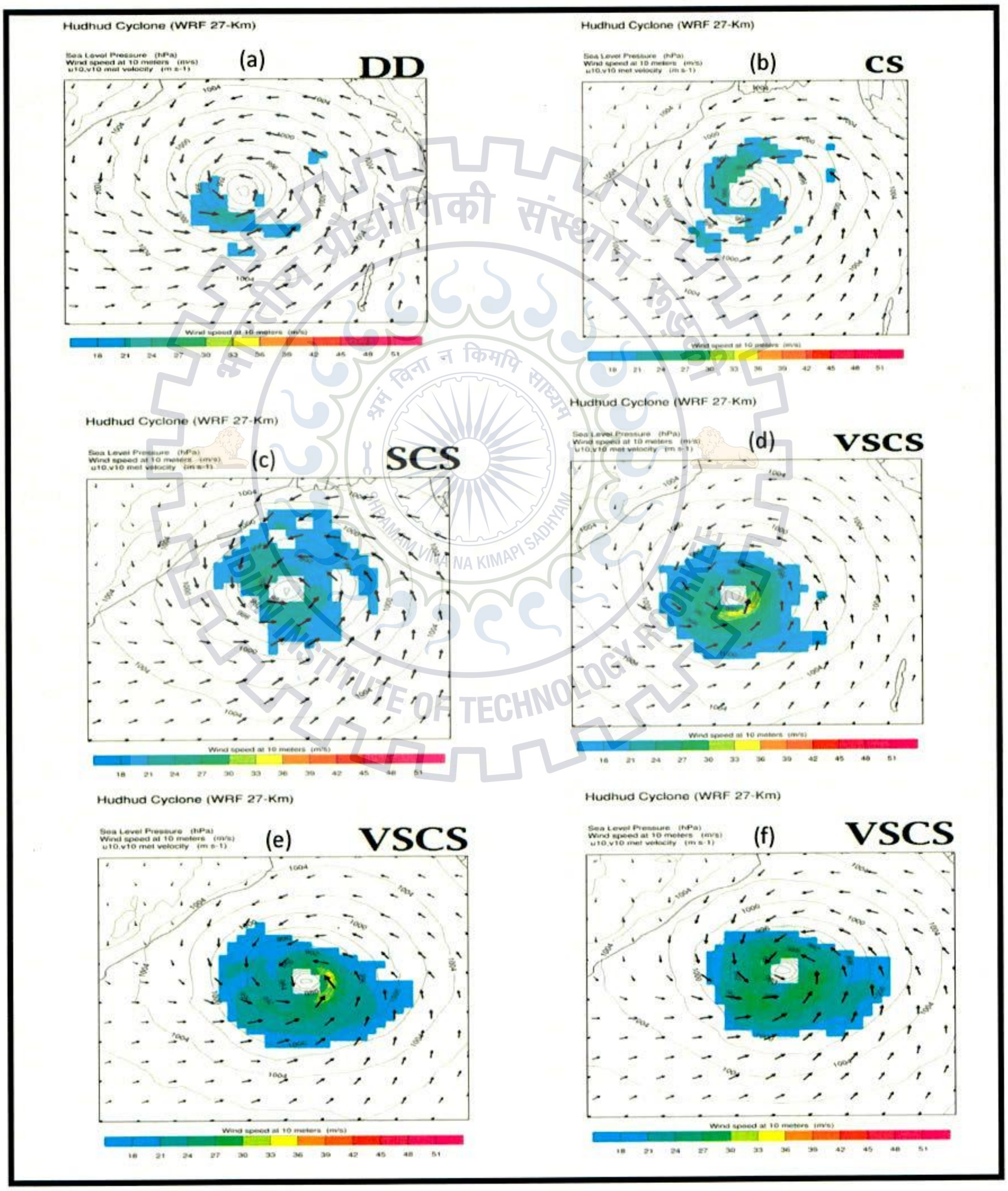


Figure 6.1: Sea Level Pressure at 10 metre wind; D = Depression, DD = Deep Depression, CS = Cyclonic Storm, SCS = Severe Cyclonic Storm, VSCS = Very Severe Cyclonic Storm; (a) D for 0300 UTC of 7th Oct.; (b) DD for 1500 UTC of 7th Oct.; (c) CS for 1500 UTC of 8th Oct. (d) SCS for 0900 UTC of 9th Oct. (e) VSCS for 1200 UTC of 10th (f) VSCS for 1200 UTC of 11th Oct. (g) CS for 0300 UTC of 13th Oct. (h) DD for 2100 UTC for 13th Oct.

The Sea Level Pressure plots elaborately depicts the movement of the system towards mainland India region. As valid for observed statistics, the model too predicted inception of the VSCS Hudhud north of the Andaman Sea. At this instant i.e. morning of 7th October 2014, the system was classified as a Depression (D), Minimum Sea Level Pressure (MSLP) being 999 hPa. Second plot reveals the intensification of into Deep Depression (DD) and MSLP value depreciated to 995 hPa. The DD moved further northwestwards intensifying into Cyclonic Storm (CS) on 8th of October 2014 and MSLP value further decreased to 992 hPa. By the early morning of 9th October 2014, the system further advanced in northwestward direction and simultaneously growing into Severe Cyclonic Storm (SCS) with Minimum Sea Level Pressure value as 988 hPa. The system was predicted to intensify to its maximum limit into Very Severe Cyclonic Storm (VSCS) on 10th October 2014 and continue moving northwestwards with same intensity till end of 11th October 2014. During this time period the MSLP value ranged of 984 hPa-973hPa. The landfall date was expected to be on 12th October 2014 between 0600 to 1200 UTC. After hitting the coast, the model predicted that the system will start decaying and by the end of 12th October 2014 it would be weaken to CS and by the end 13th October 2014 into a Depression. Thereafter, it was predicted to shrink into a low pressure area over east of Uttar Pradesh & neighbourhood in the evening of 14th October 2014.

6.1.2 Maximum Sustained Wind (MSW)

Figure 6.2 depicts Intensification and Decay of VSCS Hudhud based on Maximum Sustained Winds (MSW).



