Study on the genesis of low intensity tropical cyclones in the Bay of Bengal using WRF Model

M. Sc. Thesis

BY

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KHULNA-9203, BANGLADESH

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DECLARATION

This is to certify that the thesis work entitled "***Study on the genesis of low intensity tropical cyclones in the Bay Bengal using WRF model"*** has been carried out by DEVBROTA KUMAR BISWAS in the Department of Physics, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

Signature of Supervisor | Signature of Candidate

(PROFESSOR DR. MD. ABDULLAH ELIAS AKHTER) | (DEVBROTA KUMAR BISWAS)

DEDICATED TO

MY PARENTS

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Devbrota Kumar Biswas

CONTENTS

List of Figures

List of Table

Nomenclature

AFWA	:	Air force weather agency
ARW	:	Advanced Research WRF
BMJ	:	Betts-Miller-Janjic
CAPE	:	Convective available potential energy
CIN	:	Convective inhibition
CS	:	Cyclonic storm
CSLP	:	Central sea level pressure
DLHF	:	Downward long wave heat flux
DSHF	:	Downward shortwave heat flux
DSSF	:	Down-welling surface shortwave radiation flux
FAA	:	The Federal Aviation Administration
FE	:	Ferrier scheme
FNL	:	Final Reanalysis
FSL	:	The Forecast Systems Laboratory
G3	:	Grell-3
GD	:	Grell-Devenyi
GF	:	Greel-Freitas
IMD	:	India Meteorological Department
ITCZ	:	Inter-tropical convergence zone
JTWC	:	Join typhoon warning center
lat	:	Latitude
lon	:	Longitude
MSLP	:	Minimum sea level pressure
MODIS	:	Moderate Resolution Imaging Spectroradiometer
MWS	:	Maximum wind speed
NCAR	:	National Center for Atmospheric Research

NCEP	:	National Center for Environmental Prediction
NWP	:	Numerical weather prediction
OKF	:	Old Kain-Fritsch
OLR	:	Outgoing long wave radiation
PBL	:	Planetary Boundary Layer
RH	:	Relative humidity
RRTM	:	Rapid radiative transfer model
SCS	:	Severe Cyclonic storm
SST	:	Sea surface temperature
TC	:	Tropical Cyclones
TH	:	Thomson
UTC	:	Universal Time Co-ordinate
VSCS	:	Very severe cyclonic storm
WSM6	:	WRF Single-moment 6-class
YSU	:	Yonsei University Scheme

ABSTRACT

In the present study, Weather Research and Forecasting (WRF) model is used to study the genesis of TC Rashmi -2008, Nisha -2008, Bijly -2009 and Viyaru -2013 with low intensity which formed on the Bay of Bengal as a depression on 03 UTC on 25 October 2008, 09 UTC on 25 November 2008, 09 UTC on 14 April 2009 and 09 UTC on 10 May 2013. Latter they intensified up to cyclonic storm. Four cases are also studies when there is no cyclone and named as normal case. The model is configured in single domain, 9 km horizontal grid spacing with 290×316 grids in the west-east and north-south directions and 32 vertical levels and run the model using KF cumulus and YSU planetary boundary layer along with Final Reanalysis (FNL) data (1° x1^o) from National Centre for Environment Prediction (NCEP), USA as initial and lateral boundary conditions (LBCs). Model is run in two steps for cyclone: firstly the formation of depression and secondly the intensification up to cyclonic storm. For the first step, model is run with 96, 72, 48 and 24 hour to trace the formative stage as depression and for the second step, model is also run for 24 hour to test the formation/intensification as cyclonic storm. For the normal cases, model is run with 96, 72, 48 and 24 hour. Wind speed (WS) at 10m, Vertical wind shear (VWS) between 850-200hPa, Vertical profile of Horizontal wind (VHW), Vertical profile of Vertical wind (VVW), Relative Vorticity (RV) (850 hPa), Sea Surface Temperature (SST), Mean Sea Level Pressure (SLP), Relative Humidity (RH), Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) obtained from cyclones and normal cases are computed. Then, for first step, values obtained from cyclone cases are compared with those obtained from normal cases and available data. Then, for second step, values obtained from cyclone cases are discussed and compared with available observed data. Significant difference between the parameters obtained from cyclone cases and normal cases are obtained. Results suggest that circular shape of wind, close circle of SLP are observed in cyclone cases without exception. RH exists from surface to middle levels. It may say that model simulates the depression and cyclonic stages with more or less intensity with considerable lead time.

CHAPTER I

Introduction

1.1 Introduction

Tropical Cyclones (TC) are known for their devastation in tropical regions over the whole globe. This devastation is mainly due to high winds, torrential rains and the associated storm surge. There is an average of five TCs annually over the Bay of Bengal, which represents 5.85% of the global frequency (Rao *et al*, 2001). TC form over warm ocean regions and intensify under favorable atmospheric conditions. Warm oceans provide the energy supply to the atmosphere in the form of latent heat and sensible heat, and favorable atmospheric thermodynamics associated with low level dynamical convergence contribute to the intensification of a low into a cyclonic storm. The degree of intensification and the movement of a TC depend on the prevailing atmospheric conditions, but in order to enable public officials to implement mitigation measures effectively, predictions with a lead time of 24-72 hours is desirable to save the life and valuable wealth.

As the TCs form and develop over remote oceanic regions, direct observational exploration of the active region of cyclone development is not possible and, consequently, predictive power is limited. Satellite observations provide useful information for locating a storm region and its intensity. Dvorak (1975) developed a technique to interpret the satellite cloud pictures to determine the different stages of a developing cyclone. The forecasting centers issue the weather bulletins of the brewing storms using synoptic analyses of the conventional observations, satellite cloud pictures and numerical model outputs. However, current conventional synoptic forecasting methods have a major limitation in the form of subjectivity, whereas current numerical models are subject to the limitation of a scarcity of observations. These problems are being met with the development of numerical models and data assimilation techniques; consequently, modeling techniques are becoming common for weather prediction and, specifically, for TC studies.

The use of numerical models for TC studies started in the early 1970s when axis-symmetric models were used to gain an understanding of the physical and dynamical mechanisms of TC

development (Rao and Askok, 1999, 2001). These studies led to an understanding of the importance of boundary layer and convective processes in TC development. For TC prediction, three-dimensional asymmetric models are being used by many National Meteorological Services (Iwasaki *et al*., 1987; Mathur, 1991; Puri *et al*. 1992; Chen *et al*. 1995; Kurihara *et al*. 1995). The India Meteorological Department issues forecasts of TCs over the North Indian Ocean using high-resolution limited-area models together with an assimilation of synthetic observations (Prasad *et al*. 1997; Prasad and Rama Rao 2003). Bangladesh Meteorological Department (BMD) also uses numerical models in the prediction of cyclones.

For years, atmospheric scientists are worried about the origin and development of TC. Climate conditions among TC systems that are badly understood. There is multi-scale interaction related to TC development, speed, and structure and intensity changes. Although motion is mostly controlled by the steering flow with large environments, as well as the potentiality of bit gears and high-tropospheric negative potential deviation disorder (Brand., 2008). Changes in structure and intensity tend to interact between internal structures and storms and both the underlying ocean and its atmospheric environments that are affected by the large and complex array of physical processes at any time (Ocean service, 2014). As a result, understanding and prediction of TC structure and intensity change is much more difficult than TC track.

The effect of vertical wind shear (VWS) between different pressure levels on TC intensity change is statistically analyzed based on the best track data of TCs in the Western North Pacific from the Joint Typhoon Warning Center (JTWC) and the ECMWF interim reanalysis data during 1981–2013. Results show that the commonly used VWS measure between 200 and 850 hPa is fewer representatives of the attenuating deep-layer shear effect than that between 300 and 1000 hPa. Moreover, scientist find that the low-level shear between 850 (or 700) and 1000 hPa is more negatively correlated with TC intensity change than any deep-layer shear during the active typhoon season, whereas deep-layer shear turns out to be more influential than low-level shear during the remaining less active seasons. Further analysis covering all seasons exhibits that a TC has a better chance to intensify than to decay when the deep-layer shear is lower than 7–9 ms-1 and the low-level shear is below 2.5 ms-1. The Probability for TCs to intensify and undergo rapid intensification (RI) increases with

decreasing VWS and increasing SST. TCs moving at slow translational speeds (less than 3 ms-1) intensify under relatively weaker VWS than TCs moving at intermediate translational speeds. The probability of RI becomes lower than that of rapid decaying when the translational speed is larger than 8 ms-1. Most TCs tend to decay when the translational speed is larger than 12 m s-1 regardless of the shear condition (Wang *et al*., 2015). A relationship between wind shear and intensity change is documented by investigating the impact of environmental wind shear on the intensity change of hurricane-strength TCs in the Australian region. Correlations between wind shear and intensity change to 36 h are of the order of 0.4. Typically a critical wind shear value of ∼10 ms-1 represents a change from intensification to dissipation. Wind shear values of less than ∼10 ms-1 favor intensification, with values between ∼2 and 4 ms-1 favoring rapid intensification. Shear values greater than ∼10 ms-1 are associated with weakening, with values greater than 12 ms-1 favoring rapid weakening. There appears to be a time lag between the onset of increased vertical wind shear and the onset of weakening, typically between 12 and 36 h (Paterson *et al*., 2005). The influence of various environmental factors on TC intensity is explored using a simple coupled ocean–atmosphere model. It is first demonstrated that this model is capable of accurately replicating the intensity evolution of storms that move over oceans whose upper thermal structure is not far from monthly mean climatology and that are relatively unaffected by environmental wind shear. A parameterization of the effects of environmental wind shear is then developed and shown to work reasonably well in several cases for which the magnitude of the shear is relatively well known. When used for real-time forecasting guidance, the model is shown to perform better than other existing numerical models while being competitive with statistical methods. In the context of a limited number of case studies, the model is used to explore the sensitivity of storm intensity to its initialization and to a number of environmental factors, including potential intensity, storm track, wind shear, upper-ocean thermal structure, bathymetry, and land surface characteristics. All of these factors are shown to influence storm intensity, with their relative contributions varying greatly in space and time. Accurate forecasts of TC intensity require not only good forecasts of environmental winds but good knowledge of upper-ocean thermal structure. Shear in suppressing storm intensity, also suppresses ocean feedback; the sudden cessation of shearing can then lead to more rapid intensification and, briery, to greater intensity than could have been reached had shear been

absent altogether. The importance of TC intensity prediction justices the inclusion of upper-ocean temperature and salinity measurements in routine airborne reconnaissance missions (Emanuel *et al*., 2003). A statistical model for predicting intensity changes of Atlantic TCs at 12, 24, 36, 48, and 72 h is described. The model was developed using a standard multiple regression technique with climatologically, persistence, and synoptic predictors. The model developmental sample includes all of the named Atlantic TCs from 1989 to 1992. The four primary predictors are 1) the difference between the current storm intensity and an estimate of the maximum possible intensity determined from the sea surface temperature, 2) the vertical shear of the horizontal wind, 3) persistence, and 4) the flux convergence of eddy angular momentum evaluated at 200 mb. The sea surface temperature and vertical shear variables are averaged along the track of the storm during the forecast period. The sea surface temperatures along the storm track are determined from monthly climatologically analyses linearly interpolated to the position and date of the storm. The vertical shear values along the track of the storm are estimated using the synoptic analysis at the beginning of the forecast period. All other predictors are evaluated at the beginning of the forecast period (De and Kaplan., 1994). Determining the proper relation between the mean sea level pressure and maximum sustained winds in TCs has been a long-standing problem. The major obstacle has been the lack of sufficient ground truth i.e. actual measurements of maximum wind speeds in TCs with a wide Ranges of central pressures. A new relationship is developed based on maximum wind observation recorded at island and coastal stations in the western north pacific area during cyclone passes during a 28-year period (www.bom.gov.au., 2014).

The intensity of TCs is sensitive to the rates at which enthalpy and momentum are transferred between sea and air in the high-wind core of the storm. When a spray droplet is ejected from the ocean, it remains airborne long enough to cool to a temperature below the local air temperature but not long enough to evaporate an appreciable fraction of its mass. The spray droplet thus gives up sensible heat and returns to the sea before it has time to extract back from the atmosphere the heat necessary to continue its evaporation. Microphysical modeling, combined with data from the Humidity Exchange over the Sea Experiment, makes it possible to derive an expression for the net enthalpy transfer of re-entrant spray. This spray enthalpy flux is roughly cubic in wind speed. When this relation is used in a numerical simulation of a hurricane, the spray more than compensates for the observed increase in the ratio of drag and

enthalpy transfer coefficients with wind speed. The momentum flux associated with sea spray is an important energy sink that moderates the effects of this spray enthalpy flux. Including a parameterization for this momentum sink along with wave drag and spray enthalpy transfer in the hurricane simulation produces results that are similar to ones based on equal transfer coefficients (Andreas and Emanuel., 2001). Little work is done on establishing relation between other environmental parameters like CAPE, CIN, Relative vorticity, moisture flux and Geopotential thickness etc with TCs intensity change rather than cyclogenesis. From above found that, most of previous work is done on other basin like Pacific Ocean, Atlantic Ocean, very few work is done on BoB and its environment.

The Fifth-Generation National Center for Atmospheric Research (NCAR)/Penn State Mesoscale Model (MM5) is a high-resolution mesoscale model that has been widely used for TC simulation and sensitivity studies. Liu et al. (1992) simulated the intensity, inner-core structure and track of a hurricane with this model using three nested domains and a 6-km resolution for the inner-most domain. Braun and Tao (2000) reported that Burk-Thompson and Bulk Aerodynamic schemes of the planetary boundary layer (PBL) produced stronger cyclones than the MRF scheme. Davis and Bosart (2001) simulated hurricane Diana and concluded that model physics plays a more important role during the transformation from marginal storm to hurricane intensity than from mesoscale vortex to marginal storm. Wang (2002) examined the sensitivity of TC development to explicit moisture schemes and reported that TC intensification is not sensible to cloud microphysics. Braun (2002) simulated the asymmetrical structure of the eye and eyewall of hurricane Bob (1991) with a fine resolution of 1.3 km of the inner-most domain. Mohanty *et al*. (2004) simulated the Orissa super cyclone with a single domain at a resolution of 30 km, and their study indicates that MM5 could predict intensification up to 48 hours but underestimated it thereafter. Rao *et al.,* (2003) also reported a good simulation of the Orissa cyclone but underestimated the intensity using Grell, MRF and Simple-Ice schemes for the physical processes. Yang and Cheng (2005) studied the sensitivity of Typhoon Tarija to different parameterization schemes and reported that the Grell convection scheme and Goddard Microphysics explicit moisture schemes gave the best track, whereas the warm rain scheme gave the lowest central surface pressure. Recent analyses of future simulations performed as part of the Coupled Model Inter comparison Project Phase 5 (CMIP5) appear equivocal: statistical downscaling indicates an increase in

both cyclone intensity and genesis (Emanuel, 2013); dynamical downscaling indicates an increase in intensity combined with a reduction in frequency (Knutson *et al*., 2013); tracking of TC-like features in global coupled models do the same (Camargo, 2013); large-scale cyclogenesis indices have shown both frequency increases (Emanuel, 2013) and decreases (Camargo, 2013).In the present study, Weather Research and Forecasting (WRF) model is used to trace the formation of low intensity TC_s Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 earlier their formation time in the Bay of Bengal.

1.2 Objectives and Scope of the Research Work

In this thesis, WRF_ARW model is used to simulation the formation stages of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 those formed in the BoB up to cyclonic storm. Four cases studies for four periods without cyclones are also taken to study to compare the conditions during the cyclone periods. These cases are designated as Normal-2008, Normal-2010, Normal-2011 and Normal-2012 when there is no cyclone.

The objectives of the present study are the followings:

- To investigate dynamical parameters of low intensity TCs and normal cases whether it trace the formation of depression up to cyclonic storm.
- To investigate thermo-dynamical parameters of low intensity TCs and normal cases whether it trace the formation of depression up to cyclonic storm.
- To compare the value from TC and normal cases and find out the conclusion**.**

Then by identifying the formation and intensification, forecasting of low intensity TC will be possible with sufficient lead time.

1.3 Social and Economic Benefit of the Research Work

The TCs, tornadoes and other meso-scale activities cause severe damage to lives, properties, infrastructures and environment. Specially, low intensity or weak cyclone has slow motion and quasi-stationary nature and it causes very heavy rainfall and in turn large amount of damage to the property. The weather activities of the country like Bangladesh are dominated by the southwest monsoon. In addition to this, Bangladesh is supposed to become the worst victim of the impacts of global warming and associated climate change. The climate change induced enhancement of nature disasters will cause its people to suffer innumerable loss to

resources and livelihood. The model predicts the structure, intensity and probable areas and time of landfall of the selected TC with high accuracy. Thus, the model may be used for operational prediction of cyclones of this area. And as a result the lives and properties of the urban people of the Bay of Bengal region will be saved.

1.4 Structure of the Thesis

The thesis has been constructed with the following structure:

Chapter 1 contains general introduction, objectives, scope of the research work, explains how the research results will be of social and economic benefit and structure of the thesis.

Chapter 2 contains introduction of TC, Classification of TCs, Life Cycle of TCs, Different parameter of TC Wind Speed (WS) at 10m, Vertical Wind Shear (VWS) between 850-200hPa, Vertical Profile of Horizontal Wind (VHW), Vertical Profile of Vertical Wind (VVW), Relative Vorticity (RV) (850 hPa), Sea Surface Temperature (SST), Mean Sea Level Pressure (SLP), Relative Humidity (RH), Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) etc.) and Weather Research & Forecasting Model.

Chapter 3 contains Model Description and Methodology.

Chapter 4 contains the results and discussions of the study of TC events. It deals the Wind Speed (WS) at 10m, Vertical Wind Shear (VWS) between 850-200hPa, Vertical Profile of Horizontal Wind (VHW), Vertical profile of Vertical Wind (VVW), Relative Vorticity (RV) (850 hPa), Sea Surface Temperature (SST), Mean Sea Level Pressure (SLP), Relative Humidity (RH), Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) of selected TCs using cumulus of WRF Model.

Chapter 5 contains the conclusion of the research

and finally references are written at the end of the thesis.

CHAPTER II

Literature Review

2.1 Overview of the Cyclone

A TC, develop over the warm tropical oceans, is a low-pressure center, strong wind, and thunder that is characterized by a circular arrangement of rain. The term "tropical" refers to the geographical source on this system, which constitutes almost exclusively on the tropical sea. The term "cyclone" refers to the nature of their cyclone, moving in the opposite direction in the Northern Hemisphere and clockwise in the Southern Hemisphere (Frank., 1977). Due to the effect of the Coriolis forces in the opposite direction of circulation. TCs start at around 5 degree astrology. Depending on its location and strength, TC_s are called "hurricanes" , in the North Atlantic and eastern North Pacific regions, and "Typhoon", in the western North Pacific ", (Merrill R. T., 1984). TCs form over large bodies of relatively warm water with diameter in between 100 and 4,000 km (62 and 2,485 mi). Through the evaporation of water from the ocean surface, they derive their energy. This energy ultimately re-condenses into clouds and rain when moist air rises and cools to saturation. The strong rotating winds of a TC are a result of the conservation of angular momentum imparted by the Earth's rotation as air flows inwards toward the axis of rotation. For this reason, they rarely form within 5° of the equator (www.srh.noaa.gov, 2015). Due to strong winds and rain, TCs are capable of generating high waves, damaging storm surge, and tornadoes. TC weaken rapidly over land where they are cut off from their primary energy source. Due to this reason, coastal regions are particularly vulnerable to damage from a TC as compared to inland regions. Heavy rains, however, can cause significant flooding inland, and storm surges can produce extensive coastal flooding up to 40 kilometers (25 mi) from the coastline. They also carry heat energy away from the tropics and transport it toward temperate latitudes. It may play an important role in modulating regional and global climate.

2.1.1 TC Basins

There are seven basins for the formation of TC which are seen in Figure 2.1. There are the North Atlantic Ocean, the eastern and western parts of the North Pacific Ocean, the

southwestern Pacific Ocean, the southwest, and the southeastern Indian Ocean and the North Indian Ocean (the Arabian Sea and the Bay of Bengal).

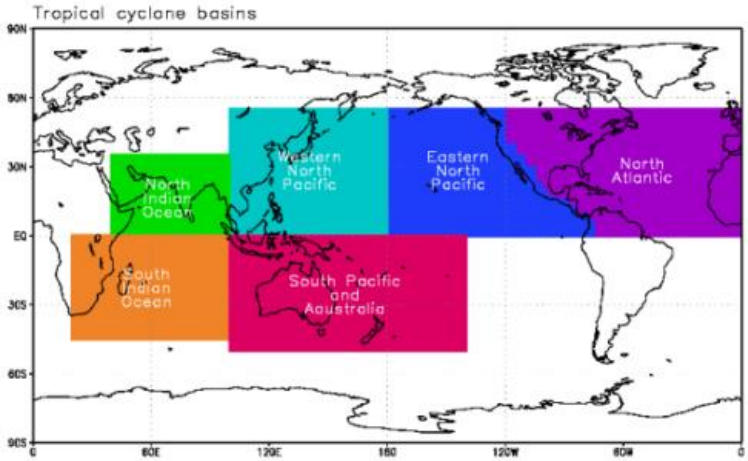


Figure 2.1: TC basins (https://en.wikipedia.org, 2015).

2.1.1.1 North Indian Ocean

The Indian Ocean is divided into two parts such as the Bay of Bengal and the Arabian Sea as shown in Figure 2.2.

Figure 2.2: Location of Indian Ocean (http://www.news18.com, 2015).

2.1.1.1.1 Bay of Bengal

The Bay of Bengal **(**BoB), located north of the Indian Ocean. The BoB's coast is shared among India, Bangladesh, Myanmar, Sri Lanka and western part of Thailand. In the BoB, a distinctly bimodal cyclone season is observed: March-May (pre-monsoon) and October-December (post-monsoon). Synoptic-scale movements of air toward the BoB can create

environments favorable for the initiation of cyclogenesis during the pre-and post-monsoon. The primary peak in cyclone frequency over BoB is in November, and the secondary peak is May, Figure 2.3 shows the annual cyclone occurrence frequency over BoB.

The BoB is responsible for the formation of some of the strongest and deadliest TCs in the world. Due to 1970 Bhola cyclone formed over the BoB, between 100,000 and 500,000 residents of Bangladesh were killed (https://www.britannica.com, 2015).