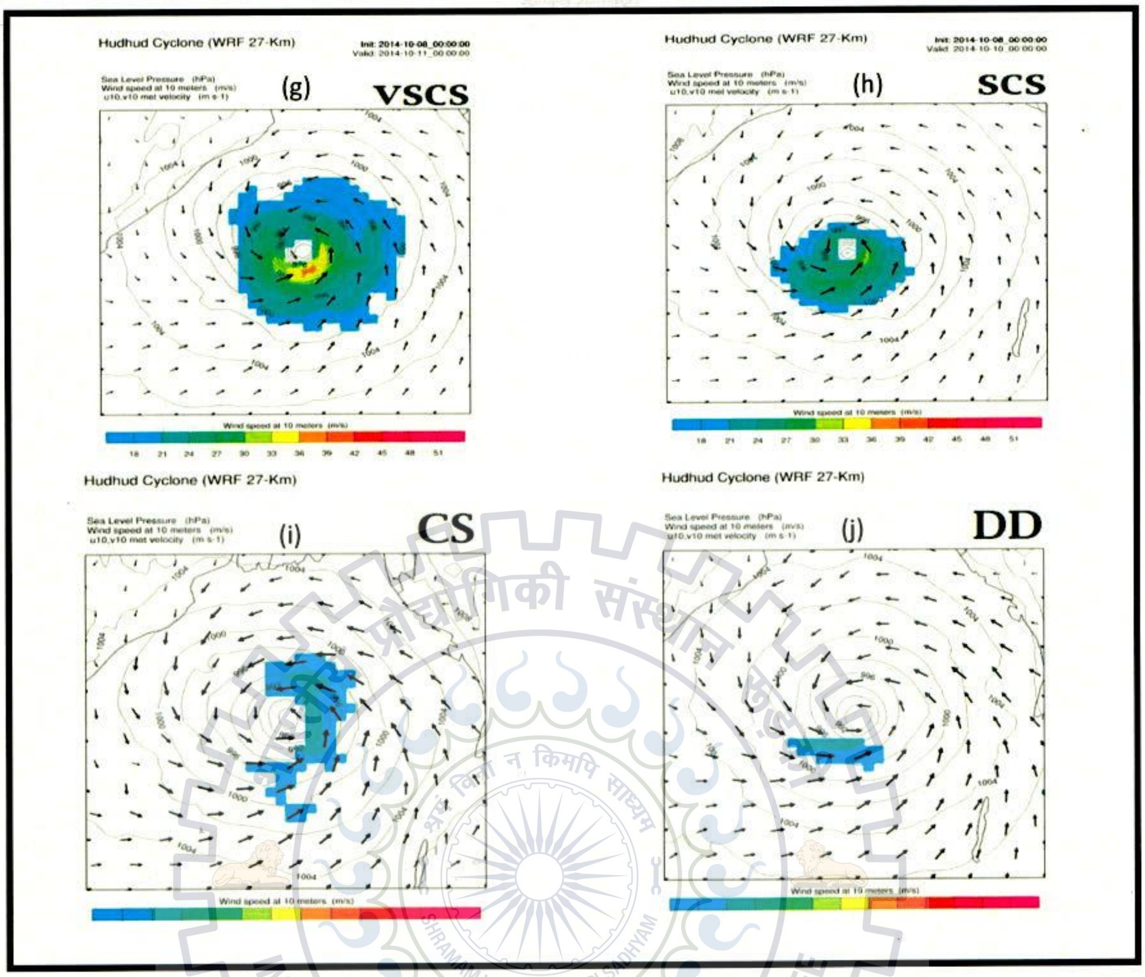


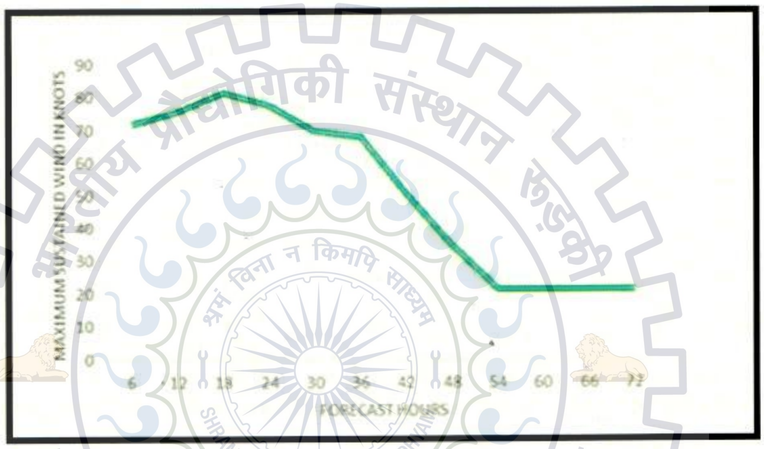
Figure 6.2: Zoomed revelation of intensification & decay of TC Hudhud based on MSW (a) DD for 1500 UTC of 7th Oct. (b) CS for 1500 UTC of 8th Oct. (c) SCS for 0900 UTC of 9th Oct. (d) VSCS for 1200 UTC of 10th (e) VSCS for 1200 UTC of 11th Oct. (f) VSCS for 2100 UTC of 11th Oct. (g) VSCS for 0300 UTC of 12th Oct. (h) SCS for 1200 UTC of 12th Oct. (i) CS for 0300 UTC of 13th Oct. (j) DD for 2100 UTC for 13th Oct.

Violent winds are the most destructive hazard of cyclones. MSW are predicted to mark the vigour and the damage potential of the system. Nomenclature of a cyclonic disturbance is based on IMD 2003 classification using MSW for the purpose (refer Table 1 on Page 1). Recent developments by IMD in classification of cyclonic disturbances have led to bifurcation of VSCS class (118 kmph-221 kmph) into VSCS (118 kmph-166 kmph) and Extensive Severe Cyclonic Storm (ESCS) (167 kmph-221 kmph) (as discussed in Pre-Cyclone Exercise, 15th April 2015).