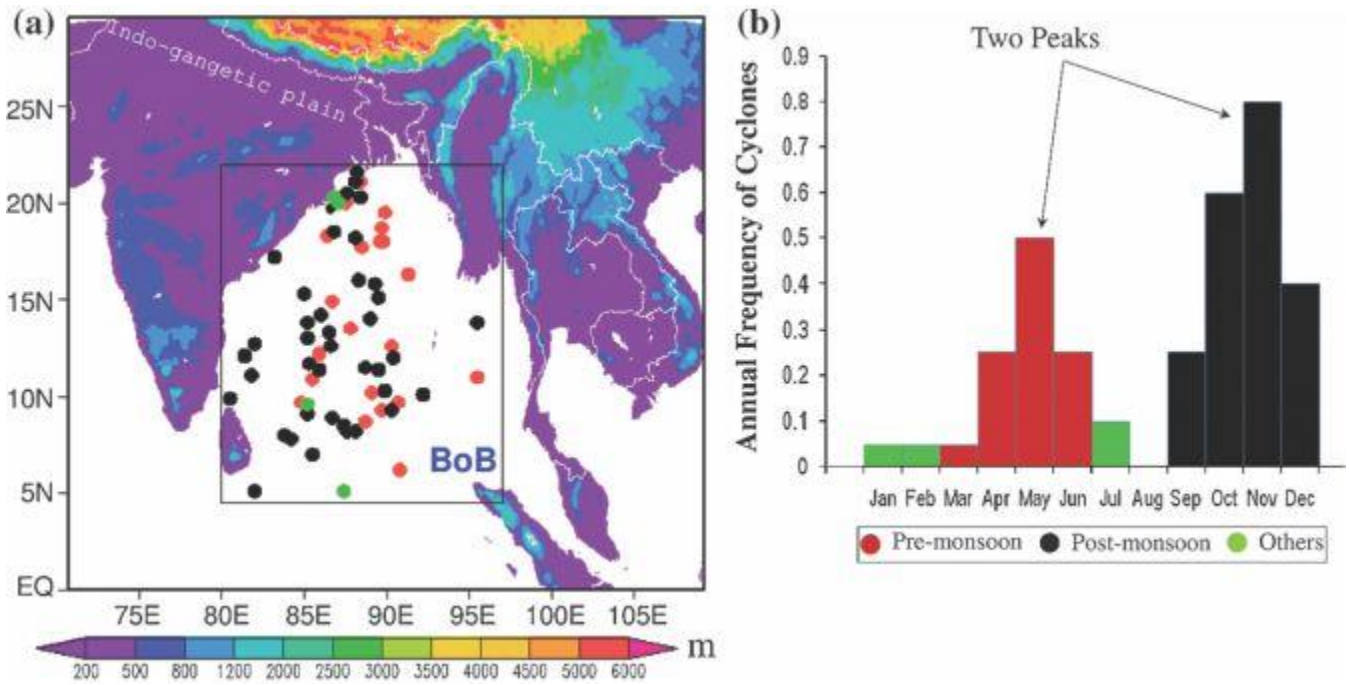


Figure 2.3: (a) TC formation over the Bay of Bengal (BoB) during 1990– 2009 (dots): red pre- monsoon; black post-monsoon; green other. (b) Annual cyclone occurrence frequency(Akter. and Tsuboki., 2014).

2.1.1.1.2 Arabian Sea

The Arabian Sea is a sea located to the north of the Indian Ocean. The Arabian Sea's coast is shared among India, Yemen, Oman, Iran, Pakistan, Sri Lanka, Maldives and Somalia. Cyclones are very rare in the Arabian Sea, but the basin can produce strong TCs. A Super Cyclonic Storm Gonu is considerd the strongest recorded TC in the basin.

2.1.2 Classification of TCs

Cyclonic disturbances in the North Indian Ocean are classified according to their intensity. The following nomenclature is in use:

Table 2.1: Classification of TCs

	km/hr	knots	m/s
Low	Wind speed < 31	<17	<9
Well marked low	Wind speed equals to 31	17	9
Depression	Wind speed Ranges from 32 - 48	17-26	9-14
Deep Depression	Wind speed Ranges from 49 - 62	26-34	14-18
Cyclonic Storm	Wind speed Ranges from 63 - 88	34-48	18-25
Severe Cyclonic Storm	Wind speed Ranges from 89-117	48-63	25-33
SCS with a core of hurricane intensity	Winds speed 118-220	63-119	33-62
Super Cyclone	Winds speed ≥ 221	≥119	≥62

2.1.3 Life Cycle of TCs

The life span of TCs with full cyclonic intensity averages at about 6 days from the time they form until the time they enter land or reserve into the Temperate Zone. Some storms last only a few hours; a few as long as two weeks. The evolution of the average storm from birth to death has been divided into four stages.

Formative Stage: Tropical storms form only in near pre-existing weather systems. Deepening can be a slow process, requiring days for the organization of a large area with diffuse winds. It can also produce a well-formed eye within 12 hours. Wind speed usually remains below hurricane force in the formative stage. Unusual fall of pressure over 24 hours by 2 - 3 hPa or more takes place in the center of the vorticity concentration.

Immature Stage: A large number of formative cyclones die within 24 hours. Others travel long distances as shallow depressions. Wind of cyclonic force forms a tight band around the center. The cloud and rain pattern changes from disorganized squalls to narrow organized bands, spiraling inward. Only a small area is as yet involved, though there may be a large outer envelope. The eye is usually visible but ragged and irregular in shape.

Mature Stage: The force of cyclonic winds may blow within a 30-50 km radius during immature stage. This radius can increase to over 300 km in mature storms. On the average, the mature stage occupies the longest part of the cycle and most often lasts several days. The

eye is prominent and circular and the cloud pattern is almost circular and smooth. The surface pressure at the center is no longer falling and the maximum wind speeds no longer increasing. At this stage, heating from convective clouds furnishes the largest amount of energy for cyclone maintenance. Pressure gradient is largest at the surface. Wind speed Ranges is between 128-322 km/hr.

Terminal Stage: Nearly, all cyclones weaken substantially upon entering land, because they lose the energy source furnished by the underlying ocean surface. The decay is especially rapid where the land is mountainous. Movement of a cyclone over land cuts off the surface energy source and increases the surface friction, especially when the land is mountainous. Some cyclones die out over sea and this event can be related to their moving over a cold ocean current or being invaded by a surface cold air mass behind a cold front or by a cold center at high levels moving over their top.

2.1.4 Physical Structure of TC

A mature TC typically consists of warm core vertical circulation, cyclonic in lower and anticyclonic in upper troposphere, with a core of intense wind and precipitation. The vertical perturbation winds upon the mean environment may extend outward well over 1000 km from the storm center. At the core, there is typically an eye of 5-50 km radius with warm, calm and deep convection surrounded with eye wall. A schematic diagram of idealized mature TC is shown in Figure 2.4 (Emanuel K.A., 2009).

2.1.4.1 Wind Field

A wind field of TC is nearly axisymmetric. The near-surface wind field of a TC is characterized by air rotating rapidly around a centre of circulation while also flowing radially inwards. Due to the Earth's rotation, the air has non-zero absolute angular momentum. As air flows radially inward, it begins to rotate cyclonically (counter-clockwise in the Northern Hemisphere, and clockwise in the Southern Hemisphere) in order to conserve angular momentum. At an inner radius, air begins to ascend to the top of the troposphere. This radius is typically coincident with the inner radius of the eyewall, and has the strongest near-surface winds of the storm; consequently, it is known as the radius of maximum winds (https://en.wikipedia.org, 2015). Wind speeds are low at the centre, increase rapidly moving outwards to the radius of maximum winds, and then decay more gradually with radius to

large radii. The wind field often exhibits additional spatial and temporal variability due to the effects of localized processes, such as thunderstorm activity and horizontal flow instabilities.

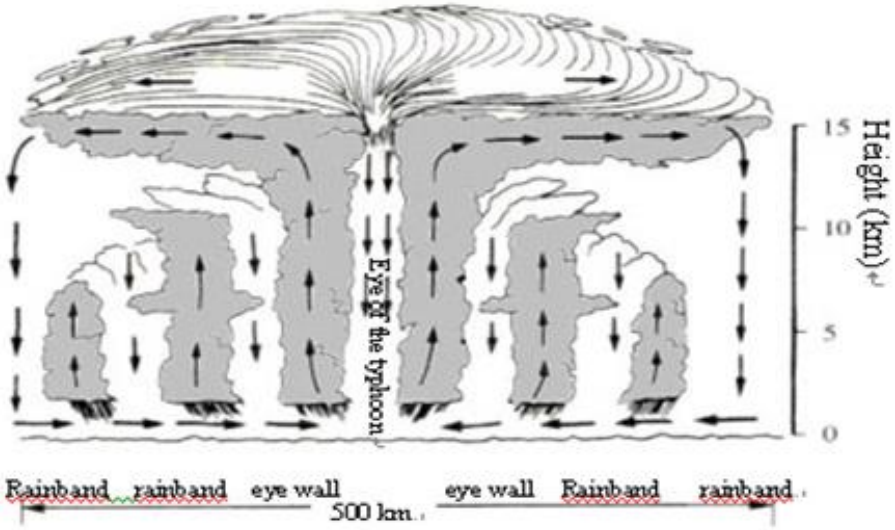


Figure 2.4: Schematic view of a typical TC (Emanuel K.A., 2009).

2.1.4.2 Eye and Center

The rainbands, the eye, and the eyewall are the main parts of a TC. At all altitudes, The environment near the center of TCs is warmer than the surroundings thus they are characterized as "warm core" systems (https://www.soest.hawaii.edu, 2015). At the center of a mature TC, air sinks rather than rises. For a sufficiently strong storm, air may sink over a layer deep enough to suppress cloud formation, thereby creating a clear "eye". A typical TC will have an eye of approximately 30–65 km (20–40 mi) across, usually situated at the geometric center of the storm. Weather in the eye is normally calm and free of clouds, although the sea may be extremely violent. An eye will usually develop when the maximum sustained wind speeds go above 74 mph (119 km/h) and is the calmest part of the storm. The cause of eye formation is still not fully understood. It probably has to do with the combination of "the conservation of angular momentum" and centrifugal force. The conservation of angular momentum means is objects will spin faster as they move toward the center of circulation. So air increases it speed as it heads toward the center of the TC. As the speed increases, an outward-directed force, called the centrifugal force, occurs because the wind's momentum wants to carry the wind in a straight line. Since the wind is turning about

the center of the TC, there is a pull outward. The sharper the curvature, and/or the faster the rotation, the stronger is the centrifugal force.

Around 74 mph (119 km/h) the strong rotation of air around the cyclone balances inflow to the center, causing air to ascend about 10-20 miles (16-32 km) from the center forming the eyewall. This strong rotation also creates a vacuum of air at the center, causing some of the air flowing out the top of the eyewall to turn inward and sink to replace the loss of air mass near the center. This sinking air suppresses cloud formation, creating a pocket of generally clear air in the center (Annamalai, *et al.*, 1999). Figure 2.5 shows the cross sectional diagram of a mature TC indicating Eye, Eyewall and rainbans position. The eyewall typically expands outward with height, resembling an arena football stadium; this phenomenon is sometimes referred to as the stadium effect. Eyewalls are typically circular; however, distinctly polygonal shapes ranging from triangles to hexagons occasionally occur.

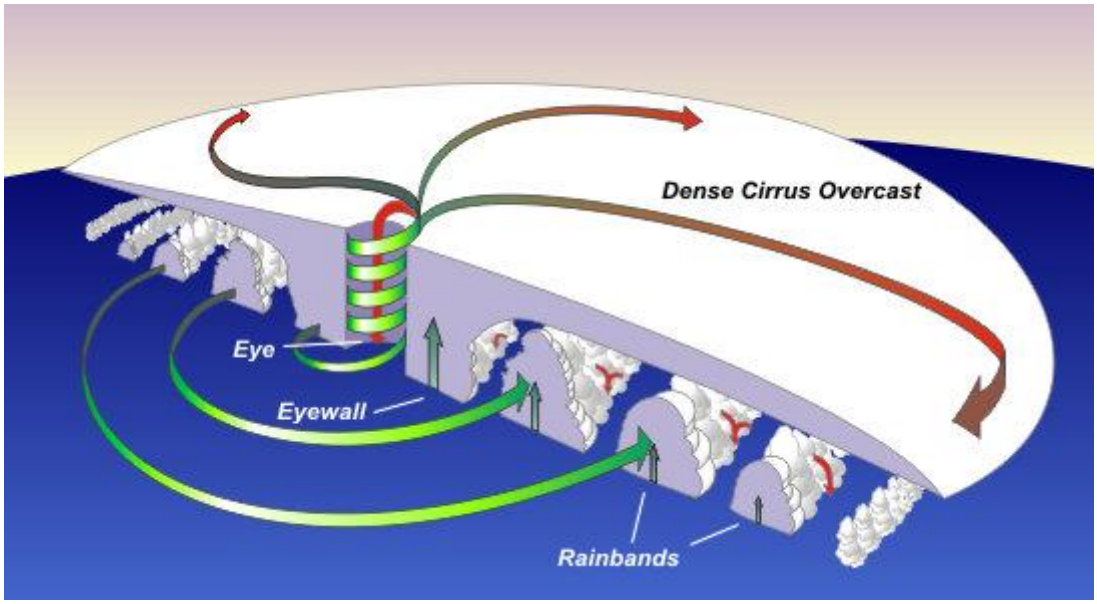


Figure 2.5: A cross section diagram of a mature TC.

The eyewall consists of a ring of tall thunderstorms that produce heavy rains and usually the strongest winds. The heaviest wind damage occurs where a TC's eyewall passes over land. The eyewall may vary over time in the form of eyewall replacement cycles, particularly in intense TCs. When TC intensity become greater than 185 km/h (115 mph) and the eyewall

contracts or is already sufficiently small. Some of the outer rainbands may strengthen and organize into a ring of thunderstorms-an outer eyewall-that slowly moves inward and robs the inner eyewall of its needed moisture and angular momentum. Since the strongest winds are located in a cyclone's eyewall, the TC usually weakens during this phase, as the inner wall is "choked" by the outer wall. Eventually the outer eyewall replaces the inner one completely, and the storm can re-intensify. Eyewall mesovortices are most common during periods of intensification in TCs. Eyewall mesovortices are a significant factor in the formation of tornadoes after TC landfall (Bister and Emanuel., 1998).

2.1.5 Formation Process of Cyclone

The three-dimensional wind field in a TC can be separated into two components: a "primary circulation" and a "secondary circulation". The primary circulation is the rotational part of the flow; it is purely circular. The secondary circulation is the overturning (in-up-out-down) part of the flow; it is in the radial and vertical directions. The primary circulation has the strongest winds and is responsible for the majority of the damage a storm causes, while the secondary circulation is slower but governs the energetic of the storm.

2.1.5.1 Secondary Circulation

TCs form when the energy released by the condensation of moisture in rising air causes a positive feedback loop over warm ocean waters. A TC's primary energy source is the evaporation of water from the ocean surface, which ultimately recondenses into clouds and rain when moist air rises and cools to saturation. The energetics of the system may be idealized as an atmospheric Carnot heat engine (www.aoml.noaa.gov, 2015). Figure 2.6 shows the overturning circulation of TC where air inflows at low levels near the surface, rises in thunderstorm clouds, and outflows at high levels near the tropopause. First, inflowing air near the surface acquires heat primarily via evaporation of water (i.e. latent heat) at the temperature of the warm ocean surface. Second, air rises and cools within the eyewall while conserving total heat content (latent heat is simply converted to sensible heat during condensation). Third, air outflows and loses heat via infrared radiation to space at the temperature of the cold tropopause. Finally, air subsides and warms at the outer edge

of the storm while conserving total heat content. The first and third legs are nearly isothermal, while the second and fourth legs are nearly isentropic. This is in-up-out-down overturning flow is known as the secondary circulation. The Carnot perspective provides an upper bound on the maximum wind speed that a storm can attain.

Scientists estimate that a TC releases heat energy at the rate of 50 to 200 exajoules (10^{18} J) per day, equivalent to about 1 PW (10^{15}watt). This rate of energy release is equivalent to 70 times the world energy consumption of humans and 200 times the worldwide electrical generating capacity, or to exploding a 10- megaton nuclear bomb every 20 minutes (www.aoml.noaa.gov, 2015).

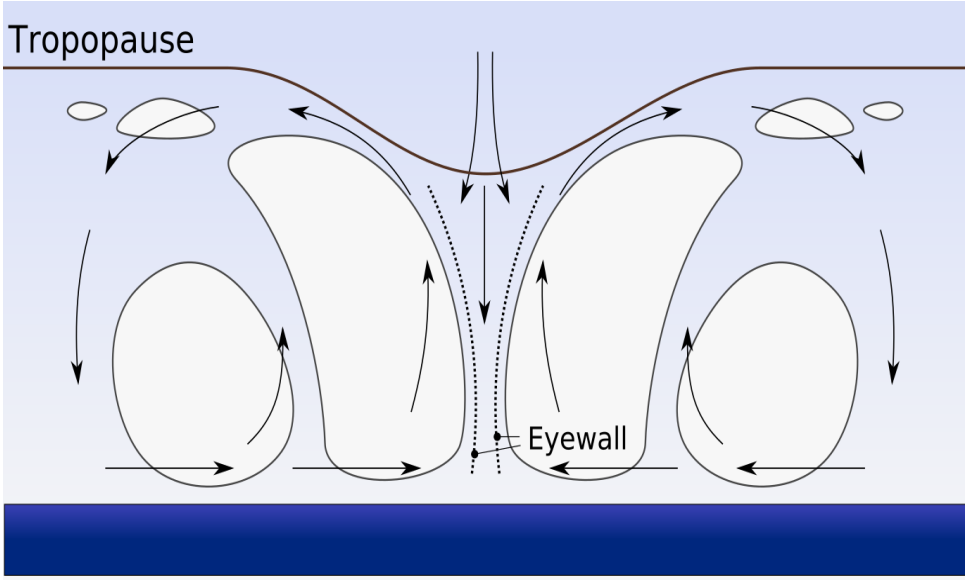


Figure 2.6: Overturning circulation of TC (D'Asaro E.A., and Black P.G., 2000).

2.1.5.2 Primary Circulation

The primary rotating flow in a TC results from the conservation of angular momentum by the secondary circulation. Absolute angular momentum on a rotating planet is given by

$$M = \frac{1}{2} fr^2 + \vartheta r$$

where is the Coriolis parameter, is the azimuthal (i.e. rotating) wind speed, and is the radius to the axis of rotation. The first term on the right hand side is the component of planetary angular momentum that projects onto the local vertical (i.e. the axis of rotation). The second term on the right hand side is the relative angular momentum of the circulation itself with

respect to the axis of rotation. Because the planetary angular momentum term vanishes at the equator (where f=0), TCs rarely form within 5° of the equator (Kikuchi *et al* and Fudeyasu., 2009). As air flows radially inward at low levels, it begins to rotate cyclonically in order to conserve angular momentum. Similarly, as rapidly rotating air flows radially outward near the tropopause, its cyclonic rotation decreases and ultimately changes sign at large enough radius, resulting in an upper-level anti-cyclone. The result is a vertical structure characterized by a strong cyclone at low levels and a strong anti-cyclone near the tropopause, this corresponds to a system that is warmer at its center than in the surrounding environment at all altitudes (Holland., 1983).

The inflow only partially conserves angular momentum, due to surface friction. Thus, the sea surface lower boundary acts as both a source (evaporation) and sink (friction) of energy for the system. This fact leads to the existence of a theoretical upper bound on the strongest wind speed that a TC can attain. Because evaporation increases linearly with wind speed, there is a positive feedback on energy input into the system known as the Wind-Induced Surface Heat Exchange (WISHE) feedback. This feedback is offset when frictional dissipation, which increases with the cube of the wind speed, becomes sufficiently large. This upper bound is called the "maximum potential intensity" υp, and is given by

$$\upsilon_p^2 = \frac{C_k}{C_d} \frac{T_s - T_o}{T_o} \Delta k$$

Where *Ts* is the temperature of the sea surface, *To* is the temperature of the outflow ([K]), ΔK is the enthalpy difference between the surface and the overlying air ([J/kg]), and C_k and C_d are the surface exchange coefficients (dimensionless) of enthalpy and momentum, respectively. The surface-air enthalpy difference is taken as $\Delta K = K^*_s - K$, where K^*_s is the saturation enthalpy of air at sea surface temperature and sea-level pressure and is the enthalpy of boundary layer air overlying the surface (www.hurricanezone.net,2015).

The maximum potential intensity is predominantly a function of the background environment alone (i.e. without a TC), and thus this quantity can be used to determine which regions on Earth can support TCs of a given intensity, and how these regions may evolve in time (https://books.google.com.bd, 2015). The passage of a TC over the ocean causes the upper layers of the ocean to cool substantially, which can influence subsequent cyclone development.

This cooling is primarily caused by wind-driven mixing of cold water from deeper in the ocean with the warm surface waters. This effect results in a negative feedback process that can inhibit further development or lead to weakening. Additional cooling may come in the form of cold water from falling raindrops (this is because the atmosphere is cooler at higher altitudes). Cloud cover may also play a role in cooling the ocean, by shielding the ocean surface from direct sunlight before and slightly after the storm passage. All these effects can combine to produce a dramatic drop in sea surface temperature over a large area in just a few days (ww2010.atoms.uiuc.edu, 2015).

2.1.6 Climatologically Conditions for TC Formation

The first global climatology of TC genesis by {Gray, 1968, 1975 and 1978} demonstrates that the distribution of genesis may relate to six environmental factors;

I. Large values of low level relative vorticity.
II. A location at last a few degrees poleward of the equator, giving a significant value of planetary vorticity;
III. Weak vertical shear of the horizontal winds;
IV. Sea-surface temperatures (SSTs) exceeding 26°C, and a deep thermocline;
V. Conditional instability through a deep atmospheric layer; and
VI. Large values of relative humidity in the lower and middle troposphere.

The first three factors are factors of the horizontal dynamics, while the last three are thermodynamic parameters. Gray defend the product of (1), (2) and (3) to be the dynamic potential for cyclone development, whiles the product of (4), (5) and (6) may be considered the thermodynamic potential .As discussed by Gray [68] the thermodynamic parameters vary slowly in time and would be expected to remain above any threshold values necessary for TC development throughout cyclone season. On the other hand, the dynamic potential can change dramatically through synoptic activity. Thus, it was hypothesized by Gray that cyclones form only during periods when the dynamic potential is perturbed to a value above its regional climatologically mean.

(Frank.,1987) reduced the list to four parameters by combining (1) and (2) into the absolute vorticity at low levels deleting (5) and adding mean upward vertical motion to (6).

Following (Palmen, 1948), it has been generally accepted that TCs only form when the underlying sea surface temperature (SST) exceeds 26°C. Palmen hypothesized that the temperature criterion is one of threshold rather than proportionality. Through a more comprehensive study, (Raper, S., 1992) concluded that higher SST's has no direct impact on the frequencies of TCs.

2.1.7 Large Scale Conditions Associated with TC Formation

TCs form only over tropical oceans where upper air observations are sparse, which has made it difficult to document the structure and evolution of the flow during the formation process. Consequently, much of the early understanding of formation was gained from case studies based on innovative use of the existing data networks (Riehl, *et al* 1948)Subsequent studies that exploited improved observational systems have led to further refinement and detail in documentation of the TC formation process. However, no well-accepted closed theory of formation exists.

The observational studies have isolated a number of synoptic-scale aspects that have an important role in the formation process:

I. TCs form from pre-existing disturbances containing abundant deep convection;
II. The pre-existing disturbances must acquire a warm core thermal structure throughout the troposphere;
III. Formation is preceded by an increase of lower tropospheric relative vorticity over a horizontal scale of approximately 1000 to2000 km;
IV. A necessary condition for cyclone formation is a large scale environment with small vertical shear of the horizontal wind;
V. An early indicator that cyclone formation has begun is the appearance of curved banding features of the deep convection in the incipient disturbance ;
VI. The inner core of the cyclone may originate as a mid-level meso-vortex that has formed in association with a pre-existing mesoscale area of altostratus (i.e; a Mesoscale Convective System or MCS); and
VII. Formation often occurs in conjunction with an interaction between the incipient disturbance and an upper-tropospheric trough.

We observe universally that tropical storms form only within pre-existing disturbance. An initial disturbance, therefore, forms part of the staring mechanism. A weak circulation, low pressure and a deep moist layer are present at the beginning. The forecaster need not look into areas which contain no such circulations. These structure of (Riehl, 1954) have stood the testof time. The structure of these tropical "cloud clusters" has been documented by many authors (e.g. Ruprecht *et al*.,1976). The cloud clusters have an upper tropospheric warm core and mean (averaged over a 4^0 latitude –longitude square) upward velocities of about 100 hPa/day (McBride *et al*., 1989).Although the diameter of the convective area is typically only a few hundred km, the rotational circulation's associated with the system usually extend over a diameter of approximately 1000-1500 km.

2.2 Parameter of TC

Dynamic and thermodynamic parameters are responsible for formation and intensification of TC. The details of these parameters are described below:

2.2.1 Dynamic Parameters

2.3.1.1 Wind Speed

Wind speed, or wind flow velocity is a fundamental atmospheric quantity. Wind speed is caused by air moving from high pressure to low pressure, usually due to changes in temperature. Wind speed affects weather forecasting, aircraft and maritime operations, construction projects, growth and metabolism rate of many plant species, and countless other implications. Wind speed is now commonly measured with an anemometer but can also be classified using the older Beaufort scale which is based on people's observation of specifically defined wind effects. In meteorology, winds are often referred to according to their strength, and the direction from which the wind is blowing. Short bursts of high speed wind are termed gusts. Strong winds of intermediate duration (around one minute) are termed squalls. Long-duration winds have various names associated with their average strength, such as breeze, gale, storm, and hurricane. Wind occurs on Ranges of scales, from thunderstorm flows lasting tens of minutes, to local breezes generated by heating of land surfaces and lasting a few hours, to global winds resulting from the difference in absorption of solar energy between the climate zones on Earth. The two main causes of large-scale atmospheric circulation are the differential heating between the equator and the poles, and the rotation of

the planet (Coriolis Effect). Within the tropics, thermal low circulations over terrain and high plateaus can drive monsoon circulations. In coastal areas the sea breeze/land breeze cycle can define local winds; in areas that have variable terrain, mountain and valley breezes can dominate local winds.

2.2.1.2 Wind Speed at 10m

In most of the world, the standard height above the surrounding vegetation for measuring open wind speed is ten meters (33 feet); in the United States, it is measured 20 feet above the surrounding vegetation (20-ft wind speed). Multiply 20-foot wind speed by 1.15 to estimate 10 m wind speed, alternately, divide 10-meter wind speed by 1.15 to estimate 20-foot wind speed.

2.2.1.3 Vertical Wind Shear (VWS)

Wind shear or wind gradient is a difference in wind speed and direction over a relatively short distance in the atmosphere. Wind shear can be broken down into vertical and horizontal components. According to Figure 2.10, VWS can be described by the change of mean large-scale horizontal wind with height. VWS is commonly measured as the horizontal wind difference (magnitude and direction) between 200 850 hPa averaged within a given radius. VWS is one of the most important dynamical parameters of the large-scale environment related to TC formation, as well as its structure and intensity change. VWS is considered as one of the major predictors in several statistical TC intensity predictions. VWS is the major factors that can lead to strong convective asymmetries in the core of a TC.

2.2.1.4 Relative Vorticity

Vorticity is the tendency for elements of the fluid to spin. Vorticity is defined as twice the angular rate of rotation of an object about a vertical axis. The vorticity is a pseudo vector field ω, defined as the curl (rotational) of the flow velocity u vector. The definition can be expressed by the vector analysis formula: $\omega = \nabla \times u$. Figure 2.7 shows the present of vorticity. The spin imparted to the air by the rotating Earth (rotation around a local vertical) called Earth vorticity. The relative vorticity is the vorticity of the air velocity field relative to the Earth. This is often modeled as a two-dimensional flow parallel to the ground, so that the relative vorticity vector is generally perpendicular to the ground, and can then be viewed as a scalar quantity, positive when the vector points upward, negative when it points downwards.

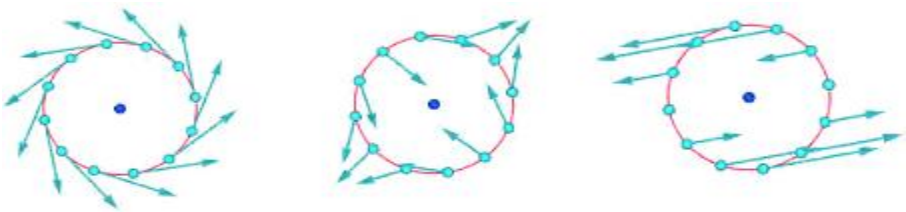


Figure 2.7: Vorticity ≠ 0 Vorticity ≠ 0 Vorticity = 0

The relative vorticity is the vorticity of the air velocity field relative to the Earth. This is often modeled as a two-dimensional flow parallel to the ground, so that the relative vorticity vector is generally perpendicular to the ground, and can then be viewed as a scalar quantity, positive when the vector points upward, negative when it points downwards. Figure 2.8 shows the positive and negative nature of vorticity. Vorticity is positive when the wind turns counter-clockwise (looking down onto the Earth's surface). In the Northern Hemisphere, positive vorticity is called cyclonic rotation, and negative vorticity is anticyclonic rotation; the nomenclature is reversed in the Southern Hemisphere. Parcels acquire relative vorticity when they encounter curved flow and horizontal differences in wind speeds. The large magnitude of low level relative vorticity is playing an important role in determining regions of high TC genesis frequency. It is well observed that TCs form only in regions of large positive low level vorticity. The larger this low level vorticity, the greater appears the potential for cyclone genesis. Other conditions being favorable and remaining constant, TC genesis should be directly related to the magnitude of low level tropospheric relative vorticity (https://en.wikipedia.org, 2015).

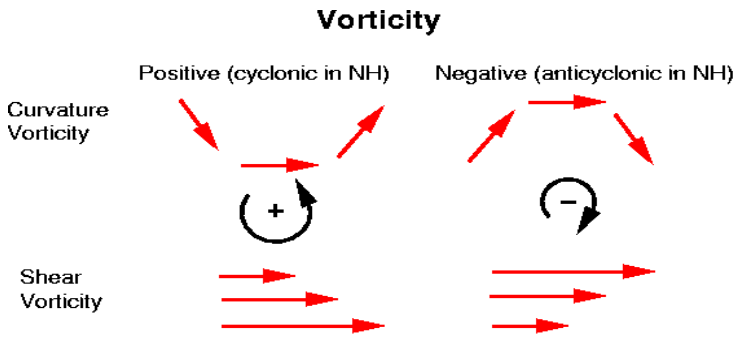


Figure 2.8: Cyclonic and anticyclonic phase of vorticity

2.2.2 Thermodynamic Parameters

2.2.2.1 Sea Surface Temperature

Sea surface temperature (SST) is the water temperature close to the ocean's surface. The distribution of SST exceeding 26 °C is one of the primary factors explaining the seasonal

distribution and frequency of TCs over the oceans. Waters of this temperature cause the overlying atmosphere to be unstable enough to sustain convection and thunderstorms and maintain the warm core that fuels tropical systems. The temperature of the underlying water is the dominant factor in TC intensification. Increasingly warmer water would enable to progressively stronger tropical storm. The formation of SCS, VSCS and SC starts after 27.50 °C and increases with increasing SST but discontinuously. The intensity of cyclone has a step-like rather than continuous relationship with SST. SST alone is an adequate predicator of TC intensity.

2.2.2.2 Sea Level Pressure (SLP)

The sea level pressure (SLP) is the atmospheric pressure at sea level at a given location. When observed at a reporting station that is not at sea level (nearly all station), it is a correction of the station pressure to sea level. This correction takes into account the standard variation of pressure with height on the pressure. The temperature used in the sea level correction is a twelve hour mean, eliminating diurnal effect. The mean sea level pressure (MSLP) is the atmospheric pressure at sea level. This is the atmospheric pressure normally given in weather reports on radio, television, and newspapers or on the Internet When barometers in the home are set to match the local weather reports, they measure pressure adjusted to sea level, not the actual local atmospheric pressure. The altimeter setting in aviation is an atmospheric pressure adjustment. Average SLP is 1013.25 mbar (101.325 kPa; 29.921 in Hg; 760.00 mmHg). In aviation weather reports (METER) QNH is transmitted around the world in millers or hectopascals (1 hectopascal = 1 mi llibar), except in the United states Canada and Colombia where it is reported in inches (to two decimal places) mercury. The United States and Canada also report SLP, which is adjusted to sea level by a different method, in the remarks section, not in the internationally transmitted part of the code, in hectopascals or millibars. However, in Canada's public weather reports, sea level pressure is instead reported in kilopascals. In the US weather code remarks, three digits are all that are transmitted; decimal points and the one or two most significant digits are omitted: 1013.2 mbar (101.32 kPa) is transmitted as 132; 1000.0 mbar (100.00 kPa) is transmitted as 000; 998.7 mbar is transmitted as 987; etc. The highest SLP on Earths occurs in Siberia, where the Siberian High often attains a SLP above 1050 mbar (105 kPa; 31 inHg), with

record highs close to 1085 mbar (108.5 kPa; 32.0 inHg). The lowest measurable SLP is found at the centers of TC and tornadoes with a record low of 870 mbar (87 kPa; 26 inHg).

2.2.2.3 Relative Humidity (RH)

Relative Humidity (RH) is the most commonly used measurements of moisture content in the air. RH is the amount of water vapor (moisture) in the air compared to the maximum amount that the air could hold at a given temperature. The relative humidity is:

$$f = \frac{\omega}{\omega_s} \times 100 = \frac{\rho_w}{\rho_{ws}} \times 100 = \frac{q}{q_s} \times 100 = \frac{e}{e_s} \times 100$$

Here q is specific humidity and q_s is specific humidity at saturation point, ω is mixing ratio and ω_s is mixing ratio at saturation point.

If the relative humidity is 100%, the air is saturated. If the relative humidity is 50%, the air contains half the water vapor required for it to be saturated. If the amount of water vapor in the air increases, the relative humidity increases, and if the amount of water vapor in the air decreases, the relative humidity decreases. However, relative humidity is dependent on air temperature, too. If the water vapor content remains the same and the temperature drops, the relative humidity increases. If the water vapor content remains the same and the temperature rises, the relative humidity decreases. This is because colder air doesn't require as much moisture to become saturated as warmer air. Warm air can hold more water vapor than cool air, so a particular amount of water vapor will yield a lower relative humidity in warm air than it does in cool air. In the summer, the relative humidity is actually higher in the morning than in the afternoon. This is because the cooler morning air is closer to saturation than the hot afternoon air, even with the same amount of water vapor. Surprisingly, there is no significant difference in daily average relative humidity between summer and winter. Since warm air is less dense than cold air, there is more room for water vapor in warm summer air as compared with cold winter air. At a given vapor pressure (or mixing ratio), relative humidity with respect to ice is higher than that with respect to water. Water is known by different names in different states. If the maximum amount of water vapor has been reached and more water is introduced into the air, an equal amount of water must transform back to liquid or solid form through condensation. At this point, the air is said to be saturated with water, and the relative humidity is 100%. On the other end of the scale, when there is no

water vapor in the air, the relative humidity is 0% whatever the temperature. In other words, relative humidity always lies between 0 and 100%. As mentioned, the ability of air to hold water vapor is strongly dependent on temperature. This means that relative humidity is also strongly temperature dependent.

2.2.2.4 Convective Available Potential Energy (CAPE)

In meteorology, convective available potential energy (CAPE), sometimes, simply, available potential energy (APE), is the amount of energy a parcel of air would have if lifted a certain distance vertically through the atmosphere. CAPE is effectively the positive buoyancy of an air parcel and is an indicator of atmospheric instability, which makes it very valuable in predicting severe weather. CAPE exists within the conditionally unstable layer of the troposphere, the free convective layer, where an ascending air parcel is warmer than the ambient air. CAPE is measured in joules per kilogram of air (J/kg). Any value greater than 0 J/kg indicates instability and the possibility of thunderstorms. Generic CAPE is calculated by integrating vertically the local buoyancy of a parcel from the level of free convection to the equilibrium Level:

$$CAPE = \int_{EL}^{LFC} \left(\frac{T_v - T_{ve}}{T_{ve}} \right) g dz \qquad (1)$$

CAPE for different stability regimes are given as follows :(Molinari *et al* .,2009)

CAPE < 1000 J/Kg	:	Instability is weak
CAPE > 1000 < 2500 J/Kg	:	Moderately unstable
CAPE > 2500 J/Kg	:	Extremely unstable

2.2.2.5 Convective Inhibition (CIN)

Convective inhibition (CIN or CINH) is a numerical measure in meteorology that indicates the amount of energy that will prevent an air parcel from rising from the surface to the level of free convection. CIN is the amount of energy required to overcome the negatively buoyant energy the environment exerts on an air parcel. In most cases, when CIN exists, it covers a layer from the ground to the level of free convection (LFC). The negatively buoyant energy exerted on an air parcel is a result of the air parcel being cooler (denser) than the air which surrounds it, which causes the air parcel to accelerate downward. The situation in

which convective inhibition is measured is when layers of warmer air are above a particular region of air. The effect of having warm air above a cooler air parcel is to prevent the cooler air parcel from rising into the atmosphere. This creates a stable region of air. Figure 2.19 shows the area of convergence positive/negative buoyancy as well as the lifted condensation level, level of free convection, and equilibrium level. Convective inhibition indicates the amount of energy that will be required to force the cooler packet of air to rise. This energy comes from fronts, heating, moistening, or mesoscale convergence boundaries such as outflow and sea breeze boundaries, or graphic lift. Typically, an area with a high convection inhibition number is considered stable and has very little likelihood of developing a thunderstorm. Conceptually, it is the opposite of CAPE. CIN is strengthened by low altitude dry air advection and surface air cooling. Surface cooling causes a small capping inversion to form aloft allowing the air to become stable. Incoming weather fronts and short waves influence the strengthening or weakening of CIN. CIN is energy per unit mass and the units of measurement are joules per kilogram (J/kg). CIN is measured as

$$CIN = \int_{Z_{bottom}}^{Z_{top}} \left(\frac{T_{v,parcel} - T_{v,env}}{T_{v,env}} \right) g dz \qquad (2)$$

The Z_{bottom} and Z_{top} limits of integration in the equation represent the bottom and top altitudes of a single CIN layer, is the virtual temperature of the specific parcel and is the virtual temperature of the environment. In many cases, the Z_{bottom} value is the ground and the Z_{top} value is the LFC. CIN is expressed as a negative energy value. CIN values greater than 200 J/kg are sufficient enough to prevent convection the atmosphere. In fact, CIN is sometimes referred to as negative buoyant energy. It is a good indicator of general stability, and convection tends to be less vigorous with higher values.

CIN	< 100	Potential Instability.
CIN	100 to 200	Marginally stable.
CIN	200 to 300	Moderately stable.
CIN	>400	Very stable.

2.3 Weather Research & Forecasting Model

The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed to serve both atmospheric research and operational forecasting needs. It features two dynamical cores, a data assimilation system, and a software architecture facilitating parallel computation and system extensibility. The model serves wide ranges of meteorological applications across scales from tens of meters to thousands of kilometers. The effort to develop WRF began in the latter part of the 1990's and was a collaborative partnership principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA) represented by the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL) the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA).

WRF offers two dynamical solvers for its computation of the atmospheric governing equations, and the variants of the model are known as WRF-ARW and WRF-NMM. The Advanced Research WRF (ARW) is supported to the community by the NCAR Mesoscale and Microscale Meteorology Division. The WRF-NMM solver variant was based on the Eta Model, and later Non hydrostatic Mesoscale Model, developed at NCEP. The WRF-NMM is supported to the community by the Developmental Test bed Center.

There are many options in the model such as physics option, map projection and computation methods. Descriptions of all of items used for the present study are written in the following sub-section. Again, there are many Physics option in the model such as microphysics, cumulus physics, radiation Physics and planetary boundary Layer Physics. Each physics option has many parameterization schemes. Descriptions of the parameterization schemes used for the present study are written as follows:

2.3.1 Microphysics Schemes in WRF-ARW Model

Microphysics includes explicitly resolved water vapor, cloud and precipitation processes. The model is general enough to accommodate any number of mass mixing-ratio variables, and

other quantities such as number concentrations. Four-dimensional arrays with three spatial indices and one species index are used to carry such scalars. Memory, i.e., the size of the fourth dimension in these arrays, is allocated depending on the needs of the scheme chosen, and advection of the species also applies to all those required by the microphysics option. In the current version of the ARW, microphysics is carried out at the end of the time-step as an adjustment process, and so does not provide tendencies.

The rationale for this is that condensation adjustment should be at the end of the time-step to guarantee that the final saturation balance is accurate for the updated temperature and moisture. However, it is also important to have the latent heating forcing for potential temperature during the dynamical sub-steps and this is done by saving the microphysical heating as an approximation for the next time-step as described.

2.3.1.1 WSM 6-class Scheme

The WRF-single-moment-6-class (WSM6) microphysics scheme has been one of the options of microphysical process in the WRF model. This scheme predicts the mixing ratios for water vapor, cloud water, cloud ice, snow, rain, and graupel. We attempt to improve such existing deficiencies in the WSM6 scheme by incorporating the prediction of number concentrations for warm rain species. A new method for representing mixed-phase particle fall speeds for the snow and grapple by assigning a single fall speed to both that is weighted by the mixing ratios, and applying that fall speed to both sedimentation and accumulation processes is introduced of the three WSM schemes, the WSM6 scheme is the most suitable for cloud-resolving grids, considering the efficiency and theoretical backgrounds (Hong *et al*., 2006). The WSM6 scheme has been developed by adding additional process related to grapple to the WSM5 scheme (Hong and Lim, 2006).

2.3.2 Cumulus Parameterization

These schemes are responsible for the sub-grid-scale effects of convective and/or shallow clouds. The schemes are intended to represent vertical fluxes due to unresolved updrafts and downdrafts and compensating motion outside the clouds. They operate only on individual columns where the scheme is triggered and provide vertical heating and moistening profiles. Some schemes provide cloud and precipitation field tendencies in the column, and future schemes may provide momentum tendencies due to convective transport of momentum. The

schemes all provide the convective component of surface rainfall. Cumulus parameterizations are theoretically only valid for coarser grid sizes, (e.g., greater than 10 km), where they necessary to properly release latent heat on a realistic time scale in the convective columns. Where the assumptions about the convective eddies being entirely sub-grid-scale break down for finer grid sizes, sometimes these schemes have been found to be helpful in triggering convection in 5-10 km grid applications. Generally they should not be used when the model can resolve the convective eddies itself. These schemes are responsible for the sub-grid-scale effects of convective and shallow clouds. The schemes are intended to represent vertical fluxes due to unresolved updrafts and downdrafts and compensating motion outside the clouds.

2.3.2.1 Kain-Fritsch Scheme

In the KF scheme the condensates in the updraft are converted into precipitation when their amount exceeds threshold value. In this scheme the convection consumes the convective available potential energy in a certain time scale. The KF scheme also includes the shallow convection other than deep convection. The shallow convection creates non-perceptible condensates and the shallowness of the convection is determined by a vertical extent of the cloud layer that is known by a function of temperature at LCL of rising air parcel. The KF scheme was derived from the Fritsch–Chappell, and its fundamental framework and closure assumptions are described by Fritsch and Chappell (1980). KF (1990, 1993) modified the updraft model in the scheme and later introduced numerous other changes, so that it eventually became distinctly different from the Fritsch–Chappell scheme. It was distinguished from its parent algorithm by referring to the more elaborate code as the KF scheme, beginning in the early 1990s. This is also deep and shallow convection sub-grid scheme using a mass flux approach with downdrafts and CAPE removal time scale. Updraft generates condensate and dump condensate into environment downdraft evaporates condensate at a rate that depends on RH and depth of downdraft leftover condensate accumulates at surface as precipitation.

2.3.3 Planetary Boundary Layer (PBL)

The PBL is the layer in the lower part of the troposphere with thickness ranging from a few hundred meters to a few kilometers within which the effects of the Earth’s surface are felt by

the atmosphere. The PBL processes represent a consequence of interaction between the lowest layer of air and the underlying surface. The interactions can significant impact on the dynamics of the upper air flows. The influences of the small-scale eddy on large scale atmospheric circulations may be included in the model equations. Accurate depiction of meteorological conditions, especially within the PBL, is important for air pollution modeling, and PBL parameterization schemes play a critical role in simulating the boundary layer. It is a very important portion of the atmosphere to correctly model to provide accurate forecasts, e.g., air pollution forecasts. As important as the PBL is, it has one basic property whose accurate and realistic prediction is paramount to its correct modeling: its height. After all, the height of the top of the PBL defines its upper boundary. This is critical since PBL parameterizations schemes in WRF-ARW models need to know the extent through which to mix properties such as heavy rainfall, relative humidity, outgoing long wave flux, downward long wave flux.

PBL schemes were developed to help resolve the turbulent fluxes of heat, moisture, and momentum in the boundary layer. Another important issue is the interaction between the atmosphere and the surface. The PBL schemes handle the latent and sensible heat fluxes into the atmosphere, the frictional effects with the surface and the strong sub–grid–scale mixing which takes place in the lower levels due to these processes.

2.3.3.1 Yonsei University (YSU) Scheme

The Yonsei University (YSU) PBL is the next generation of the Medium Ranges Forecast (MRF), Non local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer. The YSU scheme is a bulk scheme that expresses non-local mixing by convective large eddies. Non-local mixing is achieved by adding a non-local gradient adjustment term to the local gradient. At the top of the PBL, the YSU scheme uses explicit treatment of the entrainment layer, which is proportional to the surface layer flux (Shin and Hong 2011; Hong *et al*. 2006).

2.3.4 Radiation schemes

There are two types of radiation schemes: Long wave and short wave. The used schemes for these are describe as follows:

2.3.4.1 Long Wave Radiation

Rapid Radiative Transfer Model (RRTM) Scheme: This RRTM, which is taken from MM5, is based on Mlawer et al., and is a spectral-band scheme using the correlated-k method. An accurate scheme using looking tables for efficiency. Accounts for multiple bands, trace gases and microphysics species.

2.3.4.2 Short Wave Radiation

MM5 (Dudhia) Scheme: This scheme is base on Dudhai and is taken from MM5. Simple downward integration is allowing efficiently for clouds and clear-sky absorption and scattering. When used in high-resolution simulations, sloping and shadowing effects may be considered.

2.3.5 Map Projection

Commonly, a map projection is a systematic transformation of the latitudes and longitudes of locations on the surface of a sphere or an ellipsoid into locations on a plane. Map projections are necessary for creating maps. All map projections distort the surface in some fashion. Depending on the purpose of the map, some distortions are acceptable and others are not; therefore, different map projections exist in order to preserve some properties of the sphere-like body at the expense of other properties. There is no limit to the number of possible map projections. More generally, the surfaces of planetary bodies can be mapped even if they are too irregular to be modeled well with a sphere or ellipsoid. Even more generally, projections are the subject of several pure mathematical fields, including differential geometry and projective geometry. However, map projection refers specifically to a cartographic projection.

2.3.5.1 Mercator Projection

The Mercator projection is a cylindrical map projection presented by the Flemish geographer and cartographer Gerardus Mercator in 1569. It became the standard map projection for nautical purposes because of its ability to represent lines of constant course, known as rhomb lines lox dorms, as straight segments which conserve the angles with the meridians. While the linear scale is equal in all directions around any point, thus preserving the angles and the shapes of small objects, the Mercator projection distorts the size and shape of large objects,

as the scale increases from the Equator to the poles, where it becomes infinite. Although the Mercator projection is still used commonly for navigation, due to its unique properties, cartographers agree that it is not suited to general reference world maps due to its distortion of land area. Mercator himself used the equal-area sinusoidal projection to show relative areas. As a result of these criticisms, modern atlases no longer use the Mercator projection for world maps or for areas distant from the equator, preferring other cylindrical projection or forms of equal-area projection. The Mercator projection is still commonly used for areas near the equator, however, where distortion is minimal.

2.3.6 Arakawa Staggered C-grids for Computation Method

The Arakawa grid system depicts different ways to represent and compute orthogonal physical quantities on (Arakawa *et al* 1977) rectangular grids used for Earth system models for meteorology and oceanography. For example, the Weather Research and Forecasting Model use the Arakawa Staggered C-Grid in its atmospheric calculations when using the ARW core. The staggered Arakawa C-grid further separates evaluation of vector quantities compared to the Arakawa B-grid. E.g., instead of evaluating both east-west (u) and north-south (v) velocity components at the grid center, one might evaluate the u components at the centers of the left and right grid faces, and the v components at the centers of the upper and lower grid face.

CHAPTER III

Model Description and Methodology

In the present study, the Weather Research and Forecasting (WRF-ARW Version 3.80) model is utilized to study the genesis of low intensity TCs in the Bay of Bengal. The model description and methodology are given below:

3.1 Model Domain and Configuration

Weather Research and Forecasting (WRF-ARW Version 3.80) model is consists of fully compressible non-hydrostatic equations and different prognostic variables. The model vertical coordinate is terrain following hydrostatic pressure and the horizontal grid is Arakawa C-grid staggering. Third-order Runge-Kutta time integration is used in the model. The model is configured in single domain, 9 km horizontal grid spacing with 290×316 grids in the west-east and north-south directions and 32 vertical levels. The model domain is given in Figure 3.1.