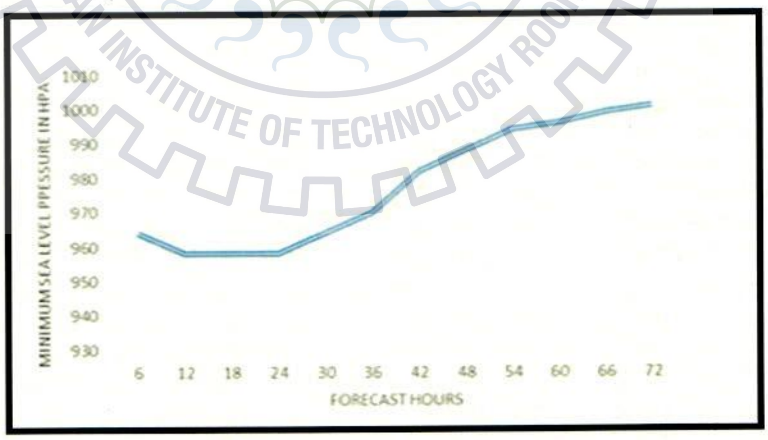
On 7th October 2014 the predicted MSW value of the system was 35 knots, hence it was categorised as DD. By the morning of 8th October 2014 the system had MSW value of 44 knots, which would come under range of CS. Model predicted that on 9th October 2014 the MSW values would be in range of 50 knots and 60 knots therefore it is named as SCS. For 10th October 2014 the MSW values would be between 65 knots and 75 knots thus making system as VSCS. By 11th October 2014 the MSW was to be in range of 76 knots and 83 knots there by system was continuing as VSCS. 12th October 2014 would be the probable landfall date in case of Hudhud (valid for this case only as system will not be weaken before landfall) as sudden abrupt decrease in MSW values are reflected. Characteristics obtained for further time period shows spontaneous depreciation in MSW values thereby reflecting decay of the system. By the end of 14th October 2014 the MSW value was predicted to be beneath 30 knots.

6.1.3 Landfall Characteristic

Figure 6.3 illustrates variation of Maximum Sustained Wind and Minimum Sea Level Pressure in accordance with Forecast hours on the basis of 00 UTC 11 October 2014 initial condition (NCEP- GFS). From the graph, sudden decrease in MSW (Figure 6.3 a) reveals landfall time between 0600 UTC - 1200 UTC of 12th October 2014 and abrupt increase in MSLP (Figure 6.3 b), determines decay of Cyclonic activity after 0600 UTC 2014.



(a) Maximum Sustained Wind

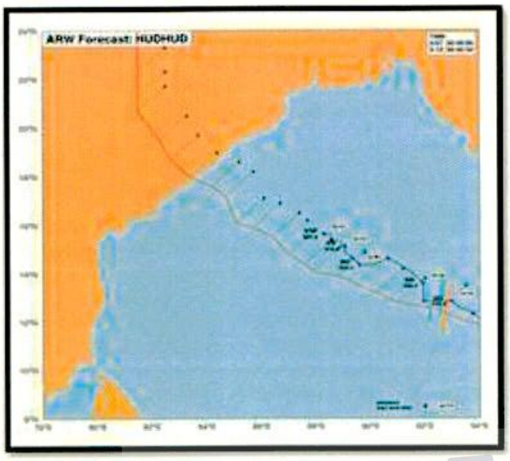


(b) Minimum Sea Level Pressure

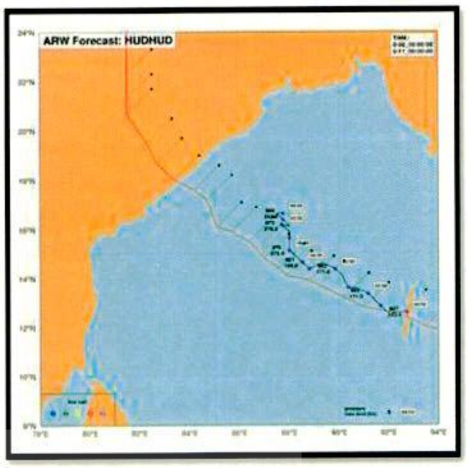
Figure 6.3: Variation of (a) (MSW) and (b) MSLP with Forecast Hours on basis of 00 UTC of 11th October 2014 initial condition

6.2 Cyclone Track Forecast

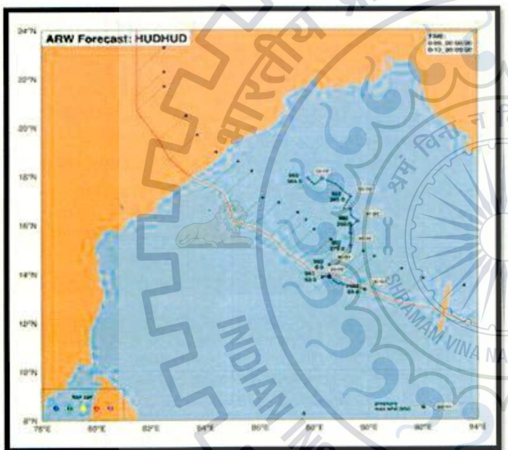
Cyclone Track Forecast based on IMD-GFS as IBC is depicted in Figure 6.4.