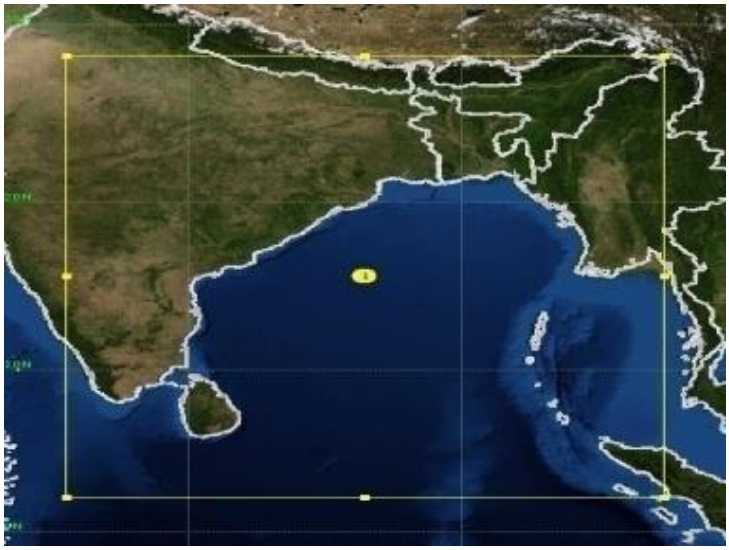


Figure 3.1: The WRF-ARW domain set up for the study.

The cumulus parameterization (CP) schemes have been used in WRF model are Kain-Fritsch (KF) scheme. The CP schemes contain prognostic equations for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio. The Ferrier scheme also contains prognostic equations for cloud water, rainwater and snow mixing ratio. Dudhia simple five-layer soil thermal diffusion scheme for soil processes, Rapid Radiative Transfer Model (RRTM) for long wave

scheme and Dudhia for short wave radiation schemes and Yonsei University scheme planetary boundary layer (PBL) have been used for the simulation of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. Other 4 cases are also done when there was no cyclone. The detail of the model and domain configuration is given in Table 3.1.

Table 3.1**:** WRF Model and Domain Configurations

Dynamics	Non-hydrostatic
Number of domain	1
Central points of the domain	Central Lat.: 15.4°N, Central Lon.: 86.5°E
Horizontal grid distance	9 km
Integration time step	30 s
Number of grid points	X-direction 290 points, Y-direction 316 points
Map projection	Mercator
Horizontal grid distribution	Arakawa C-grid
Nesting	One way
Vertical co-ordinate	Terrain-following hydrostatic-pressure co-ordinate (32 sigma levels up to 100 hPa)
Time integration	3rd order Runge-Kutta
Spatial differencing scheme	6th order centered differencing
Initial conditions	Three-dimensional real-data (FNL: 1° × 1°)
Lateral boundary condition	Specified options for real-data
Top boundary condition	Gravity wave absorbing
Bottom boundary condition	Physical or free-slip
Diffusion and Damping	Simple Diffusion
Microphysics	WSM 6-class graupel scheme
Radiation scheme	Dudhia for short wave radiation/ RRTM long wave
Cumulus parameterization schemes	Kain-Fritsch (KF)
PBL parameterization	Yonsei University Scheme

3.2 Description of the Case Study and Methodology

At first, 4 TCs Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 have been selected which formed on the Bay of Bengal during 25-27 October 2008, 25-28 November 2008, 14-17 April 2009 and 10-17 May 2013 respectively. The pre event of the selected cyclone, model run duration, initial and final dates of model run, date of formation of depression of the cyclone, selected cyclones and post event of the selected cyclone are written in the columns 1, 2, 3, 4, 5 and 6 respectively of the Table 3.2. These 4 TCs Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are formed as a depression on 03 UTC on 25 October 2008, 09 UTC on 25 November 2008, 09 UTC on 14 April 2009 and 09 UTC on 10 May 2013 respectively.

Finally, they gradually intensified up to cyclonic storm. For this reason they are considered as low intensity TC. Here among the four cyclones, two are formed in pre-monsoon season and two are formed in post-monsoon season. It is noted that TCs Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are formed as a cyclonic storm on 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009 and 03 UTC on 11 May 2013 respectively.

The WRF model is used to study the genesis of these low intensity cyclones in the Bay of Bengal. Here, study is done in two steps: firstly the formation of depression and secondly the intensification up to cyclonic storm. Final Reanalysis (FNL) data (1° x1^o) from National Centre for Environment Prediction (NCEP), USA is used as initial and lateral boundary conditions (LBCs) which is updated at six hourly interval i.e. the model is being initialized with 0000, 0600, 1200 and 1800 UTC initial field of corresponding date. The NCEP FNL data will be interpolated to the model horizontal and vertical grids.

Table 3.2**:** Information of case study of the selected cyclones for formation of depression

Previous events	Model run to capture depression		Formed as a depression	Cyclone (for case study)	Post events
	Run duration	Run dates			
1	2	3	4	5	6
Depression-2008 (15-19) September	96 h	(22-26) Oct	03 UTC 25 OCT/2008	Rashmi-2008 (25-27) October	Khaimuk-2008 (13-16) November
	72 h	(23-26) Oct			
	48 h	(24-26) Oct			
	24 h	(25-26) Oct			
Khaimuk-2008 (13-16) November	96 h	(22-26) Nov	09 UTC 25 Nov/2008	Nisha -2008 (25-28) November	Depression-2008 (04-07) December
	72 h	(23-26) Nov			
	48 h	(24-26) Nov			
	24 h	(25-26) Nov			
Depression-2008 (04-07) December	96 h	(11-15) April	09 UTC 14 April/2009	Bijly-2009 (14-17) April	Aila-2009 (23-26) May
	72 h	(12-15) April			
	48 h	(13-15) April			
	24 h	(14-15) April			
Depression-2012 (17-19) November	96 h	(7-11) May	09 UTC 10May/2013	Viyaru -2013 (10-17) May	Depression-2013 (29-31)May
	72 h	(8-11) May			
	48 h	(9-11) May			
	24 h	(10-11) May			

For first step, model is run using initial condition of 4 days before the formation of earlier stage (depression) of the aforementioned cyclones to simulate the very earlier formation stage (depression). This run is treated as 96 hours run. Again, 72, 48 and 24 hours run are made by starting the run from 3, 2 and 1 day before the formation of earlier stage (depression) respectively of the aforementioned cyclones. Run duration and initial and final dates of the model run of the cyclone are written in the column 2 and 3 of the Table 3.2 respectively.

Table 3.3**:** Information of case study of the selected cyclones for formation of cyclonic storm

Previous events	Model run to capture cyclonic storm		Formed as a cyclonic storm	Cyclone (for case study)	Post events
	Run duration	Run dates			
1	2	3	4	5	6
Depression-2008 (15-19) September	24 h	(26-27) Oct	12 UTC 26 OCT/2008	Rashmi-2008 (25-27) October	Khaimuk-2008 (13-16) November
Khaimuk-2008 (13-16) November	24 h	(26-27) Nov	03 UTC 26 Nov/2008	Nisha -2008 (25-28) November	Depression-2008 (04-07) December
Depression-2008 (04-07) December	24 h	(15-16) April	12 UTC 15 April/2009	Bijly-2009 (14-17) April	Aila-2009 (23-26) May
Depression-2012 (17-19) November	24 h	(11-12) May	03 UTC 11 May/2013	Viyaru -2013 (10-17) May	Depression-2013 (29-31)May

For second step, Model is run for further 24 hours using initial conditions 00 UTC on 26 October 2008, 00 UTC on 26 November 2008, 00 UTC on 15 April 2009 and 00 UTC on 11 May 2013 for the TCs Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively to test the formation/intensification as cyclonic storm. These dates of initial condition are chosen within 24 hours earlier of the formation as cyclonic storm of the respective cyclone. Run duration and initial and final dates of the model run of the cyclone are written in the column 2 and 3 of the Table 3.3 respectively.

Again, 4 cases have been selected during the period 1-5 April 2008, 1-5 April 2010, 1-5 August 2011 and 1- 5 August 2012 when there is no cyclone on the Bay of Bengal and they are treated as Normal-2008, Normal-2010, Normal-2011 and Normal-2012.

Table 3.4**:** Information of case study of the normal case

Previous events	Model run		Normal (for case study)	Post events
	Run duration	Run dates		
1	2	3	4	5
Sidr-2007 (11-16)November	96 h	(01-05) April	Normal -2008 (01-05) April	Nargis-2008(27 April-03 May)
	72 h	(02-05) April		
	48 h	(03-05) Aril		
	24 h	(04-05) April		
Ward-2009 (10-15) December	96 h	(01-05) April	Normal -2010 (01-05) April	Laila-2010 (17-21) May
	72 h	(02-05) April		
	48 h	(03-05) April		
	24 h	(04-05) April		
Depression-2011 (16-23) Jun	96 h	(01-05) August	Normal -2011 (01-05) August	Depression-2011 (22-23) September
	72 h	(02-05) August		
	48 h	(03-05) August		
	24 h	(04-05) August		
Thane-2011 (25-31) December	96 h	(01-05) August	Normal -2012 (01-05) August	Depression-2012 (10-11) October
	72 h	(02-05) August		
	48 h	(03-05) August		
	24 h	(04-05) August		

The pre event of the selected normal cases, model run duration, initial and final dates of model run, selected normal cases and post event of the selected normal cases are written in the columns 1, 2, 3, 4 and 5 respectively of the Table 3.4. From the date of the pre events and post events in Table 3.4, it is clear that that there are long gap between normal case events and pre events also the normal events and post events. It is chosen in this way to find out environmental parameters when there is no event for a long time. Using initial conditions, model is run starting 4 days before a fixed date (last date of the each case). This fixed date for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are 00 UTC on 5 April 2008, 5 April 2010, 5 August 2011 and 5 August 2012 respectively. This run is treated as 96 hours run. Again, 72, 48 and 24 hours are made by starting the run from 3, 2 and 1 day before the same fixed date of the normal case. Run duration and initial and final dates of the model run of the cyclone are written in the column 2 and 3 of the Table 3.4 respectively.

Dynamical and thermo-dynamical parameters are obtained from the model output for both cyclones and normal cases. Dynamical parameters are Wind Speed (WS) at 10m, Vertical Wind Shear (VWS) between 850-200hPa, Vertical Profile of Horizontal Wind (VHW), Vertical Profile of Vertical Wind (VVW) and Relative Vorticity (RV) (850 hPa). Again, thermo-dynamical parameters are Sea Surface Temperature (SST), Mean Sea Level Pressure (SLP), Relative Humidity (RH), Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN). Then, for first step, values obtained from cyclone cases are compared with those obtained from normal cases and available data. Then, for second step, values obtained from cyclone cases are discussed and compared with available observed data. Microsoft Excel and GrADS software is used for post-processing and data visualization.

CHAPTER IV

Result and Discussions

To study the selected normal cases, WRF Model is run up to 00 UTC on 5 April 2008,5 April 2010,5 August 2011 and 5 August 2012 for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 respectively with different initial conditions to make 96, 72, 48 and 24 hours run for each normal case taken in this study. It is noted that study is done in two steps: firstly the formation of depression and secondly the intensification up to cyclonic storm. For first step, model is also run up to 00 UTC on 26 October 2008, 00 UTC on 26 November 2008, 00 UTC on 15 April 2009 and 00 UTC on 11 May 2013 for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively with different initial conditions to make 96, 72, 48 and 24 hours run for each cyclone to test the formation as a depression. For second step, model is run for further 24 hours using initial conditions 00 UTC on 26 October 2008, 00 UTC on 26 November 2008, 00 UTC on 15 April 2009 and 00 UTC on 11 May 2013 for the TCs Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively to test the formation/intensification as cyclonic storm.

Wind Speed (WS) at 10m, Vertical Wind Shear (VWS) between 850-200hPa, Vertical Profile of Horizontal Wind (VHW), Vertical Profile of Vertical Wind (VVW), Relative Vorticity (RV) (850 hPa), Sea Surface Temperature (SST), Mean Sea Level Pressure (SLP), Relative Humidity (RH), Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) are obtained from cyclones and normal cases. Then values obtained from cyclone cases with 96, 72, 48 and 24 hours run (formed as depression) are compared with those obtained from normal cases in the following sub-sections. It is noted that the spatial distribution of all parameters for 96, 72, 48 and 24 hours for normal cases (without cyclones) and with cyclones cases (formation of depression only) are simulated and plotted in the left-above, right-above, left-below and right-below corner of the Figure respectively. Again, to test the formation/intensification as cyclonic storm, model is run further 24 hours for each cyclonic case. Simulated outputs of each cyclone are also analyzed. Microsoft Excel and GrADS software is used for post-processing and data visualization.

4.1 Synoptic Situation of TCs

The Synoptic Situation of the four TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are discussed in the as follows.

4.1.1 Description of TC Rashmi

On October 24, 2008, an area of low pressure formed in the North Indian Ocean, within the central Bay of Bengal. Later that day the Joint Typhoon Warning Center, designated it as a Tropical Disturbance and assessed its chances of forming into a significant TC within the next 24 hours as fair. The next day as the India Meteorological Department reported that the disturbance had intensified into a depression and assigned the number BOB 05 to the depression. The JTWC then upgraded the depression's chances of forming into a significant cyclone and issued a TC Formation Alert on the depression. Early on October 26, the IMD upgraded the depression to a deep depression, with wind speeds of 30 knots (35 mph, 55 km/h). At the same time, the JTWC designated the depression as Cyclone 04B. Later that day the IMD reported that the Deep Depression had intensified into a Cyclonic Storm and named as Rashmi. During that evening the IMD reported that Rashmi had reached its peak 3 minute wind speeds of 40 knots, whilst the JTWC also reported that Rashmi had reached its peak 1 minute wind speeds of 45 knots. Early the next day, the IMD reported that Rashmi had made landfall on Bangladesh coast near Barisal. As a result of making landfall Rashmi started to weaken rapidly by becoming a Deep Depression, early that morning before being downgraded to a well marked area of low pressure, later during the morning.

4.1.2 Description of TC Nisha

On November 24, an area of low pressure formed over land in Sri Lanka. Later that day, the Joint Typhoon Warning Center assessed the low-pressure area's chance of becoming a significant TC within 24 hours as 'poor', due to the minimal convection near the low-level circulation center. The next morning, the JTWC issued a TC Formation Alert on the low-pressure area, stating it had a 'good' chance of becoming a significant TC within 24 hours, as the Low Level Circulation Center was moving into the Bay of Bengal. Two hours later, the IMD upgraded the area of low pressure to Depression BOB 07. Three hours later, the India Meteorological Department reported that the depression had intensified into a Deep Depression whilst remaining stationary. Later that day the JTWC upgraded the Deep

Depression to TC 06B and reported that the depression had wind speeds equivalent to a tropical storm, on the Saffir–Simpson hurricane scale. Early on November 26, the deep depression was intensified into a cyclone at 03 UTC on 26 November 2008 as reported by IMD and named it Nisha. Later that day as Nisha moved northwest towards India, both the JTWC and the IMD reported that Nisha had reached its peak wind speeds of It is severe cyclonic storm because wind speed is >89 kph. Early the next day the IMD reported that Cyclonic Storm Nisha had made landfall in Tamil Nadu, India at 0030 UTC. Later that day as the IMD reported that Nisha had weakened into a deep depression, the JTWC issued their final advisory on Nisha. The IMD then reported that Nisha had weakened into a Depression and then issued their last advisory the next day, reporting that Nisha had weakened into a well-marked area of low pressure.

4.1.3 Description of TC Bijli

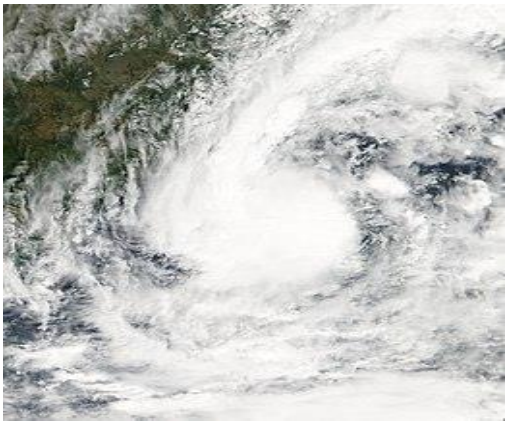
On April 13, 2010 0900 UTC an area of shower and thunderstorms became slightly organized over the central Bay of Bengal. Later that day, an area of low pressure developed underneath the convection as the system developed. Weak banding features also formed around the periphery of the storm. By April 14, deep convection persisted around the center of circulation; following the development the RSMC in New Delhi, India designated the system as Depression BOB 01. Following further development, the Joint Typhoon Warning Center (JTWC) issued a TC Formation Alert (TCFA) as they anticipated the system to develop into a tropical storm. Early the next morning, the JTWC reported that the depression had intensified into a tropical storm and designated it as Cyclone 01B. The storm tracked towards the west-northwest due to a ridge over India. Later that morning, RSMC New Delhi reported that the depression had intensified into a deep depression and reported that it was expected to intensify into Cyclonic Storm Bijli. Around 1500 UTC, the RSMC New Delhi Reported that the system was intensified to a cyclonic storm and was given it the name Bijli. Partial convective banding developed around the periphery of the system as it intensified. The conditions for good outflow were present but did not develop. Around this time, the forward motion of the storm also slowed. On April 16, the storm turned towards the northeast, paralleling the eastern coast of India. Around 0600 UTC, RSMC New Delhi reported that Bijli had reached its peak intensity with winds of 75 km/h (45 mph 3-minute winds). Early on April 17, RSMC New Delhi reported that Bijli had weakened into a deep depression as it

started to move the northeast.

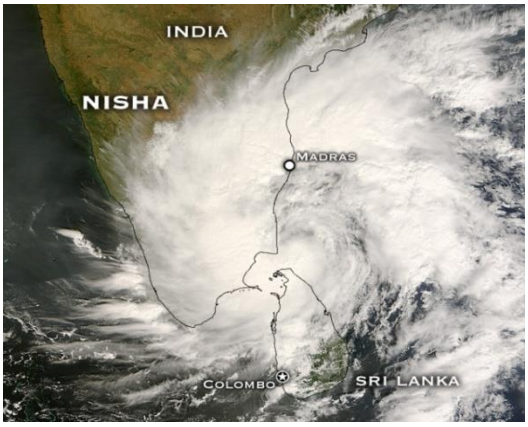
4.1.4 Description of TC Viyaru

In early 10 May 2013, at 0900 UTC an area of disturbed weather formed over the southern Bay of Bengal. Remaining nearly stationary, the system gradually developed. By May 8, organized convection formed around a defined low pressure area, with banding feature present. With conditions favoring intensification, low wind shear, excellent poleward outflow, and unusually high sea surface temperatures (estimated at 31 °C (88 °F), the system was anticipated to become a TC over the following days. A pulse in the Madden–Julian oscillation, coupled with a convective Kelvin wave allowed the system, along with its Southern Hemisphere counterpart Tropical Storm Jamala, to further develop. Following additional organization, the Joint Typhoon Warning Center (JTWC) issued a TC Formation Alert for the low on May 10. Despite an increase in wind shear, causing the low to become dislocated from the deepest convection, the system further intensified and a scatter meter pass from the Oceansat-2 satellite indicated winds up to 65 km/h (40 mph). In light of this data, the JTWC classified the system as TC 01B while it was situated roughly 1,950 km (1,210 mi) south of Chittagong, Bangladesh. At the time, the agency anticipated significant strengthening of the cyclone, forecasting it to attain winds in excess of 155 km/h (100 mph). The India Meteorological Department (IMD) followed submits hours later, designating the system as Depression BOB 01 and soon upgrading it to a deep depression.

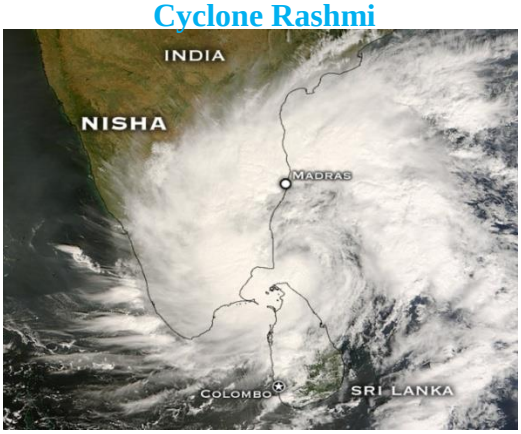
Situated to the south of a subtropical ridge, the storm tracked west-northwestward to northwestward. Early on May 11, the IMD reported that the system intensified into a cyclonic storm and it was assigned the name *Mahasen*. Deep convection, with cloud tops estimated as cold as −85 °C developed near the storm's center. Despite moderate to strong wind shear, Viyaru prominent outflow offset the negative influence of the shear, allowing a central dense overcast to form. . This allowed Viyaru to intensify, with the JTWC estimating one-minute sustained winds reaching 95 km/h. By May 12, the central dense overcast broke apart into fragmented banding features that wrapped into the center. Dry air soon began to flow into the circulation, disrupting convection and causing the low to relocate eastward and become partially exposed. Later that day, the system began turning northward as it approached the western edge of the subtropical ridge. By this time, the circulation had become broad and ill-defined, indicating that the storm weakened.



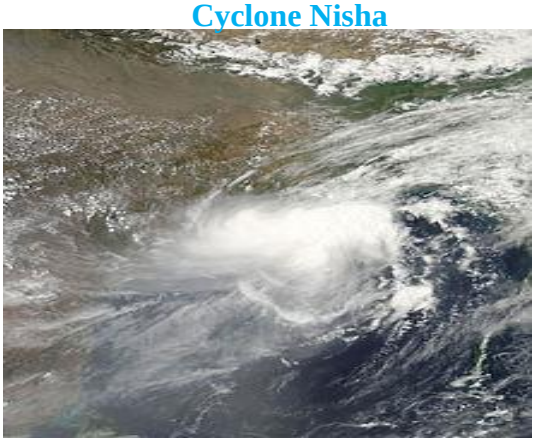
Cyclone Rashmi



Cyclone Nisha



Cyclone Bijli



Cyclone Viyaru

Figure 4.1: Cyclone Rashmi, Nisha, Bijli and Viyaru as a cyclonic storm.

On May 13, steering currents weakened around the cyclone due to a trough over India, causing Viyaru to slowly move northwestward. Wind shear also increased once again as the outflow degraded. By May 14, the exposed and elongated circulation of Viyaru turned northeastward as the ridge became more pronounced. The majority of convection remained sheared to the west, though upper-level conditions were anticipated to become somewhat favorable for restring thinning. As the system approached Bangladesh, large area convection and rebuilt over the center. Slight strengthening took place on May 15, with the IMD reporting winds reaching 85 km/h (50 mph). Viyaru also began to accelerate somewhat as a trough became established to the west. Early on May 16, the system attained its peak intensity with a barometric pressure estimated at 990 hPa. Around 0800 UTC (1330 IST), Viyaru made landfall in Bangladesh coast between Feni and Chittagong. Within hours of moving ashore, rapid weakening ensued as the circulation deteriorated and convection became shallow. In light of this, the JTWC issued their final advisory on the cyclone. The

IMD downgraded Viyaru to a deep depression shortly after as it moved over Mizoram, India. The system further degraded as it moved over mountainous terrain and was last noted as a well-marked area of low pressure over Nagaland on May 17.

4.2 Dynamic Parameters

4.2.1 Wind Speed 10 (m/s)

Time variation of WS with Normal-2008, Normal-2010, Normal-2011 and Normal-2012 for the forecast hours 96, 72, 48 and 24 hours are shown in Figure 4.2 (a-d). All cases have a gradually decreasing tendency with little bit oscillating pattern. Ranges of the WS values for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 (with the forecast hours 96, 72, 48 and 24 hours) are (7-17, 6-22, 7-21 and 7-15), (11-19, 11-17, 9-15 and 10-16), (15-24, 15-21, 14-18 and 13-15) and (13-23, 14-21, 16-23 and 16-22) m/s respectively. Model simulated values of WS for a specific time are difference with different initial conditions/forecast hours. It happens because model has bias with different initial conditions. Ranges of WS for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are 6-22, 9-19, 13-24 and 13-23 m/s respectively. The Ranges above mentioned WS is from 6 to 23 m/s. The value of wind from 8.89 to 13.33 m/s (32-48 km/hour) and from 17.5 to 24.44 m/s (63-88 km/hour) are required for the formation of depression and cyclone respectively, The Ranges above mentioned wind are marginally satisfied but could not sustained to formation of depression as well as cyclone.

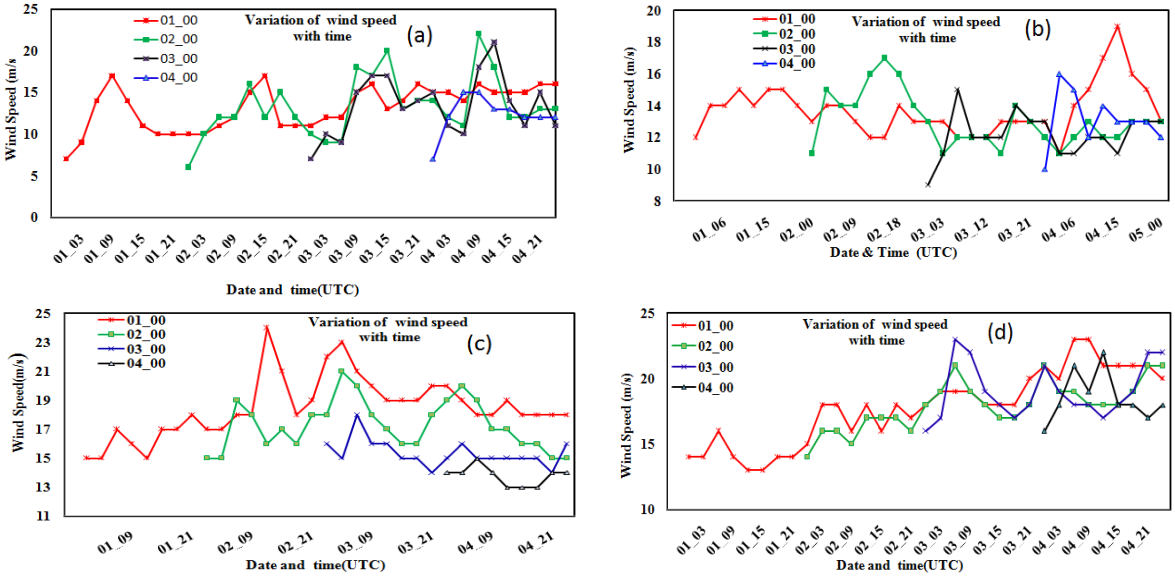


Figure 4.2 (a-d): Variation of model simulated WS of Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with time.

For first step, model simulated time variation WS for TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with forecast hours 96, 72, 48 and 24 hours along with observed value are shown in Figure 4.2 (e-h). All cases have an oscillating pattern. Ranges of value of WS for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 (with the forecast hours 96, 72, 48 and 24 hours) are (12-33, 11-19, 12-33 and 13-17), (10-35, 12-30,12-34 and 13-23), (9-47, 9-37, 9-14 and 11-14) and (12-27, 12-38, 14-32 and 17-26) m/s respectively. Finally Ranges of values of WS for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 11-33, 10-35,9-47 and 12-38 m/s respectively. Model simulated WS are more or less than that of observed. The value of wind from 8.89 to 13.33 m/s or (32-48) km/hour and from 17.5 to 24.44 m/s or (63-88) km/hour are required for the formation of depression and cyclone respectively. The Ranges above mentioned WS are satisfied for the formation of depression and also more than the required value in most of cases especially for the long time run. Model captured and intensified the system earlier than the observed time of formation of depression. It is noted that the value of WS for cyclone is more than that of normal cases.

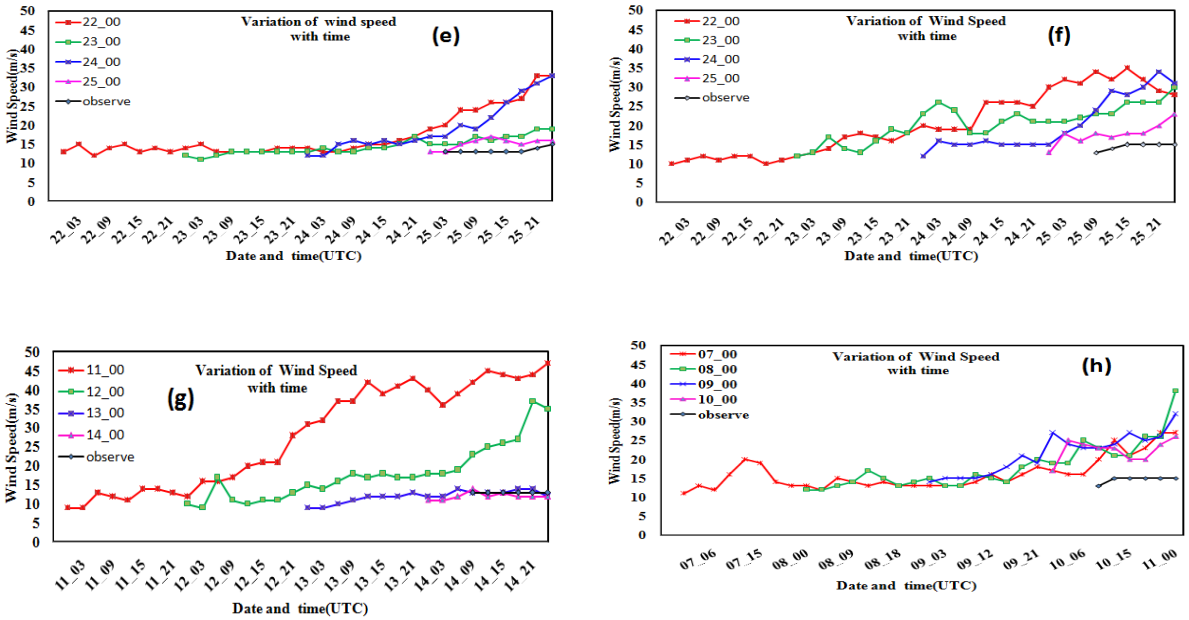


Figure 4.2(e-h): Variation of observed and model simulated WS of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

To test the formation/intensification as cyclonic storm, model is run for further 24 hours using initial conditions 00 UTC on 26 October 2008, 00 UTC on 26 November 2008, 00 UTC on 15 April 2009 and 00 UTC on 11 May 2013 for the TCs Rashmi-2008, Nisha-2008, Bijli-

2009 and Viyaru-2013 respectively and model simulated time variation WS of TCs along with observed value are shown in Figure 4.2 (i-l). All cases have a little bit oscillating pattern. Ranges of value of WS for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 13-21, 12-24, 10-11and 22-38 m/s respectively. Whereas the observed value of WS for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 15-23, 15-23, 13-20 and 15-20 m/s respectively. Simulated WS are more or less than that of observed. It is noted that the value of wind 17.5 to 24.44 m/s or (63-88) km/hour are required for the formation of cyclonic storm. The Ranges above mentioned values of WS are satisfied for the formation of cyclonic storm for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. But for the cyclone Viyaru intensity is more than the cyclonic storm due to its rapid intensification and it does not sustained for long duration.

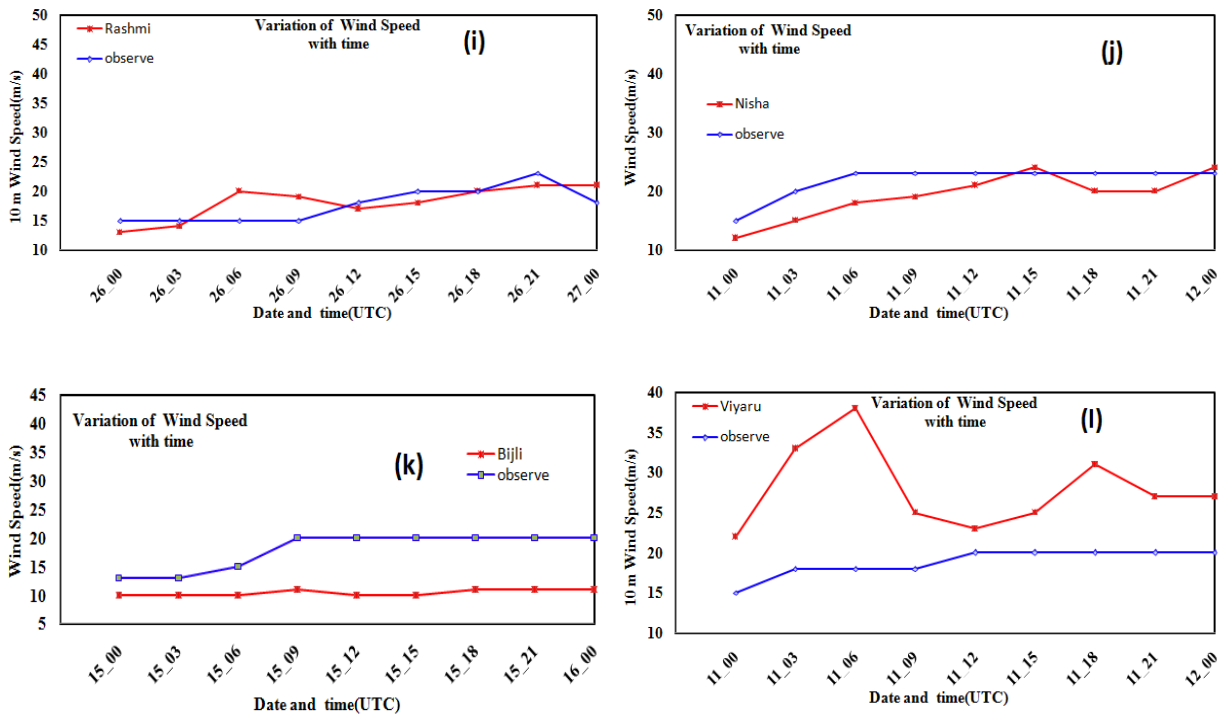


Figure 4.2(i-l): Variation of observed and model simulated WS of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

The spatial distribution of WS for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are shown in Figure 4.3 (a-d) at 00 UTC on 5 April 2008, 00 UTC on 5 April 2010, 00 UTC on 5 August 2011 and 00 UTC on 5 August 2012 respectively. For each case, WS are derived for the forecast hours 96, 72, 48 and 24 hours inside the area (6-18°N, 80-90°E).

Model simulated maximum WS values for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 (with the forecast hours 96, 72, 48 and 24 hours) are (10.5, 6-7, 6-7 and 5-6), (12.5, 10-11, 10-11 and 6-8), (14.5-16.5, 14.5-16.5, 14.5-16.5 and 13-14.5) and (18-19.5, 19.5-21, 16-18 and 16-18) m/s respectively. The value of wind from 8.89 to 13.33 m/s or (32-48) km/hour and from 17.5 to 24.44 m/s or (63-88) km/hour are required for the formation of depression and cyclone respectively, The Ranges above mentioned wind are more or less than the required value and marginally satisfied but could not sustained to formation of depression and cyclone. It may be due to other factors. So, no depression is formed in any forecast time.

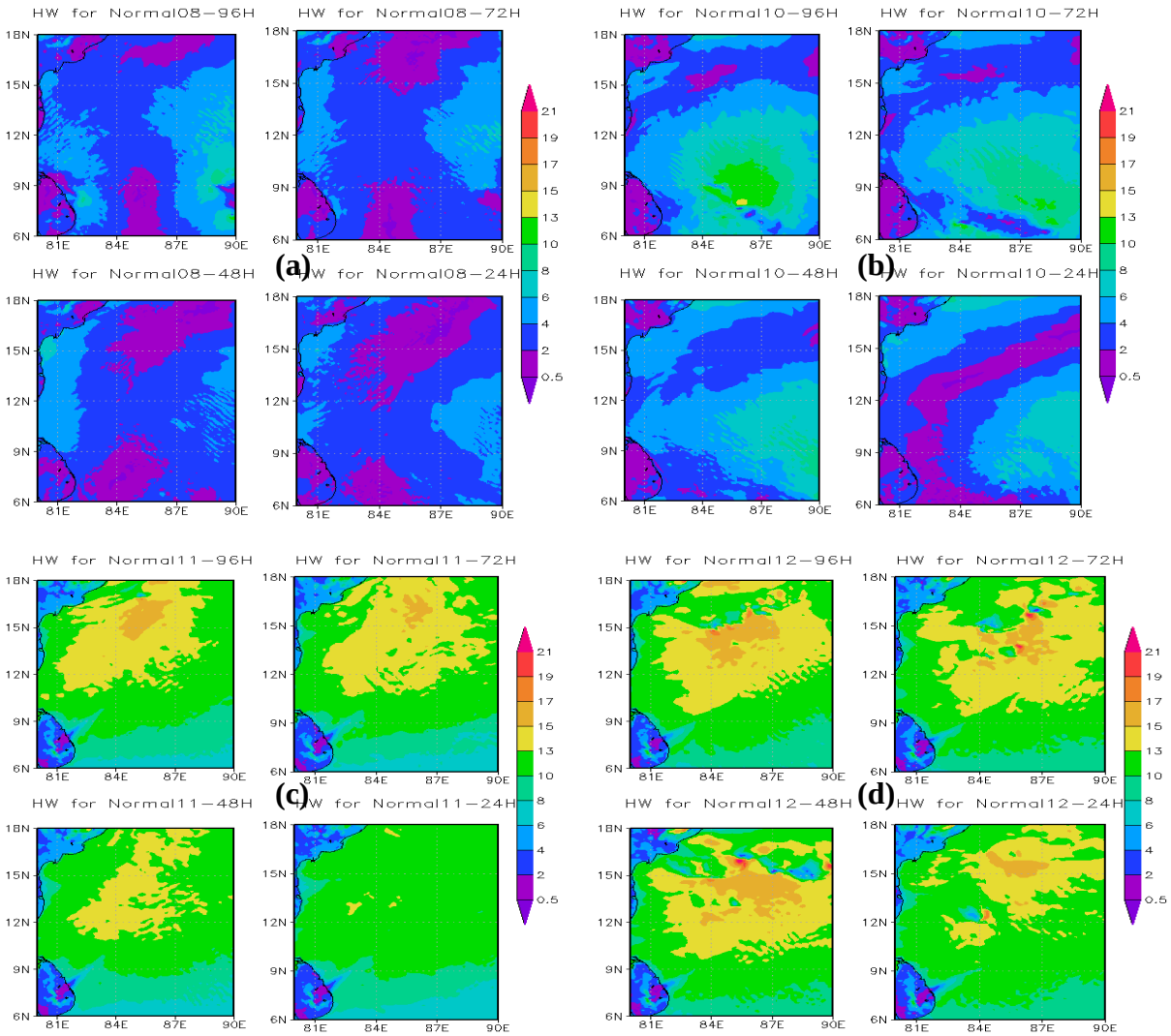


Figure 4.3 (a-d): The spatial distribution of WS with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

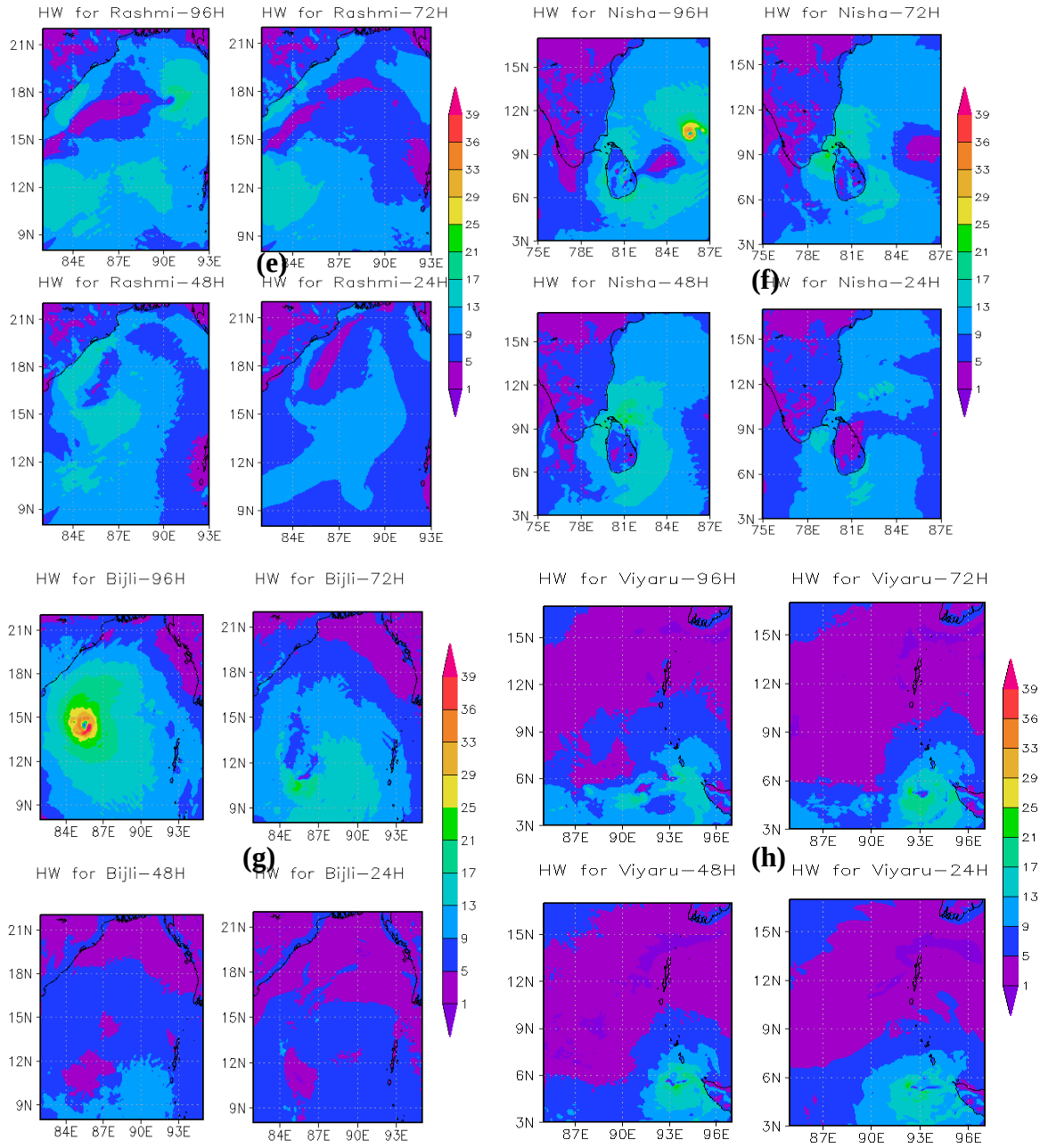


Figure 4.3 (e-h): The spatial distribution of WS with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

The spatial distribution of WS for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.3 (e-h) at 03 UTC on 25 October 2008, 09 UTC on 25 November 2008, 09 UTC on 14 April 2009 and 09 UTC on 10 May 2013 respectively. These are the observed time of formation of depression of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, WS

are derived for the forecast hours 96, 72, 48 and 24 hours with the area (8-22° N, 82-95° E), (3-17° N, 75-87° E), (8-22° N, 82-95 °E) and (3-17° N, 85-97 °E) respectively. Ranges of the Maximum WS values for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 (with the forecast hours 96, 72, 48 and 24 hours) are (19, 15-17, 15-17 and 11-13), (32, 22-25, 19-22 and 13-16), (39, 25-29, 9-13 and 5-9) and (20-22, 22, 20-22 and 20-22) m/s respectively. The Ranges of above mentioned wind is from 5 to 39 m/s. The value of wind from 8.89 to 13.33 m/s or (32-48) km/hour and from 17.5 to 24.44 m/s or (63-88) km/hour are required for the formation of depression and cyclonic storm respectively. The Ranges of above mentioned WS are satisfied for the formation of depression and some time intensity are more than the formation of depression due to rapid intensification of model. It is noted that model at least trace the system. The values of WS with cyclone are more than that of normal cases which causes depression.

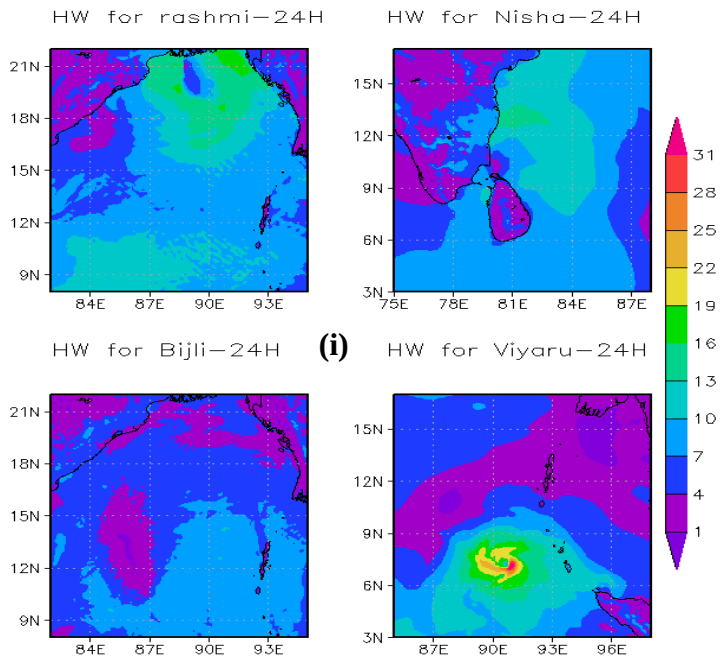


Figure 4.3 (i): The spatial distribution of WS with the forecast time for 4 cyclones.

To test the formation/intensification as cyclonic storm, the spatial distribution of WS for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.3 (i) at time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009 and 03 UTC on 11 May 2013 respectively. These are the observed time of formation as cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For

cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, WS are derived for the forecast hours 24 hours with the area (8-22° N, 82-95° E), (3-17° N, 75-87° E), (8-22° N, 82-95 °E) and (3-17° N, 85-97 °E) respectively. Ranges of the Maximum WS values for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 16-19, 13-16, 10-13 and 28-31 m/s respectively. The Ranges of above mentioned wind is from 10 to 31 m/s. The value of wind from 17.5 to 24.44 m/s (63-88km/hour) is required for the formation of cyclonic storm. The Ranges of above mentioned WS are satisfied for the formation of cyclonic storm.

Considering four normal and four cyclone cases, the average value of WS in cases of cyclone is more than that of normal cases. Again, circular shape is observed in all cases of cyclone. It is noted that difference of values WS between cyclone and normal is less due to weak intensity cyclone.

4.2.2 Vertical Wind Shear

The spatial distribution of VWS for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are shown in Figure 4.4 (a-d) at 00 UTC on 5 April 2008, 00 UTC on 5 April 2010, 00 UTC on 5 August 2011 and 00 UTC on 5 August 2012 respectively. Maximum VWS is (10 m/s),(5m/s),(15-20,15-20,5-10 and 5-10 m/s) and (25,18-25,18-25 and 18-25 m/s) and lies around a very small area for all forecast time. VWS 5, 0-5, (0-10,0-10,0-5 and 0-5) and 0-6 m/s lies around a comparable large area between (3.0-12.0°N and 87-99 °E), (3.0-15.0 °N and 81-99 °E), (9.0-18.0° N and 92-99 °E) and (12.0-27.0°N and 75-99 °E) while negative VWS are exist in most of area. Shape of VWS does not have any circulation pattern and do not indicate any information about formation of cyclone.