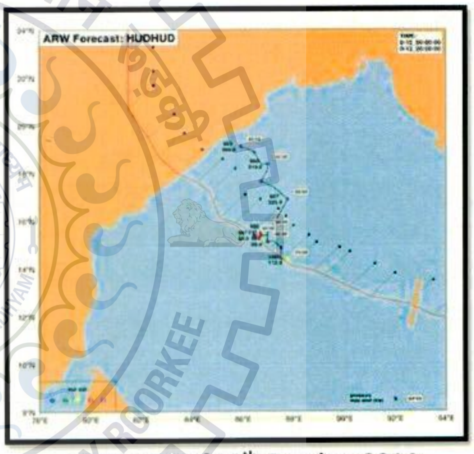
(a) 00 UTC of 7th October 2014



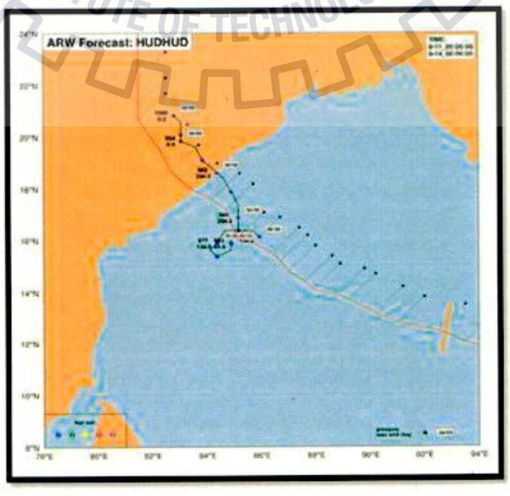
(b) 00 UTC of 8th October 2014



(c) 00 UTC of 9th October 2014



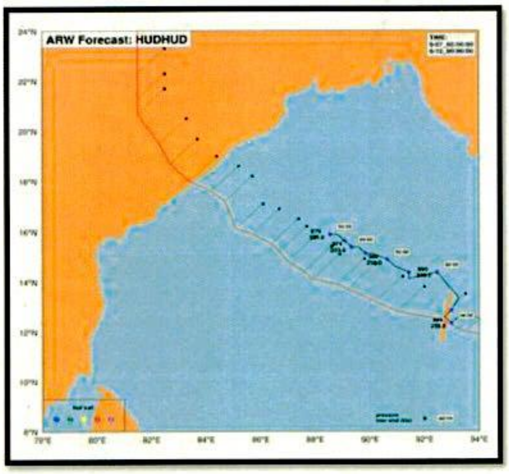
(c) 00 UTC of 10th October 2014



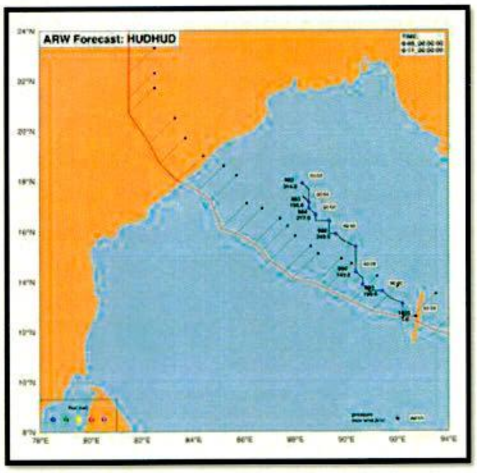
(e) 00 UTC of 11th October 2014

Figure 6.4: Cyclone Track based on IMD-GFS as IBC

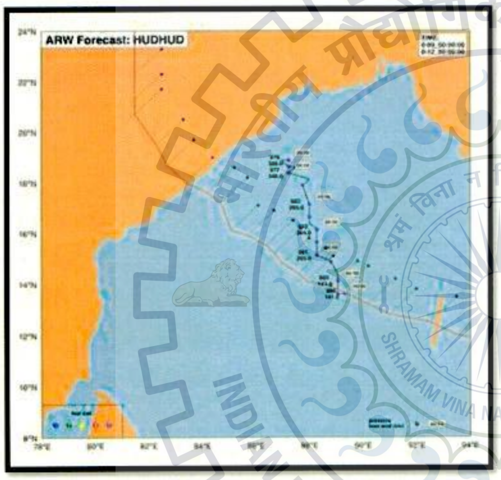
Cyclone Track Forecast based on NCEP-GFS as IBC is depicted in Figure 6.5.



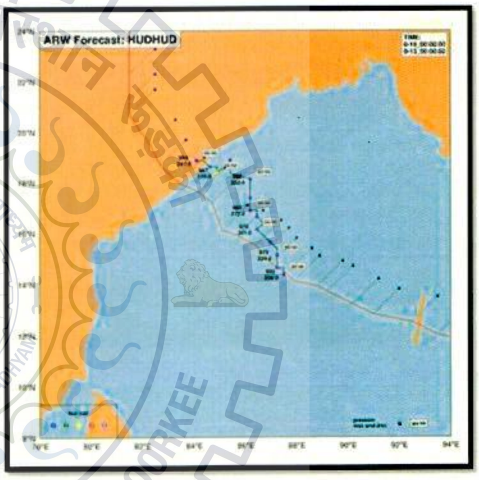
(a) 00 UTC of 7th October 2014



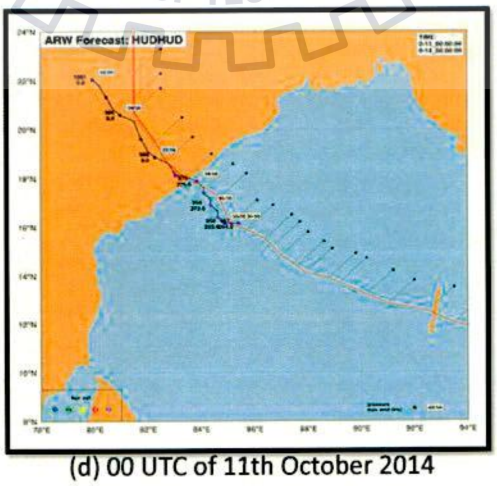
(b) 00 UTC of 8th October 2014



(c) 00 UTC of 9th October 2014



(d) 00 UTC of 10th October 2014



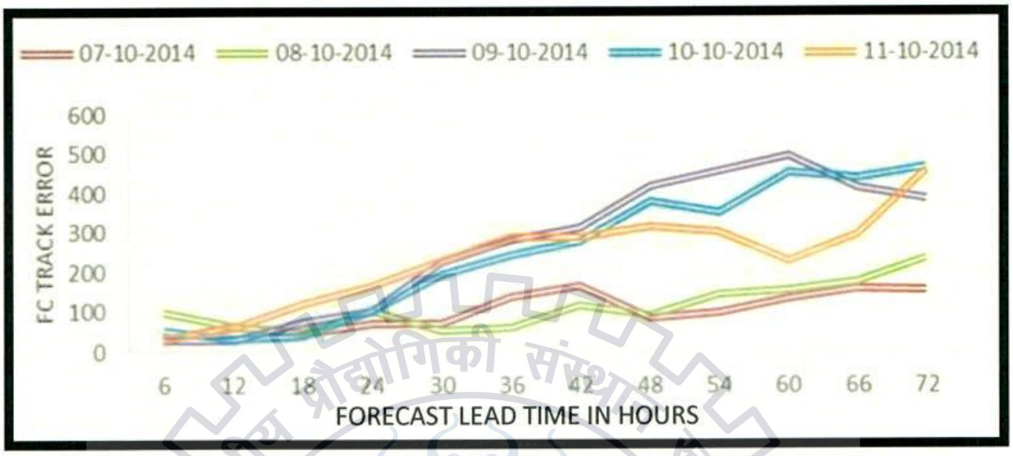
(d) 00 UTC of 11th October 2014

Figure 6.5: Cyclone Track based on NCEP-GFS as IBC

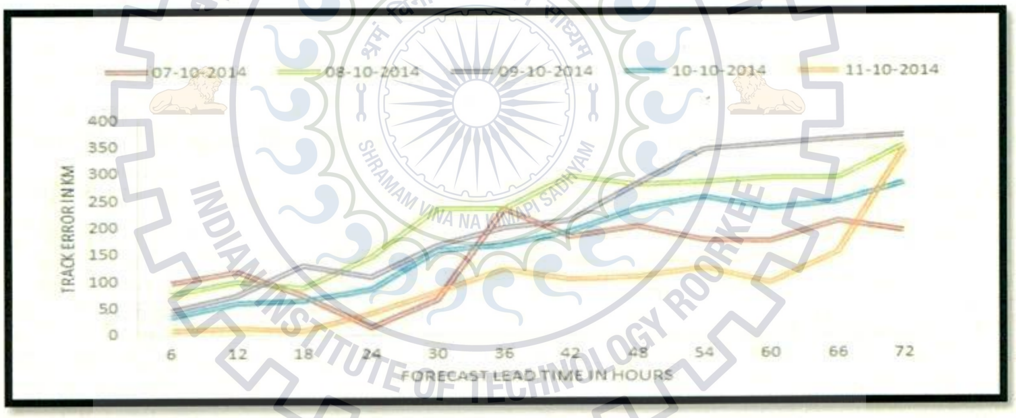
6.3 Verification Results

6.3.1 Track Error

Track error obtained per initial condition in accordance with forecast lead time is shown in Figure 6.6. Table 8 reflects DPE value for the two sources used as Initial and Boundary Condition (IBC) i.e. NCEP- GFS and IMD-GFS. The average track forecast errors of WRF models inclusive of results obtained from both the sources.