The spatial distribution of VWS for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.4 (e-h) at 03 UTC on 25 October 2008, 09 UTC on 25 November 2008, 09 UTC on 14 April 2009 and 09 UTC on 10May 2013 respectively. Maximum VWS is (10-15, 10-15, 15 and 5-10), (35, 20-30, 20-30 and 10-20), (40, 20-30, 10-20 and 0-10) and (20,15-20,15-20 and 15-20) m/s and lies around a very small area for all forecast time. VWS (0-10, 0-10, 0-15 and 0-5), (0-20,0-20,0-20 and 0-10), (0-15,0-15,0-5 and 0-5) and (0-15,0-15,0-5 and 0-5) m/s lies around a comparable large area between (8-22° N, 82-95° E), (3-17° N, 75-87° E), (8-22° N, 82-95 °E) and (3-17° N, 85-97 °E) while negative VWS are exist in most of area. The circulation pattern in case of 96, 72 and 48 hour is very

clear than those for 24 hour forecast. So, the Value VWS and its shape indicate for the formation of cyclone.

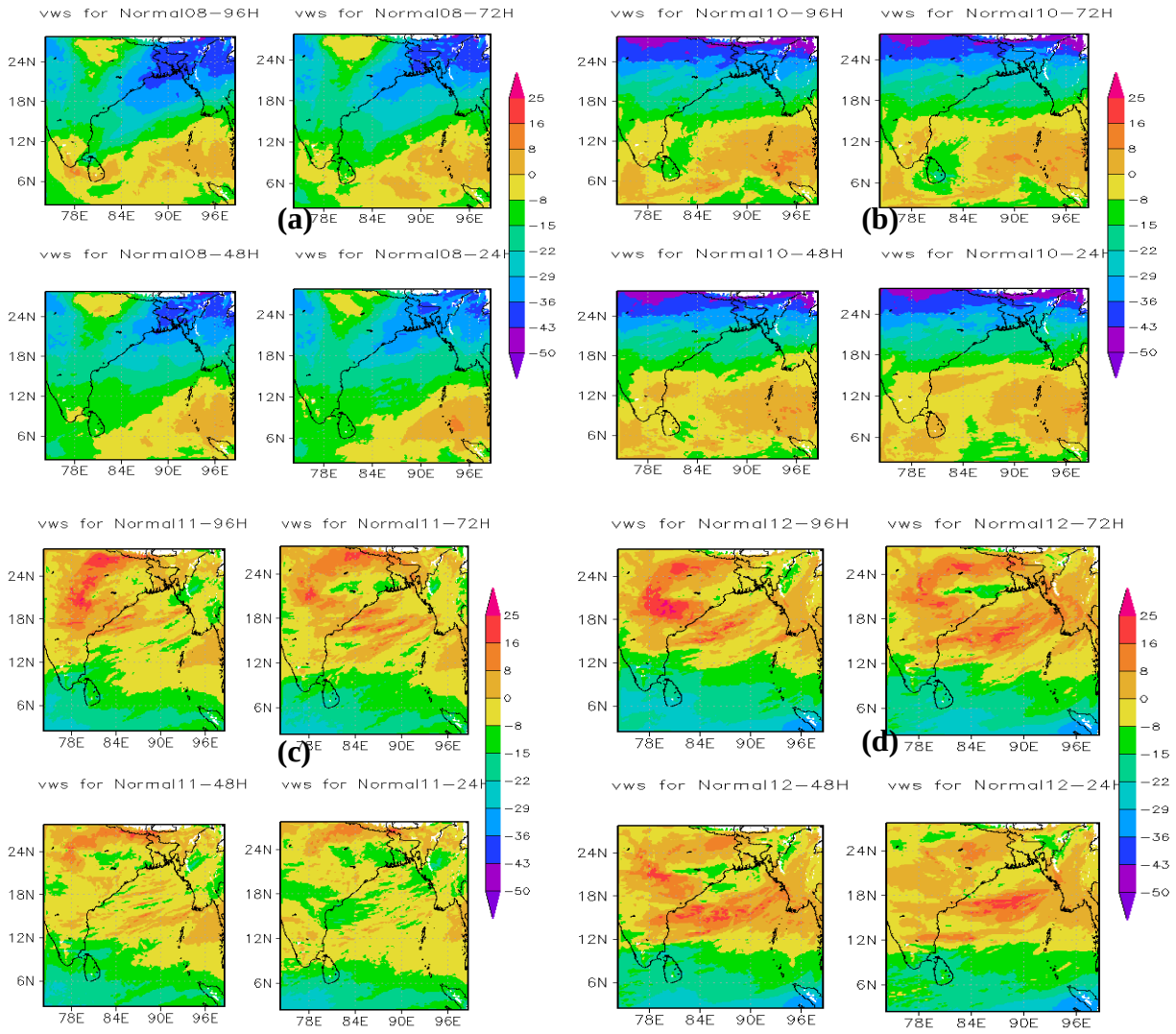


Figure 4.4 (a-d): The spatial distribution of VWS for the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

From the above discussion using four normal cases, model simulated positive VWS exist with negative value in the area with larger latitude and in almost cases vertical wind shear is found at earth surface for normal cases. So, depression does not form. The value of VWS for cyclone is relatively greater than that of normal cases that causes depression.

To test the formation/intensification as cyclonic storm, the spatial distribution of VWS for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.4 (i) at time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009

and 03 UTC on 11 May 2013 respectively. These are the observed time of formation as cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, Vertical wind shear (VWS) are derived for the forecast hours 24 hours with the area (8-22°N, 82-95°E), (3-17°N, 75-87°E), (8-22°N, 82-95°E) and (3-17°N, 85-97°E) respectively. Ranges of the Maximum VWS values for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 12-16, 12-16, 8-12 and 20-25 m/s respectively. The Ranges of above mentioned VWS is from 8 to 25 m/s. The Ranges of above mentioned VWS are satisfied for the formation of cyclonic storm.

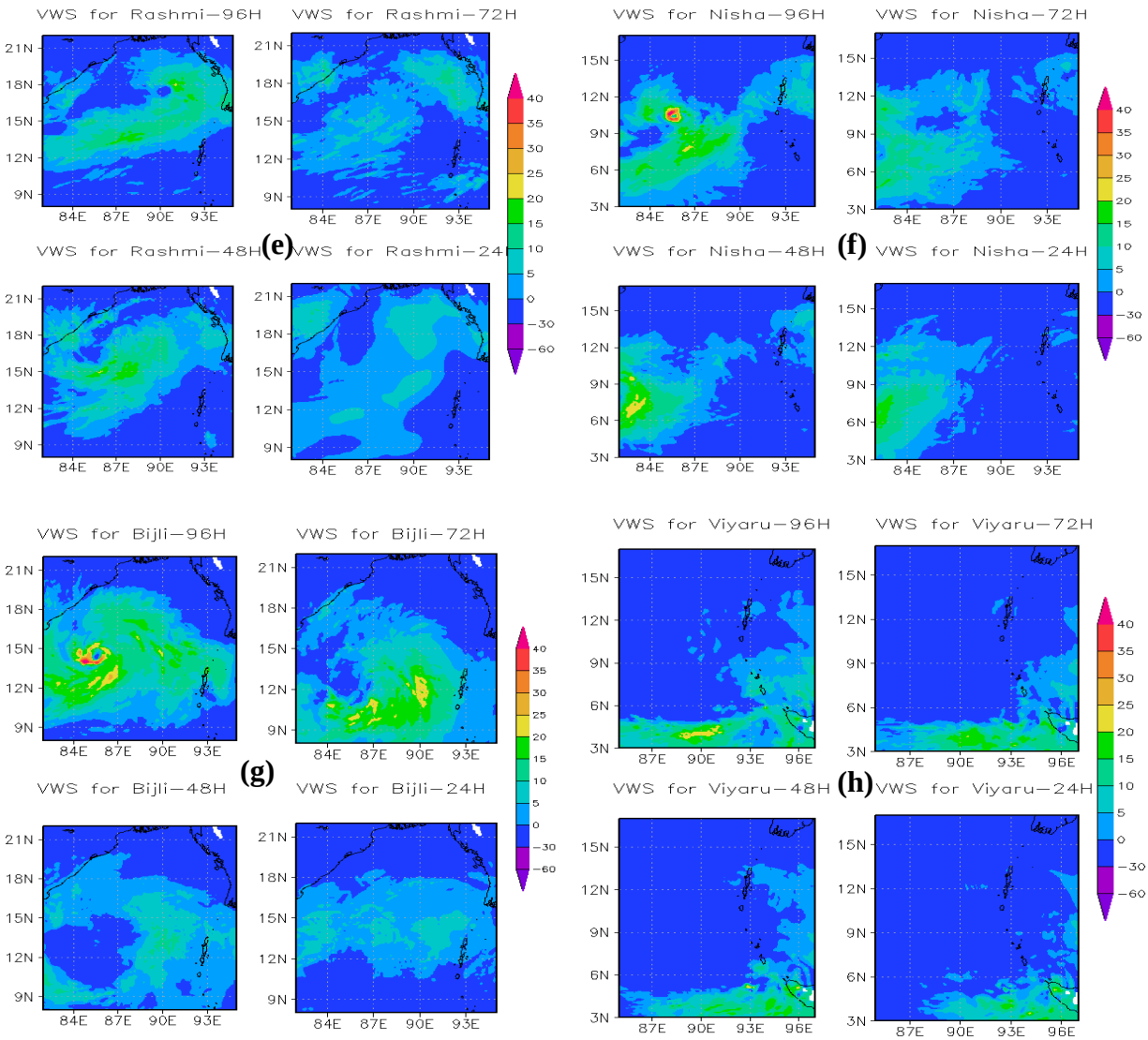


Figure 4.4 (e-h): The spatial distribution of VWS with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

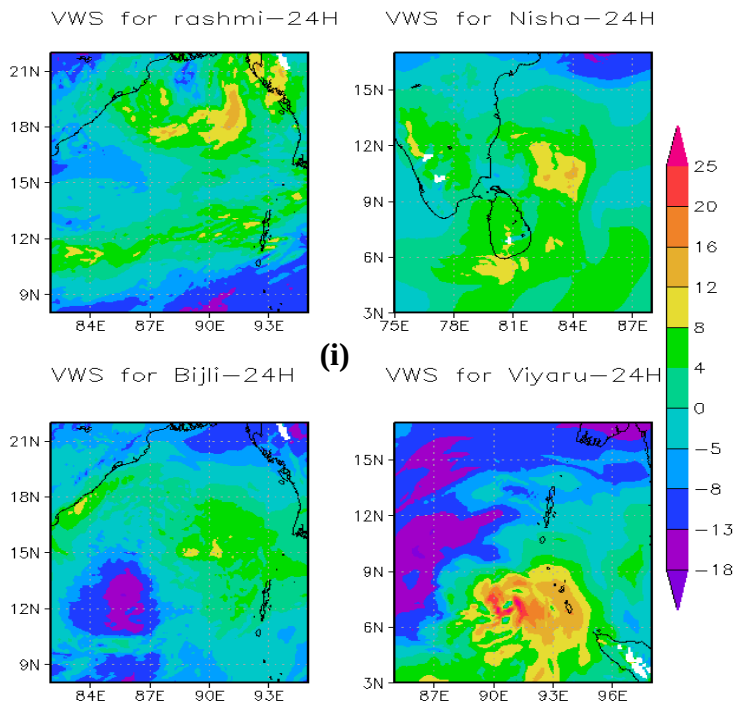


Figure 4.4 (i): The spatial distribution of VWS with the forecast time for 4 cyclones.

4.2.3 Vertical Profile of Horizontal Wind

The Vertical distribution of Horizontal wind (VHW) at 00 UTC on 5 April 2008, 00 UTC on 5 April 2010, 00 UTC on 5 August 2011and 00 UTC on 5 August 2012 cases with 96, 72, 48 and 24 hours are plotted in Figure 4.5 (a-d) through the center (12°N, 90 °E). Model simulated maximum VHW exist around (200 hPa), (200, 200, 250 and 550 hPa), (100 hPa) and (200 ,100, 100 and 100 hPa) level and the values are (22, 20-22, 18-20 and 18-20 m/s), (19, 16.5-18, 9-11 and 9-11), (44, 40-44, 36-40 and 31.5-36) and (32, 29-32, 32 and 29-32) (for 96, 72, 48 and 24) m/s hours forecast time respectively. 10, (8, 10, 9 and 7), (15, 15, 15 and 12) and 15 m/s or more VHW exit in the both side of the center between the level (350 to 100), (250 to 150, 225-175, 400-200 and 600-300), (200-100 to 200-100, 200-100 and 150-100) and (250-100 to 250-100, 250-100 and 200-100) hPa for all forecast time. The minimum value of wind exit in the lower level for all forecast time and values are (less than 5), (5, 8, 7 and 5), (15, 15, 15 and 12) and (less than 12) m/s. It indicates normal weather in lower level. So, no depression is formed in any forecast time.

The Vertical distribution of VHW at 03 UTC on 25 October 2008, 09 UTC on 25 November 2008, 09 UTC on 14 April 2009 and 09 UTC on 10May 2013 of cyclone Rashmi-2008,

Nisha-2008, Bijli-2009 and Viyaru-2013 for 96, 72. 48 and 24 hours are plotted in Figure 4.5 (e-h) through the center {(17.5 °N, 90.5 °E) (14.22 °N, 85 °E), (16.5 °N, 83.8 °E) and (18.0 °N, 82.8 °E)},{(10.5 °N, 85.3 °E) (8.5 °N, 79.8 °E), (9.0 °N, 80.8 °E) and (7.5 °N, 83.0 °E)}, {(14.5 °N, 85.9 °E) (11.0 °N, 87 °E), (10.5 °N, 82.0 °E) and (12.0°N, 82.5 °E)} and {(6.0 °N, 94.0 °E) (5.5 °N, 92.5 °E), (5.5 °N, 93.0 °E) and (5.5 °N, 92.2 °E)} respectively. This is the observed time of formation of depression of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 and Maximum VHW (26, 18-20, 20-22 and 13-16), (45, 29-33, 33-37 and 19-24), (45, 24-29, 29-33 and 19-24) and (39, 27-30, 27-30 and 33-36) m/s lies around a very small area in the level (900, 900,900 and 900),(900, 900, 900 and 900), (900, 490, 770 and 750),(900, 700, 400 and 600) hPa for 96, 72. 48 and 24 hours forecast time respectively. VHW (9, 8, 10 and 7), (14, 15, 12 and 12), (20, 18, 10and 10) and (15-21, 27-30, 10-20and 27-30) m/s lies around a comparable large area from surface up to (500 hPa level 82.8-90.5), (500 hPa level 84-88), (500 hPa level 82- 87) and (200 hPa level 80-90) with a large Ranges of longitude. All of these values in the different levels indicate about the formation of depression.

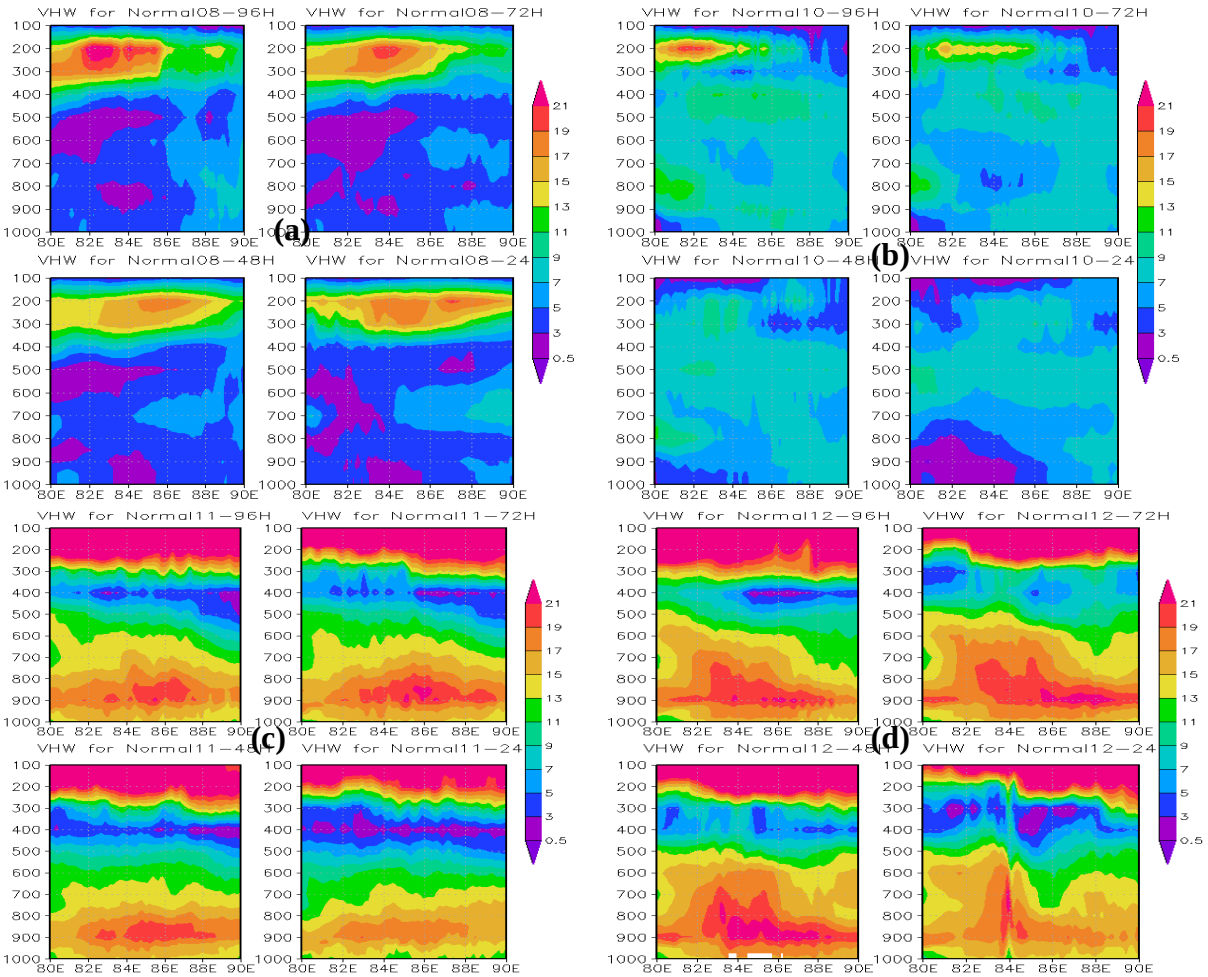


Figure 4.5 (a-d): VHW with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

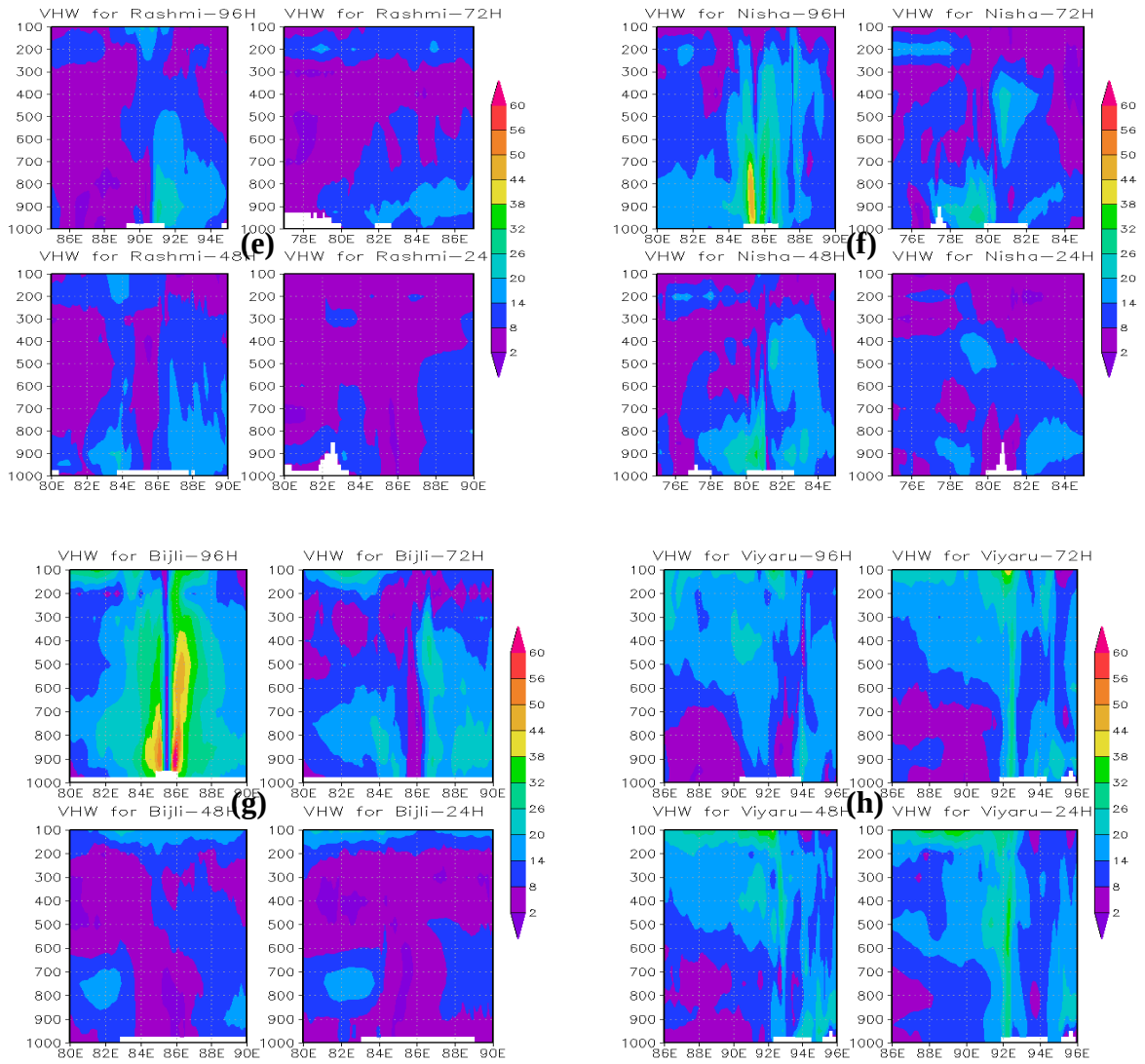


Figure 4.5 (e-h): VHW with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

The values of VHW with cyclone are higher where as for normal it is very poor. The maximum of VHW for normal and cyclone lies in the levels between 300 to 100 hPa and 1000-400 hPa respectively. The value and position of VHW for cyclone are favorable for the formation of depression.

To test the formation/intensification as cyclonic storm, the spatial distribution of VHW for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.5 (i) at time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009 and 03 UTC on 11 May 2013 respectively. These are the observed time of formation as cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For

cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, VHW are derived for the forecast hours 24 hours with the area (20.5° N, 85-95° E), (10.5° N, 75-85° E), (13.5° N, 80-90 °E) and (7.5° N, 85-95 °E) respectively. Ranges of the Maximum HW values for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 21-24, 13-18, 13-18 and 33-36 m/s respectively and lies around a very small area in the level 900, 900, 100 and 1000-300 hPa with 24 hours forecast time respectively. Existence of values of VHW in the different levels indicates the formation of depression. The Ranges of above mentioned VHW is from 13 to 36 m/s. The Ranges of above mentioned VHW are satisfied for the formation of cyclonic storm.

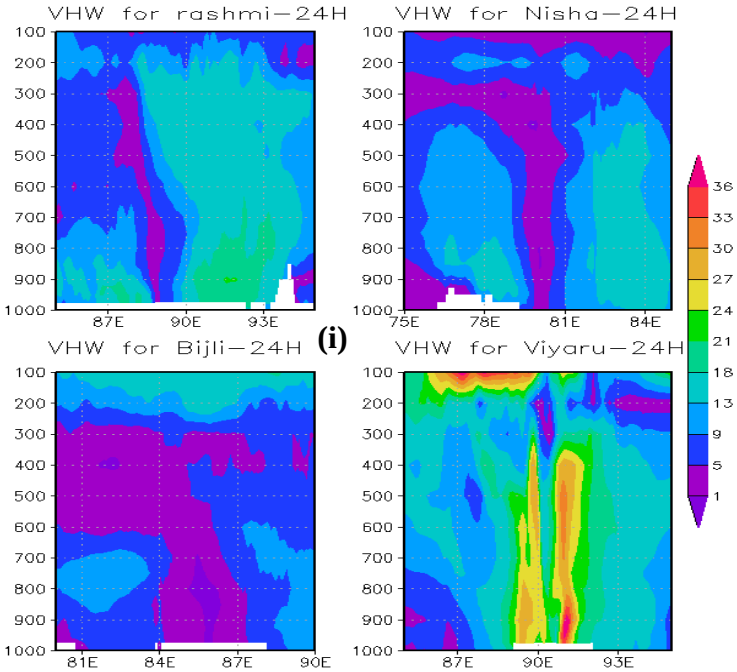


Figure 4.5 (i): VHW with the forecast time for 4 cyclones.

4.2.4 Vertical Profile of Vertical Wind

The vertical distribution of VVW at 00 UTC on 5 April 2008, 00 UTC on 5 April 2010, 00 UTC on 5 August 2011and 00 UTC on 5 August 2012 normal case for 96, 72, 48 and 24 hours are plotted in Figure 4.6 (a-d) through the center (12°N, 85 °E). Model simulated maximum VVW exists around (850, 875, 730 and 950), (800, 850, 250 and 750), (600, 450, 700 and 330) and (500, 640, 350 and 900) hPa level and the values are (0.1, 0.1, 0.04 and 0.12), (0.1, 0.05, 0.20 and 0.03), (0.25, 0.3, 0.2 and 0.4) and (0.2, 0.1, 0.3 and 1.2) m/s for 96, 72, 48 and 24 hours forecast time respectively. 0, (-0.05, -0.05, 0and -0.06), (-0.1, -0.05, -0.1and -0.1) and (-0.05, -0.05, -0.1and 0) m/s or less VVW exit in the both side of the levels

mentioned above for all forecast time. It is noted that negative value indicates downward motion. The minimum value of VVW (less than .04), (less than 0), (less than -0.05) and (less than 0) exit in the lower level for all forecast time. It indicates normal weather in lower level. So, no depression is formed in any forecast time.

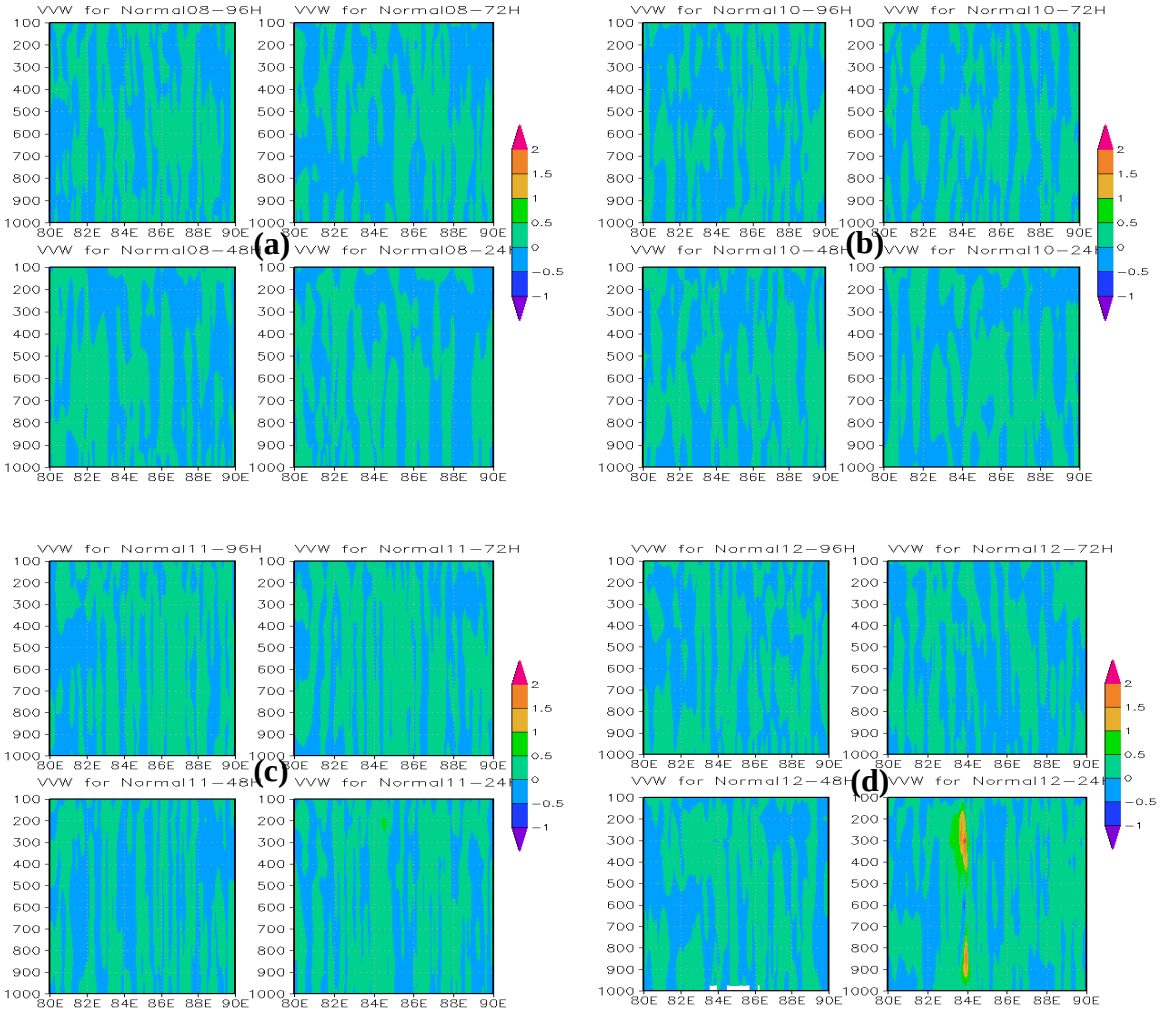


Figure 4.6 (a-d): VVW with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

VVW at 03 UTC on 25 October 2008, 09 UTC on 25 November 2008, 09 UTC on 14 April 2009 and 09 UTC on 10 May 2013 of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 for 96, 72. 48 and 24 hours are plotted in Figure 4.6 (e-h) through the center {(17.5 °N, 90.5 °E) (14.22 °N, 85 °E), (16.5 °N, 83.8 °E) and (18.0 °N, 82.8 °E)},{(10.5 °N, 85.3 °E) (8.5 °N, 79.8 °E), (9.0 °N, 80.8 °E) and (7.5 °N, 83.0 °E)}, {(14.5 °N, 85.9 °E) (11.0 °N, 87 °E), (10.5 °N, 82.0 °E) and (12.0°N, 82.5 °E)} and {(6.0 °N, 94.0 °E) (5.5 °N,

92.5 °E), (5.5 °N, 93.0 °E) and (5.5 °N, 92.2 °E)} respectively. The above mentioned times are the observed time of formation of depression of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively. Maximum VVW is(0.7, 0.6, 0.6 and 0.5), (4.5, 1.5, 6 and 0.3), (3, 2.5, 0.6 and 0.6) and (9, 2.5, 4 and 11) m/s lies around a very small area in the level (300, 370, 520 and 930), (750, 600, 500 and 350), (600, 800, 320 and 350) and (450, 850, 600 and 650) hPa for the cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 96, 72. 48 and 24 hours forecast time respectively. VVW (-0.3, -0.2.-0.4and 0), (-0.5, -0.2,-0.1and -0.1), (-0.5, 0,0and -0.1) and (1-9, 0.5-2.0.5-4and 3-10) m/s lies around a comparable area from surface up to 300, 350, 320 and 400 hPa level for above. All of these values in the different levels indicate about the formation of depression.

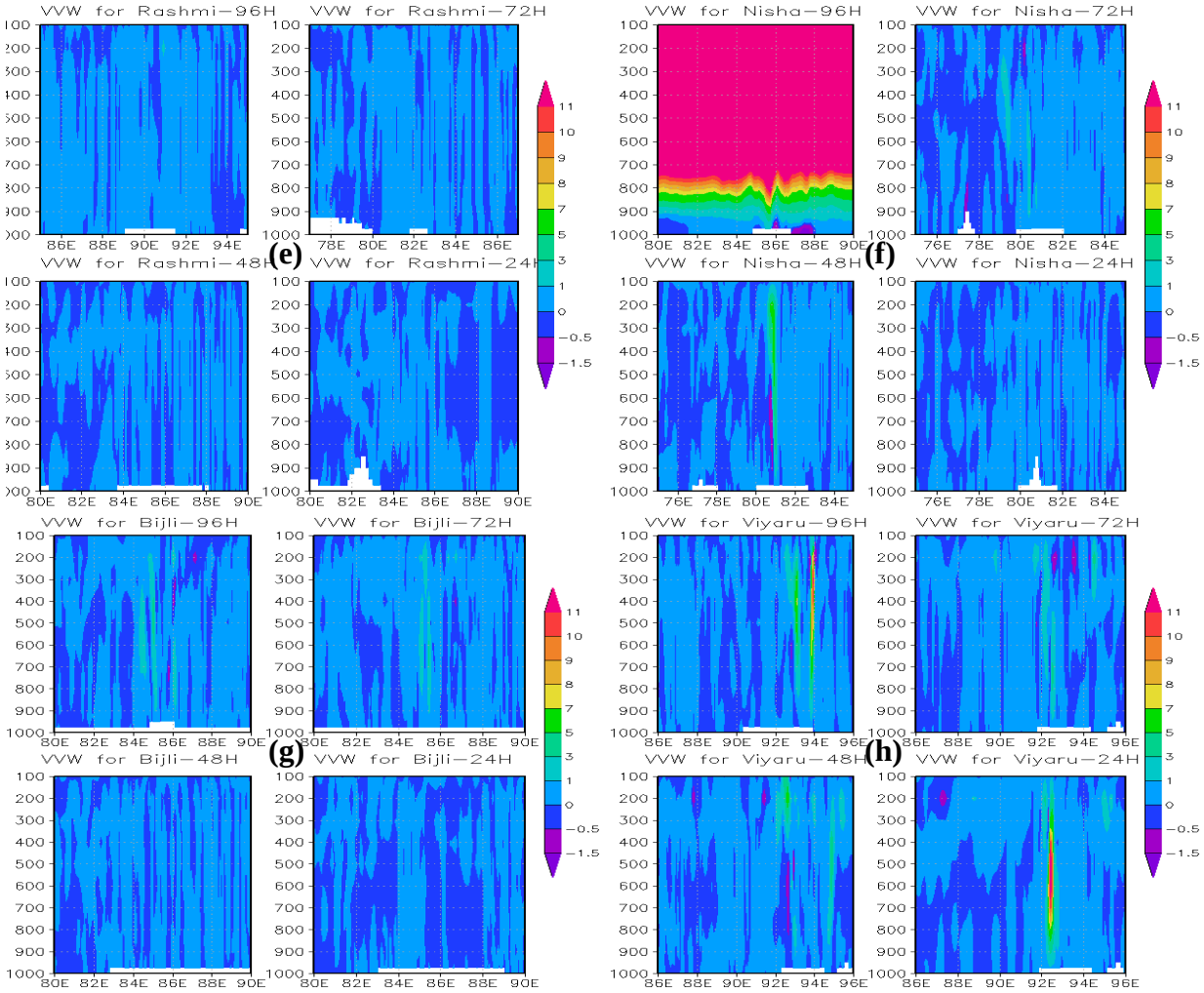


Figure 4.6 (e-h): VVW with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

Considering the above discussion with 4 normal's and 4 cyclones cases, almost VVW value is negative for normal causes. On the hand, the value of VVW for cyclone is positive / negative. The value of VVW for cyclone is relatively greater than that of normal causes. Model could simulate the formation of the depression for all cyclone cases for their higher value.

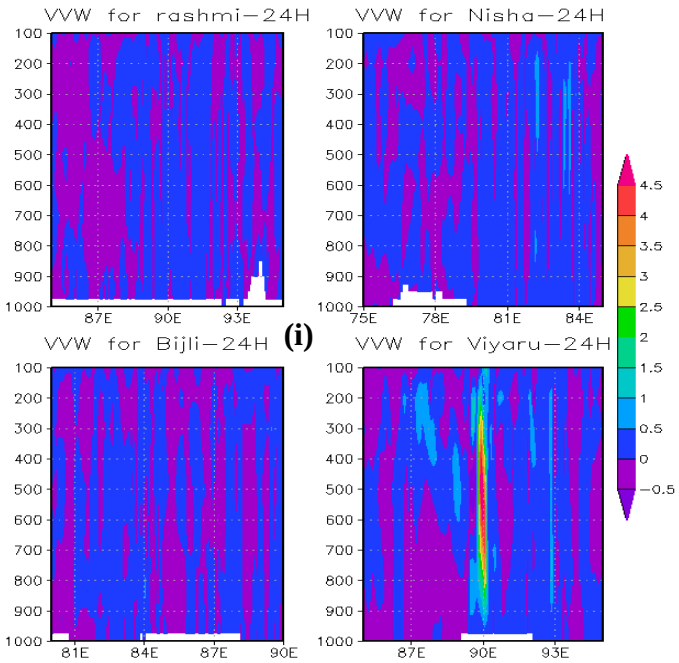


Figure 4.6 (i): VVW with the forecast time for 4 cyclones.

To test the formation/intensification as cyclonic storm, the spatial distribution of VVW for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.6 (i) at time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009 and 03 UTC on 11 May 2013 respectively. These are the observed time of formation as cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, VVW are derived for the forecast hours 24 hours with the area (20.5° N, 85-95° E), (10.5° N, 75-85° E), (13.5° N, 80-90 °E) and (7.5° N, 85-95 °E) respectively. Ranges of the Maximum VVW values for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 0-0.5, 0.5-1, 0-0.5 and 4-4.5 m/s respectively and lies around a very small area in the level 930 hPa, 350hPa, 800hPa and 500 hPa. The Ranges of above mentioned VVW are satisfied for the formation of cyclonic storm.

4.2.5 Relative Vorticity at 850 hPa:

Time variation of relative Vorticity (RV) at 850 hPa in case of Normal-2008, Normal-2010, Normal-2011 and Normal-2012 for the forecast hours 96, 72, 48 and 24 hours shown in Figure 4.7 (a-d) have a oscillating pattern and Ranges of the RV values are (10-240×10^{-5}, 8-190×10^{-5}, 10-140×10^{-5} and 8-130×10^{-5}), (17-180×10^{-5}, 17-130×10^{-5}, 13-120×$10^{-5}$and 19-90×10^{-5}), (12-80×10^{-5} ,16-110×10^{-5}, 17-70×10^{-5} and 14-70×10^{-5}) and (15-80×10^{-5},15-90×10^{-5}, 14-120×$10^{-5}$and 15-80×10^{-5}) s^{-1} respectively. Finally, Ranges of the values of RV for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are 8-240×10^{-5} ,13-180×10^{-5},12-110×10^{-5} and 14-120×10^{-5} s^{-1} respectively. The Ranges of RV are larger but do not indicate the formation depression because of other reasons.

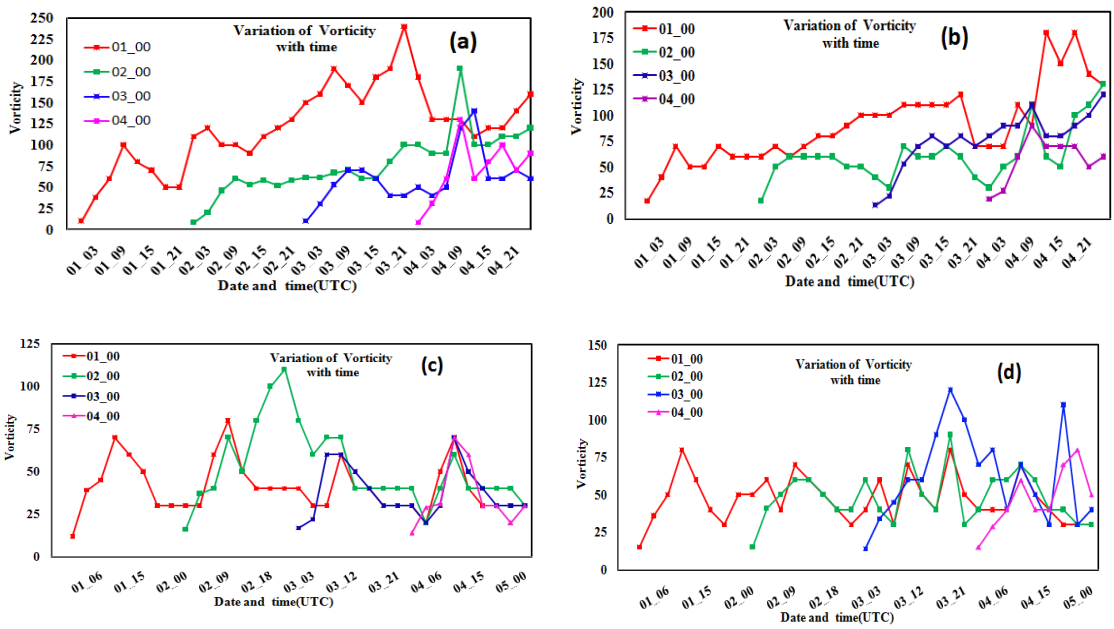


Figure 4.7 (a-d): Variation of model simulated vorticity of Normal (2008), Normal (2010), Normal (2011), and Normal (2012) with time.

Time variation of RV in case of the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with the forecast hours 96, 72, 48 and 24 hours are shown in Figure 4.7 (e-h) have a oscillating pattern and Ranges of the lowest values of RV are (34-210×10^{-5}, 14-180×10^{-5}, 13-150×$10^{-5}$and 14-170×10^{-5}), (11-260×10^{-5}, 17-200×10^{-5},24-150×$10^{-5}$and 18-260×10^{-5}), (12-150×10^{-5}, 10-70×10^{-5}, 9-70×$10^{-5}$and 11-61×10^{-5}) and (10-160×10^{-5}, 10-170×10^{-5}, 19-180×$10^{-5}$and 25-180×10^{-5}) s^{-1} respectively. Finally Ranges of the values of RV for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 13-210×10^{-5}, 11-260×10^{-5},9-150×10^{-5} and 10-180×10^{-5} s^{-1} respectively. The Ranges of RV are higher which indicate the formation and intensification of depression.

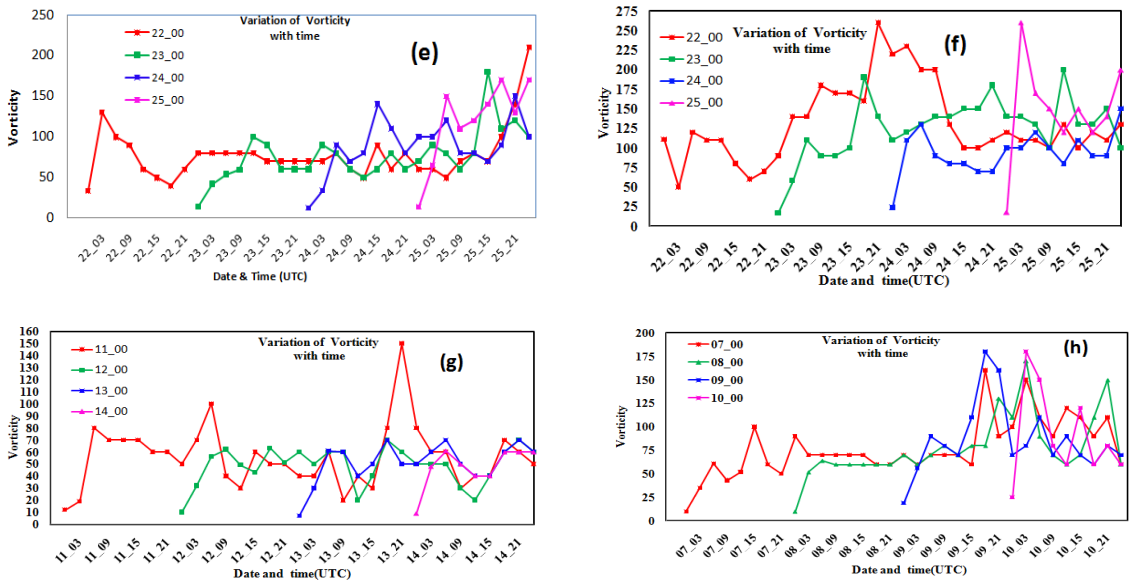


Figure 4.7(e-h): Variation of observed and model simulated vorticity of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

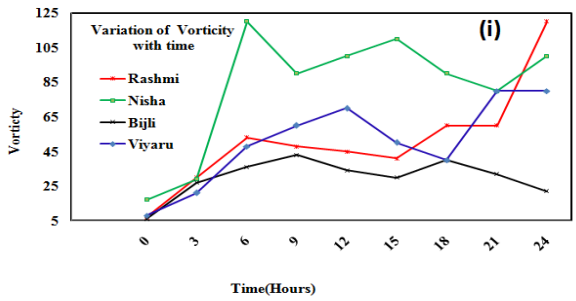


Figure 4.7(i): Variation of observed and model simulated vorticity of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

To test the formation/intensification as cyclonic storm, model is run for further 24 hours using initial conditions 00 UTC on 26 October 2008, 00 UTC on 26 November 2008, 00 UTC on 15 April 2009 and 00 UTC on 11 May 2013 for the TCs Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively and model simulated time variation RV of TCs along with observed value are shown in Figure 4.7 (i). All cases have an oscillating pattern. Ranges of value of RV for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 7-120×10^{-5}, 17-120×10^{-5}, 6-43×10^{-5} and 8-80×10^{-5} s^{-1} respectively. The Ranges above mentioned WS for 4 TCs is between 6 to 120×$10^{-5}s^{-1}$. The Ranges above mentioned RV are satisfied for the formation of cyclonic storm for all cyclones.