(a) IMD-GFS as initial and boundary condition



(b) NCEP-GFS as initial and boundary condition

Figure 6.6: Forecast Track Error using (a) IMD-GFS as IBC (b) NCEP-GFS as IBC

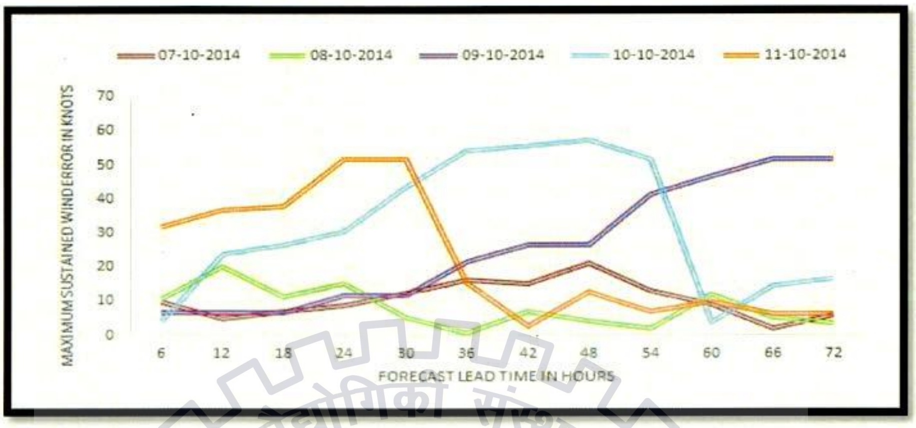
SOURCE OF INITIAL CONDITIONS	12 h	24 h	36 h	48 h	60 h	72 h
IMD- GFS	49.1	108	201.5	258.2	293	340.7
NCEP- GFS	72.3	79	191.9	221.7	230.1	309.2

Table 8: Average track forecast errors (Direct Position Error) in Km

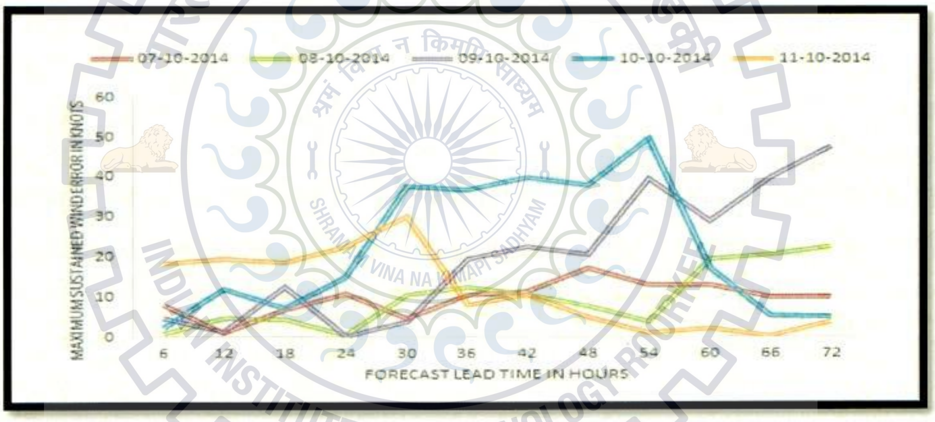
6.3.2 Intensity Error

MSW error (knots) and MSLP error (hPa) obtained per initial condition in accordance with forecast lead time is shown in Figure 6.7 and 6.8 respectively. Table 9 and Table 10 reflects Mean MSW error (knots) and Mean MSLP error (hPa) respectively.

1. Maximum Sustained Wind Verification



(a) IMD-GFS as initial and boundary condition



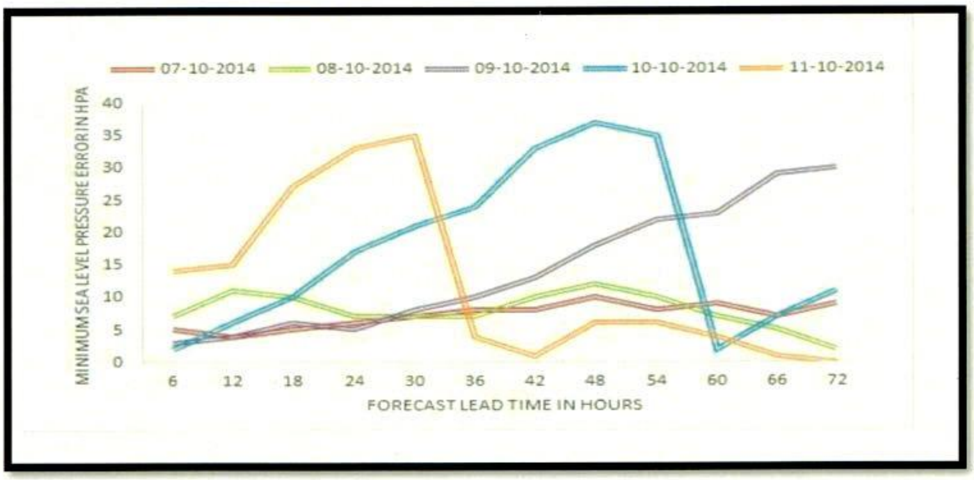
(b) NCEP-GFS as initial and boundary condition

Figure 6.7: Forecast Maximum Sustained Wind error using (a) IMD-GFS as initial and boundary condition (b) NCEP-GFS as initial and boundary condition

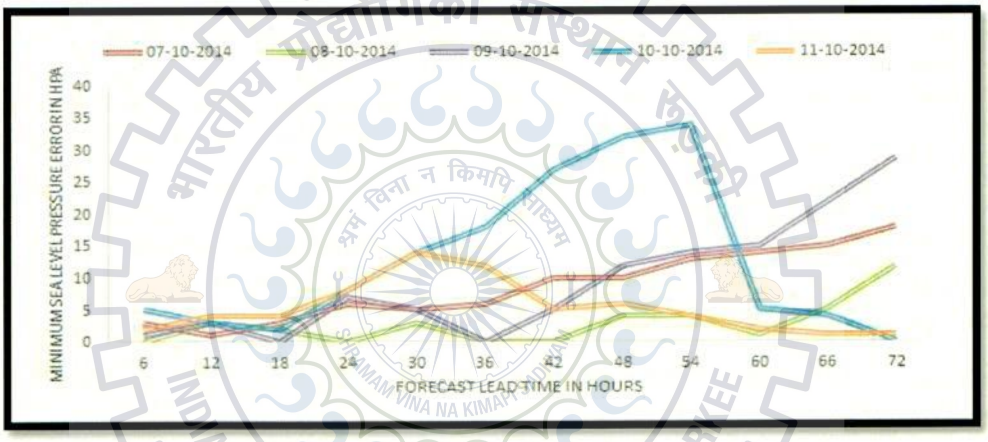
SOURCE OF INITIAL CONDITIONS	12 h	24 h	36 h	48 h		72 h
IMD- GFS	19.1	24.6	24.0	24.7	17	16.2
NCEP-GFS	7.6	9.7	17.4	17.6	16.2	17.7

Table 9: Mean Maximum Sustained Wind Error in Knots

2. Minimum Sea Level Pressure Verification



(a)) IMD-GFS as Initial and Boundary condition



(c) NCEP-GFS as initial and boundary condition

Figure 6.8: Forecast Minimum Sea Level Pressure error using (a) IMD-GFS as Initial and Boundary condition (b) NCEP-GFS as initial and boundary condition

SOURCE OF INITIAL CONDITIONS	12 h	24 h	36 h	48 h	60 h	72 h
IMD-GFS	8	13.6	10.6	16.6	9	10.4
NCEP-GFS	2.8	5.8	7.2	12.8	7.4	12

Table 10: Mean Minimum Sea Level Pressure Error in hPa

6.3.3 Comparative analysis of IBC

1. **Comparative Analysis of Direct Position Error (DPE):** Figure 6.9 depicts comparative analysis between two sources of IBC for DPE.

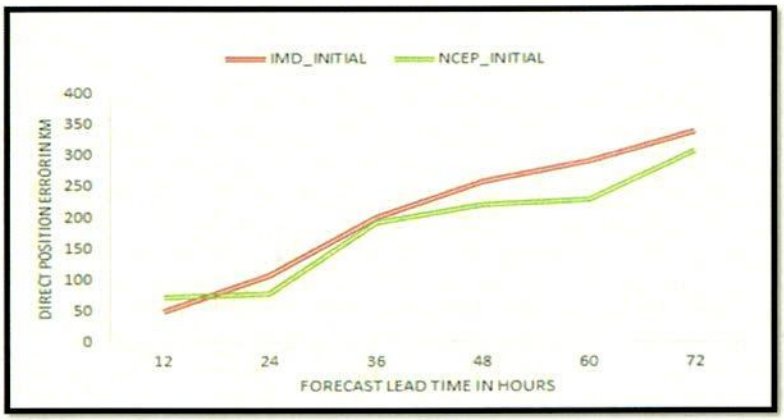


Figure 6.9: Comparative analysis between two sources of IBC for DPE

2. **Comparative Analysis of Maximum Sustained Winds (MSW):** Figure 6.10 depicts comparative analysis between two sources of IBC for MSW.

Figure 6.10: Comparative analysis between two sources of IBC for MSW

3. **Comparative Analysis of Minimum Sea Level Pressure (MSLP):** Figure 6.11 depicts comparative analysis between two sources of IBC for MSLP.

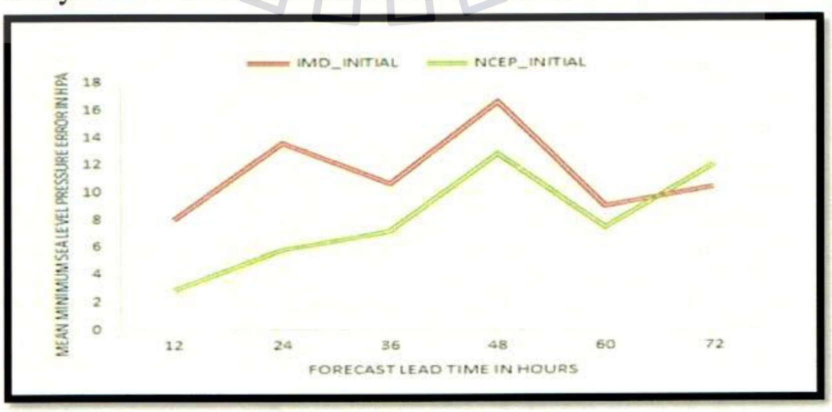


Figure 6.11: Comparative analysis between two sources of IBC for MSLP

7. THREE DIMENSIONAL VISULALIZATION

VAPOR software package used for 3-dimensional visualization of WRF data. VAPOR is a product of the NCARs Computational and Information Systems Lab. It is a Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers. VAPOR provides an interactive 3D visualization environment that can also produce animations and still frame images. VAPOR runs on most UNIX and Windows systems equipped with modern 3D graphics cards. VAPOR supports various visualizations of the WRF model's simulation output data through a direct data conversion process.

7.1 Features of VAPOR

WRF-ARW Data Support: Tools and translators to facilitate importing data output by the WRF-ARW community model.

Direct Volume rendering (DVR): Any 3D variable in the WRF data can be viewed as a density. Users control transparency and color to view temperature, water vapor etc. in 3D.

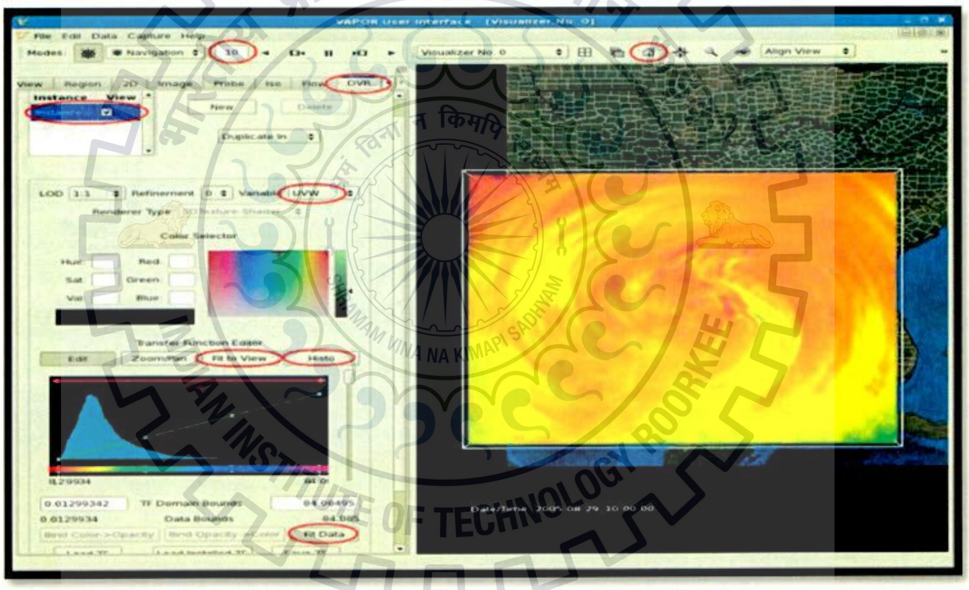


Figure 7.1: Direct Volume Rendering

Iso-surfaces: The iso-surfaces of variables are displayed interactively. Users can control iso-values, color and transparency of the iso-surfaces.

Contour planes and Probes: 3D variables can be intersected with arbitrarily oriented planes. Contour planes can be interactively positioned. Users can interactively pinpoint the values of a variable and establish seed points for flow integration.

Animation: Control the time-stepping of the data, for interactive replaying and for recording animated sequences.

Terrain rendering: The ground surface can be represented as a colored surface or can display a terrain image for geo-referencing.

7.2 Getting Started with VAPOR and WRF

WRF-ARW Data importing: VAPOR GUI can directly import WRF-ARW output data, with no data conversion. From the VAPOR GUI Data menu, click Import WRF-ARW data into default session. Then select all the WRF-ARW files to visualize. They must be on the same grid and the same level of nesting.

WRF-ARW Data conversion: Visualization of very large WRF-ARW datasets in VAPOR GUI can be sluggish if you import the data as above. To improve interactivity, convert the WRF-ARW data to a VAPOR VDC, and then, from the GUI Data menu, click Load a Dataset into default session. See Creating a .vdf file and Populating a VDC for instructions on performing this conversion.

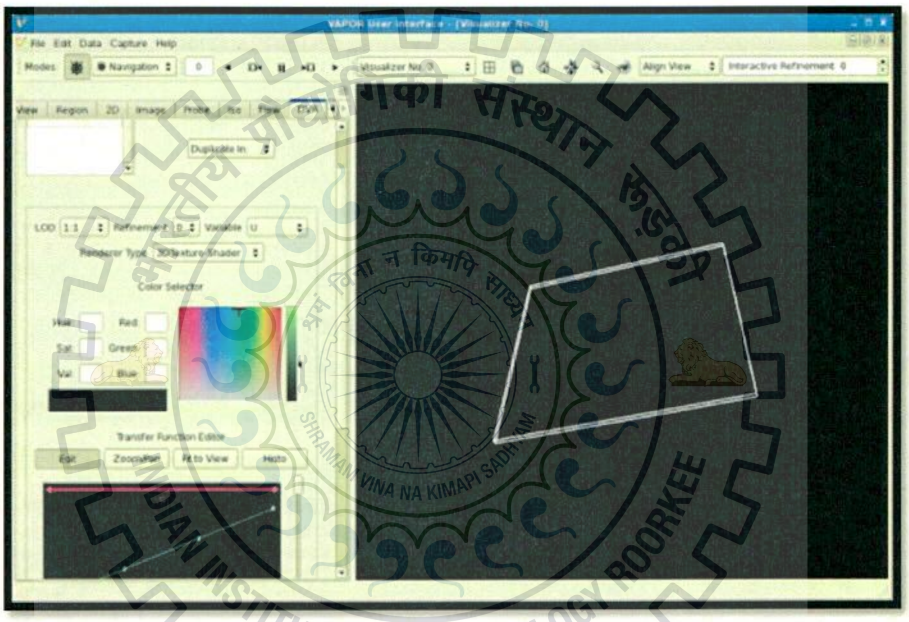


Figure 7.2: Importing WRF-ARW data

Image preparation: Georeferenced images displayed in the VAPOR scene are useful for providing a geospatial context for the visualization. Some images are pre-installed with VAPOR; others can be downloaded from Web Mapping Services. These images can be mapped to the terrain, indicating mountain heights other terrain features.

Analysis capabilities: When visualizing WRF-ARW data, several weather-related variables can be calculated in Python and immediately visualized, using the vapor_wrf module. The available derived variables include cloud-top temperature, equivalent potential temperature, radar reflectivity, vorticity and potential vorticity, relative humidity, wind shear, sea-level pressure, dew point temperature, and temperature in degrees Kelvin.

Transfer Function: A transfer function is a mapping from data to color and opacity. The transfer function editor is used to control the color and opacity in the volume rendering of data.

7.3 Representative Outputs

Following illustrative outputs are procured by visualising through VAPOR package.

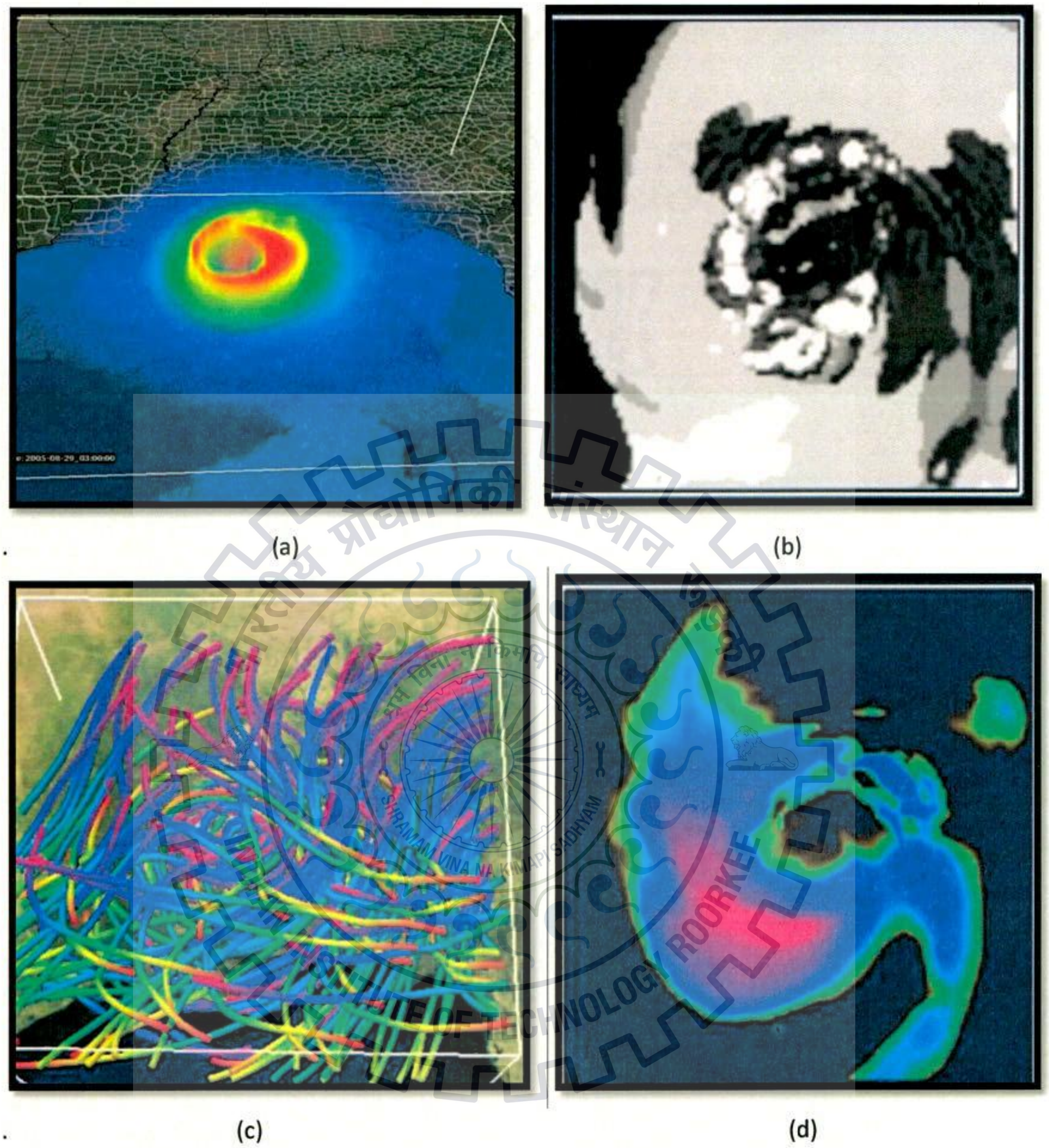


Figure 7.3: Representative Outputs of Hurricane Katrina from VAPOR package
(a) 3 Dimensional Winds (b) Cloud Top Temperature (c) Streamline Representation of Wind (d) 2D Radar Reflectivity

8. CONCLUSION

The current "Cyclone Mitigation Infrastructure" in the country is a glorious corroboration of a fact where "Science Saves Humanity" which is evident from the recent instances, where accurate and timely prediction have alleviated the wrath of Mother Nature to copious limits. These Success Stories have manifested that it's not always costly equipment and complex methodologies that saves life but, it's a methodical sense of crisis management with tinge of technology and desideration to do something good for people that actually creates difference.

Section 3 of the document provided an exhaustive detail of Cyclone Mitigation Procedures in India. It included information about hazard profile of cyclones, the vulnerable regions of country, the inducement of Cyclone Early Warning, Structural Mitigation and concept of Pre-Impact Preparedness. The script included information pertaining to prediction and monitoring of cyclones, warning generation, presentation & dissemination, public preparedness and community awareness and education.

The Numerical Simulation of "VSCS Hudhud" using two source of Initial and Boundary Conditions (IBCs) by using open source WRF model program was decisive in predicting track and intensity skilfully. The intension of study was to promote standalone and independent individual research and development in field of Cyclone Management. The study was conducted to show the performance of easily accessible data in an experimental replication. The results obtained are quite encouraging. Specifics of the experiments and prediction obtained reveal that minimum track error was 6.3 Km (6 Hour) which was obtained for 00 UTC of 11th October 2014 (NCEP-GFS as IBC) in 72 hours simulation. Maximum track error was 438.5 Km (66 Hour) which was obtained for 00 UTC of 10th October 2014 (IMD-GFS as IBC) in 72 hours simulation. Per Initial Condition, Maximum Direct Position Error (DPE) was for 00 UTC of 9th October 2014 (IMD-GFS as IBC) error value being 238.4 Km in 72 hours simulation. DPE obtained by using IMD-GFS as source for IBC was in range of 48.5 Km-340.6 Km in 72 hours simulation. DPE obtained by using NCEP-GFS as source for IBC was in range of 51 Km- 309.2 Km in 72 hours simulation. Mean error in Maximum Sustained Wind (MSW) from IMD-GFS as IBC is in range of 8.2 knots- 23.9 knots in 72 hours simulation. Mean error in Maximum Sustained Wind (MSW) from NCEP-GFS as IBC is in range of 6.7 knots- 21.3 knots in 72 hours simulation. Mean error in Minimum Sea Level Pressure (MSLP) from IMD-GFS as IBC is in range of 6.2 hPa-16.6 hPa. Mean error in Minimum Sea Level Pressure (MSLP) from NCEP-GFS as IBC is in range of 2.2 hPa-13.8 hPa. Forecast obtained depicted landfall on 12th October 2014 between 0600 UTC to 1200 UTC.

In totality, simulation results obtained by using NCEP-GFS as source of IBC were more accurate with the observed values than results obtained while using IMD-GFS for the same. The model performed skilfully for 48 hours forecast but 48 – 72 hours forecast reflected unprecedented deviation from the observed values. Overall it was observed that obtained forecast Under-Estimated VSCS Hudhud characteristics. The results clearly depicted considerable fallacy in the initial conditions of 9th October 2014 and 10th October 2014 which proposed that initial conditions cannot be solely relied for generating forecast but a consensus approach comprising a blend of personal experience and expertise, account of current observational scenario and model products prediction is necessary for delivering a quality forecasting service. Absence of data assimilation was lucidly evident from the errors demonstrated in the experiment. It is proposed that full-fledged inclusion of radar, satellite and automatic weather station data are necessary to produce skilful forecast along with contemporary ones. A sheer need of inclusion of real time observational data as model input and utilising ensemble approach for forecast generation is recommended and justified. The scope of three dimensional visualization was limitedly harnessed due certain time and equipment constrains.

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