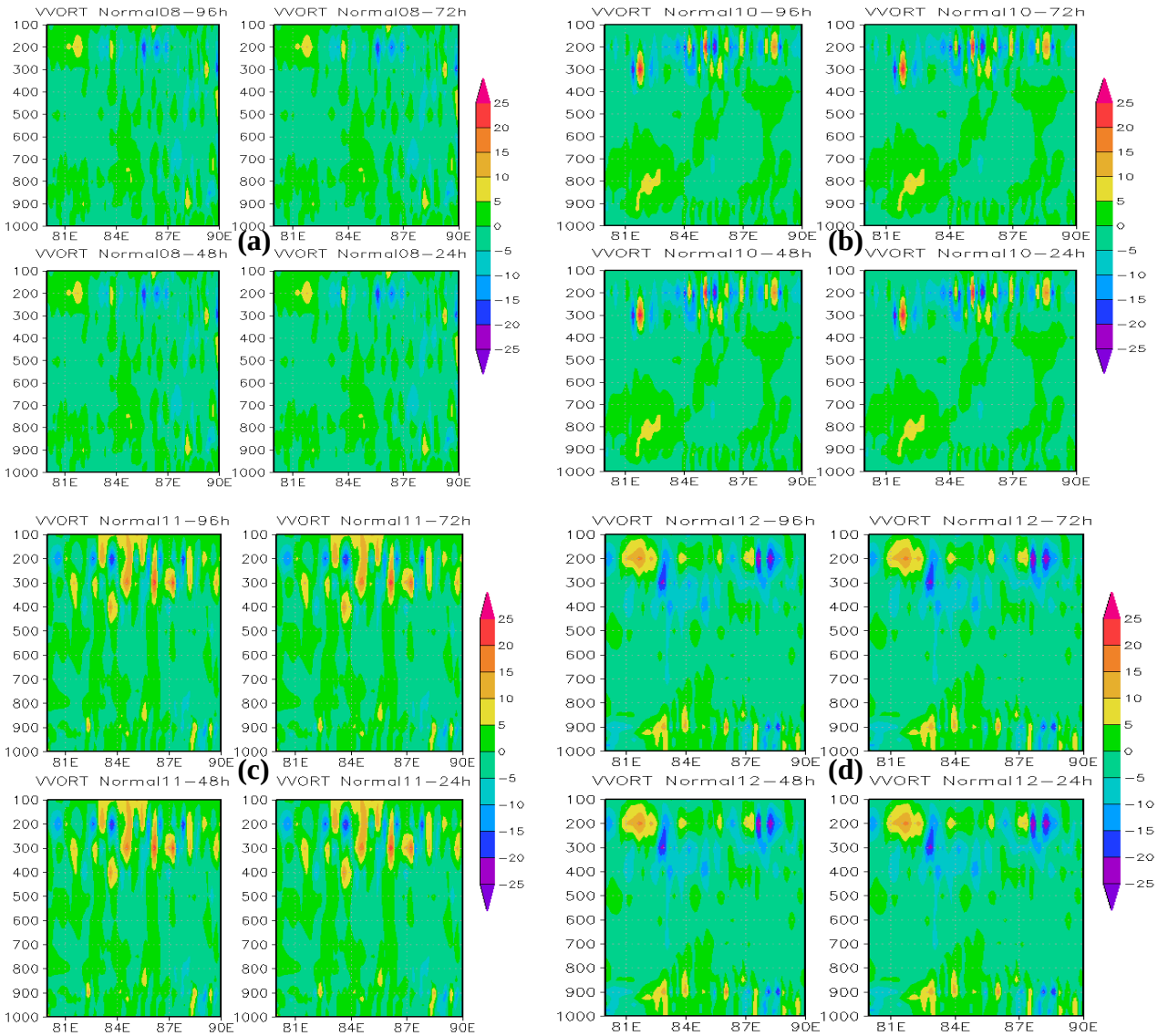


Figure 4.8 (a-d): Vertical profile of relative vorticity with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

The Vertical distribution of RV at 00 UTC on 5 April 2008, 00 UTC on 5 April 2010, 00 UTC on 5 August 2011and 00 UTC on 5 August 2012 normal cases for 96, 72, 48 and 24 hours are plotted in shown in Figure 4.8 (a-d) through the center (lat 12 N°, lon 85 E°). Maximum RV are (7.5-10 $\times 10^{-5}$), (5-10 $\times 10^{-5}$), (15.5-18.5 $\times 10^{-5}$) and (10-13.5 $\times 10^{-5}$) s^{-1} lies at 900 hPa for all forecast hours. This lower value of RV at the lower level is not considered as the favorable situation for the formation of depression.

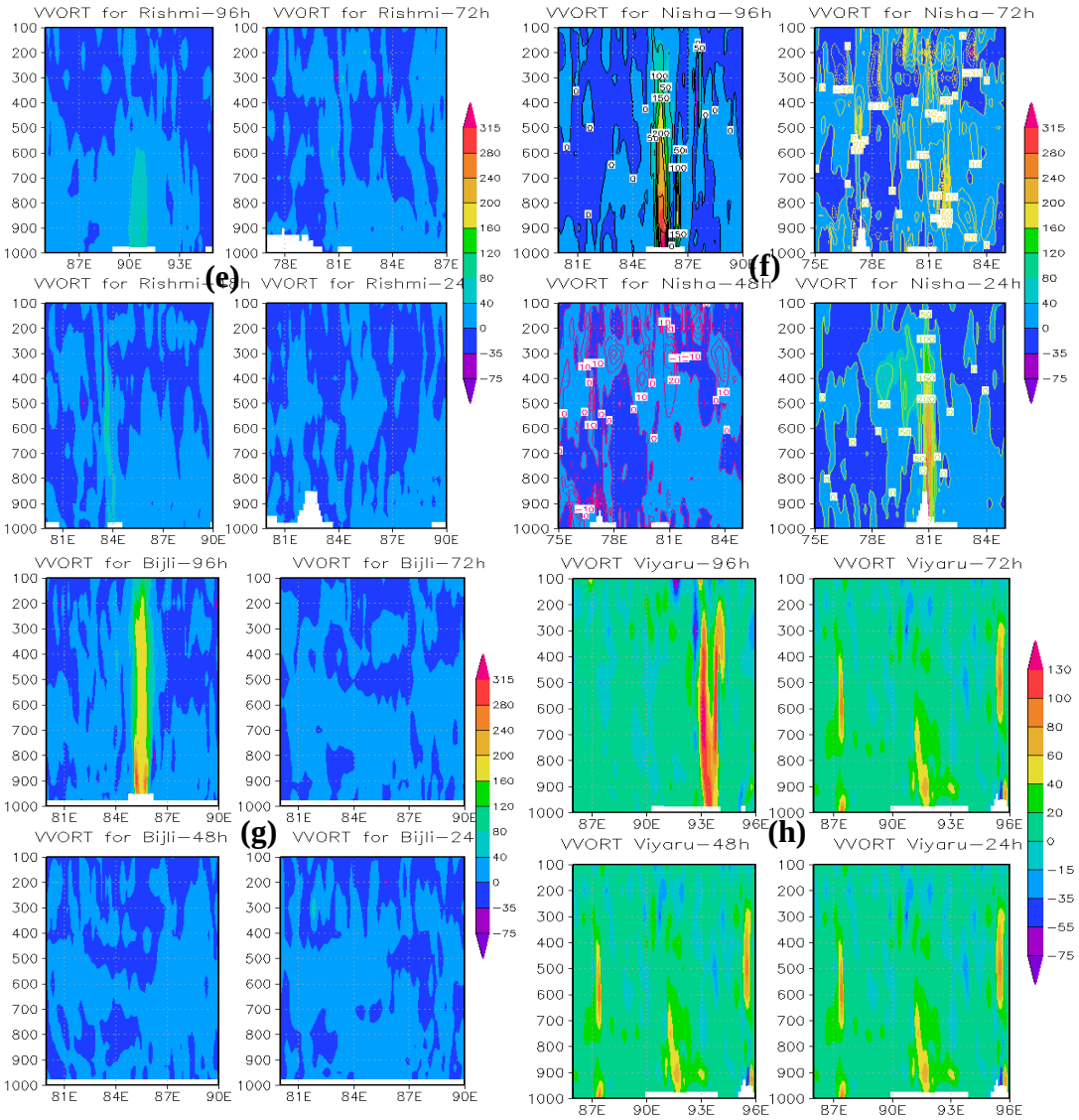


Figure 4.8 (e-h): Vertical profile of relative vorticity with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

The Vertical distribution of RV at 03 UTC on 25 October 2008, 09 UTC on 25 November 2008, 09 UTC on 14 April 2009 and 09 UTC on 10 May 2013 of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 for 96, 72. 48 and 24 hours are plotted in Figure 4.8 (e-h) through the center {(17.5 °N, 90.5 °E) (14.22 °N, 85 °E), (16.5 °N, 83.8 °E) and (18.0 °N, 82.8 °E)},{(10.5 °N, 85.3 °E) (8.5 °N, 79.8 °E), (9.0 °N, 80.8 °E) and (7.5 °N, 83.0 °E)}, {(14.5 °N, 85.9 °E) (11.0 °N, 87 °E), (10.5 °N, 82.0 °E) and (12.0°N, 82.5 °E)} and {(6.0 °N, 94.0 °E) (5.5 °N, 92.5 °E), (5.5 °N, 93.0 °E) and (5.5 °N, 92.2 °E)} respectively. This is the observed time of formation of depression of cyclone Rashmi-2008, Nisha-2008, Bijli-

2009 and Viyaru-2013. Maximum RV are (85×10^{-5}, 40×10^{-5}, $95\times10^{-5}$and 40×10^{-5}), (310×10^{-5}, 65×10^{-5}, $30\times10^{-5}$and 315×10^{-5}), (275×10^{-5}, 30×10^{-5}, $20\times10^{-5}$and 20×10^{-5}) and (130×10^{-5}, 85×10^{-5}, $85\times10^{-5}$and 85×10^{-5}) s^{-1} lies at 900-400 hPa for all forecast hours.

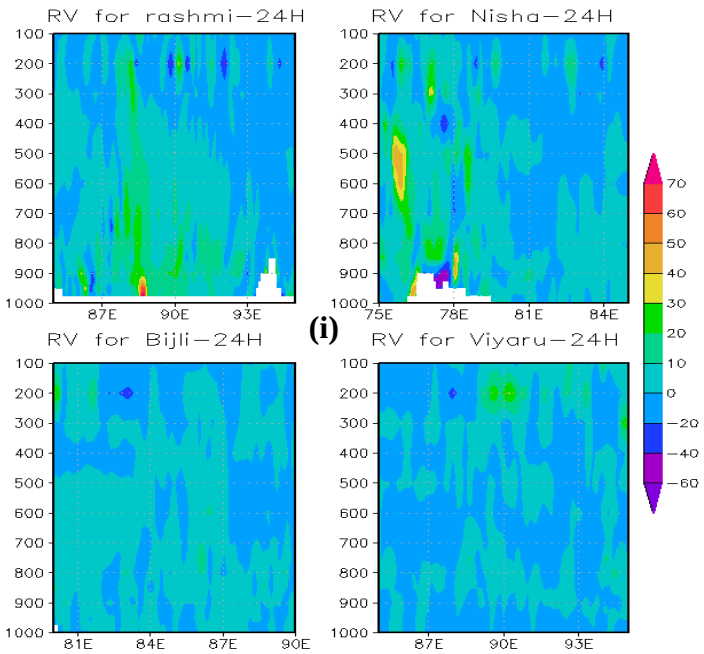


Figure 4.8 (i): Vertical distribution of relative vorticity with the forecast time for 4 cyclones.

Finally, considering 4 cyclones and 4 normal cases, the value of RV for normal and cyclone causes are between -22.5 to 25 $\times10^{-5}$and -75 to 315×10^{-5} s^{-1} respectively. For normal causes the value is found at upper level and for cyclone the value is found at lower level. The highest value of relative vorticity is observed between 300 to 100 hPa and 1000 to 400 hPa for normal and cyclone cases respectively. Again, the value of relative vorticity is higher for cyclone than that of normal causes. Higher value of RV at the lower level is considered as the favorable situation for the formation of depression.

Finally, the value of relative vorticity is higher for cyclone than that of normal causes. The value of RV for normal causes is -22.5 to 25 $\times10^{-5}$ and -75 to $315\times10^{-5}s^{-1}$ for cyclone. For normal causes the value is found at upper level and for cyclone the value is found at lower level. The highest value of relative vorticity is occurred at 300-100 and 1000-400 hPa for normal and cyclone cases respectively.

To test the formation/intensification as cyclonic storm, the spatial distribution of RV for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.8 (i) at

time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009 and 03 UTC on 11 May 2013 respectively. These are the observed time of formation as cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, RV are derived for the forecast hours 24 hours with the area (20.5° N, 85-95° E), (10.5° N, 75-85° E), (13.5° N, 80-90 °E) and (7.5° N, 85-95 °E) respectively. Maximum RV are 60-70×10^{-5}, 40-50×10^{-5}, 20-30×10^{-5} and 20-30×10^{-5} s^{-1} lies at 950, 550, 200 and 200 hPa respectively with cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively. The Ranges of above mentioned RV are satisfied for the formation of cyclonic storm.

4.3 Thermodynamical Parameters

4.3.1 Sea Surface Temperature (SST):

Sea surface temperature (SST) is an adequate predicator of TC intensity. The distribution of SST exceeding 26 °C is one of the precursors needed to maintain a TC. To understand the value of SST, different cases cyclone and normal are considered.

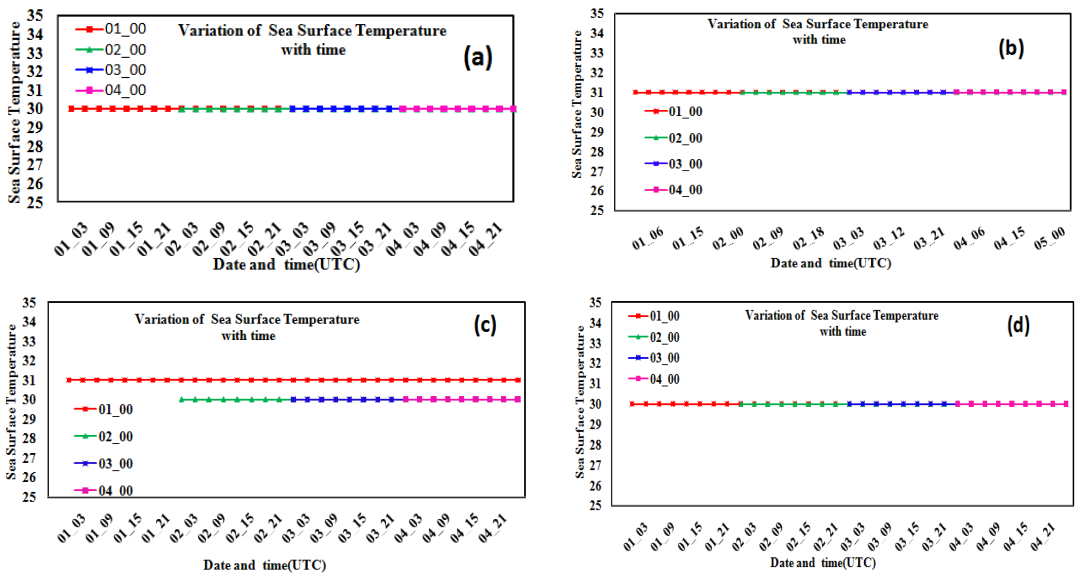


Figure 4.9 (a-d): Variation of model simulated sea surface temperature of Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with time.

Time variation of the maximum value of SST for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 for the forecast hours 96, 72, 48 and 24 hours are shown in Figure 4.9 (a-d). It has almost constant values and those are (30, 30, 30 and 30), (31, 31, 31 and 31), (31,

30, 30 and 30) and (30, 30, 30 and 30) °C for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with the forecast hours 96, 72, 48 and 24 hours respectively.

Average values of SST for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are almost 30, 31, 31 and 30 °C respectively. In all of these four cases, values of SST are more than 26.5 °C. This value is favorable condition of SST for cyclone formation but cyclone has not formed. It may be for other reasons. Again, it is a necessary condition but not the sufficient condition.

Time variation of the maximum values of temperature in case of the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 for the forecast hours 96, 72, 48 and 24 hours are shown in Figure 4.9 (e-h). It has almost constant values and those are (30, 30, 30 and 30), (29, 29, 29 and 29), (31, 30 , 30 and 30) and (34, 34 , 33 and 33)°C for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with the forecast hours 96, 72, 48 and 24 hours.

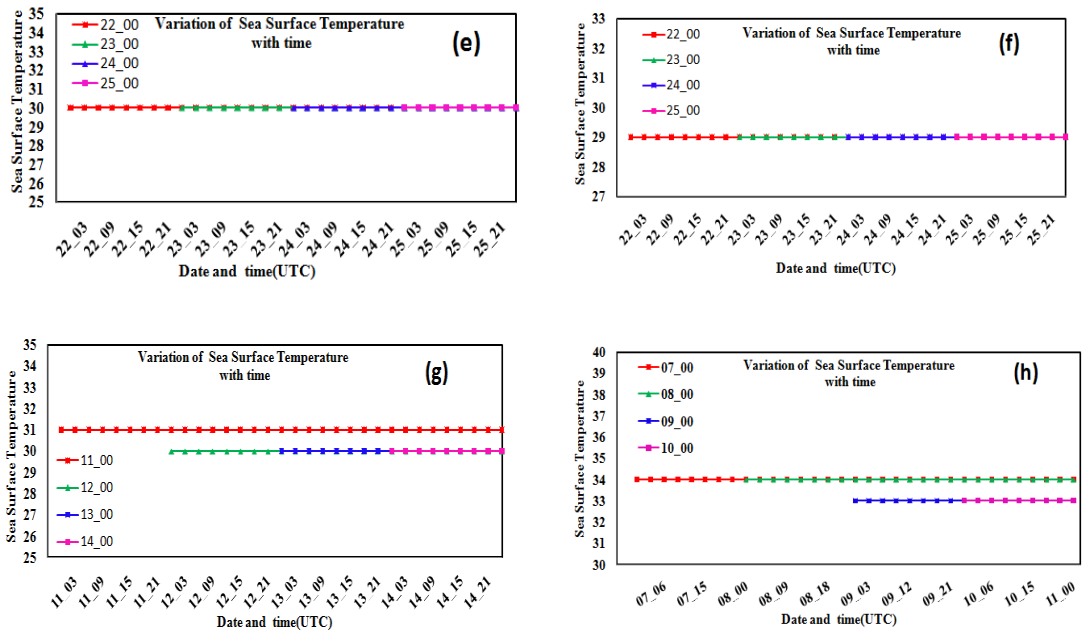


Figure 4.9 (e-h): Variation of model simulated sea surface temperature with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

Finally average values of the SST for cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are almost 30, 29, 30 and 33°C. In all of these four cyclone cases, values of SST are more than 26.5°C. So, these values are favorable condition for the cyclone intensification.

Again, these values are more than the values obtained from normal cases and these values are favorable condition for the cyclone intensification. It is understood that SST more than 26.5°Cis a necessary condition for cyclone formation but not sufficient condition for cyclone formation. It is observed from experiment that for cyclone and normal period SST is always over 26.5 C. So, SST is not a sufficient condition for Cyclone formation but it is a necessary condition because it does not confirm formation of cyclone.

To test the formation/intensification as cyclonic storm, model is run for further 24 hours using initial conditions 00 UTC on 26 October 2008, 00 UTC on 26 November 2008, 00 UTC on 15 April 2009 and 00 UTC on 11 May 2013 for the TCs Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively and model simulated time variation SST of TCs along with observed value are shown in Figure 4.9 (i). It has almost constant values and those are 30, 29, 30 and 31°C for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with the forecast 24 hours. The Ranges above mentioned SST are satisfied for the formation of cyclonic storm for all cyclones.

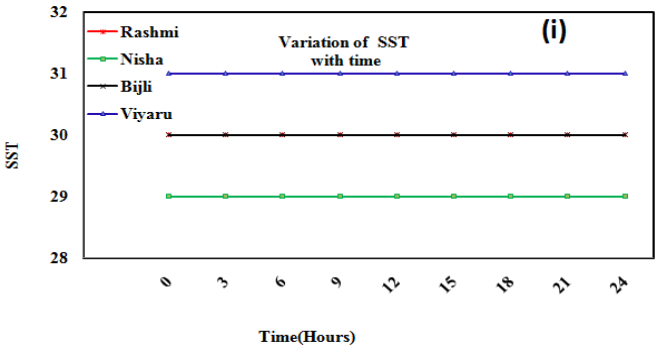


Figure 4.9 (i): Variation of model simulated Sea surface temperature with the forecast time for 4 normal cases.

The spatial distributions of average SST for four normal cases are plotted in Figure 4.10 (a-d). The spatial distribution of average SST for the forecast time 96, 72, 48 and 24 hours for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 observed around in a significant area. The values are almost same and these are (25-30, 25-30, 25-30 and 25-30), (27.5, 27.5, 27.5and 27.5), (25 -28.5, 25 -28.5, 25 -28.5and 25 -28.5) and (28 , 28, 28 and 28)°C for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with forecast time 96, 72, 48 and 24 hours respectively. Average SST for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are 25-30, 27.5, 25 -28.5 and 28°C respectively. SSTs are more or less than

26.5 °C. It means that in normal cases SST may have more than 26.5 °C. But cyclone will be formed when other factors will be satisfied.

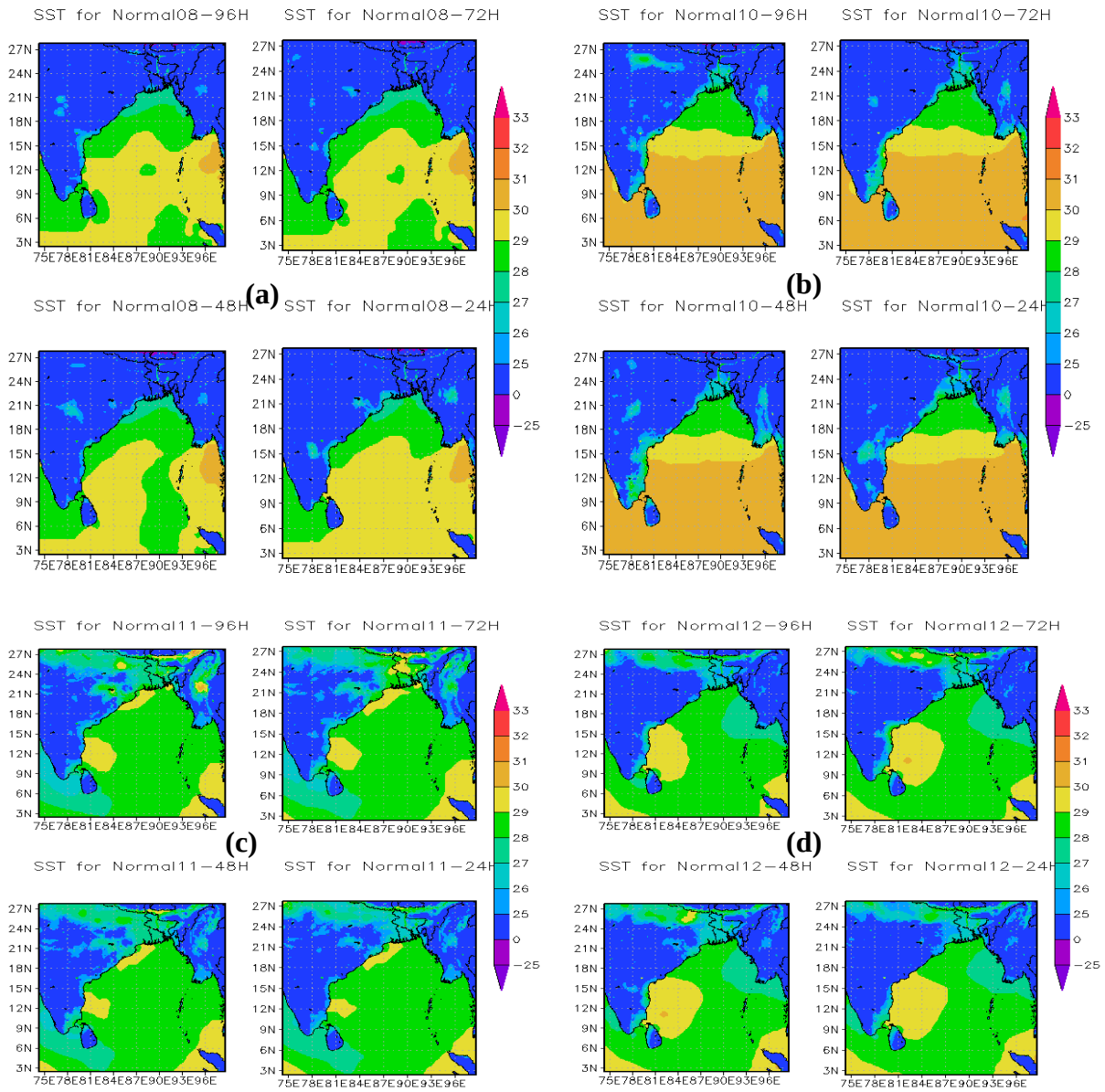


Figure 4.10 (a-d): The spatial distribution of sea surface temperature with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

The spatial distributions of average SST of the forecast time for four cyclone cases are plotted in Figure 4.10 (e-h). In case of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 SST for 96, 72, 48 and 24 hours persists around in a significant area with almost same value and their values are 29-30, 28-30, 29-31 and 30-32 °C. These values are favorable condition for the cyclone intensification and these are more than the values obtained from normal cases and these values are favorable condition for the cyclone intensification. It is

understood that SST more than 26.5°C is a necessary condition for cyclone formation but not sufficient condition for cyclone formation. Finally, it is observed that the average value of SST for cyclone is higher than that of normal cases. For all cyclone and normal cases, the lowest values of SST are around 26.5°C or more.

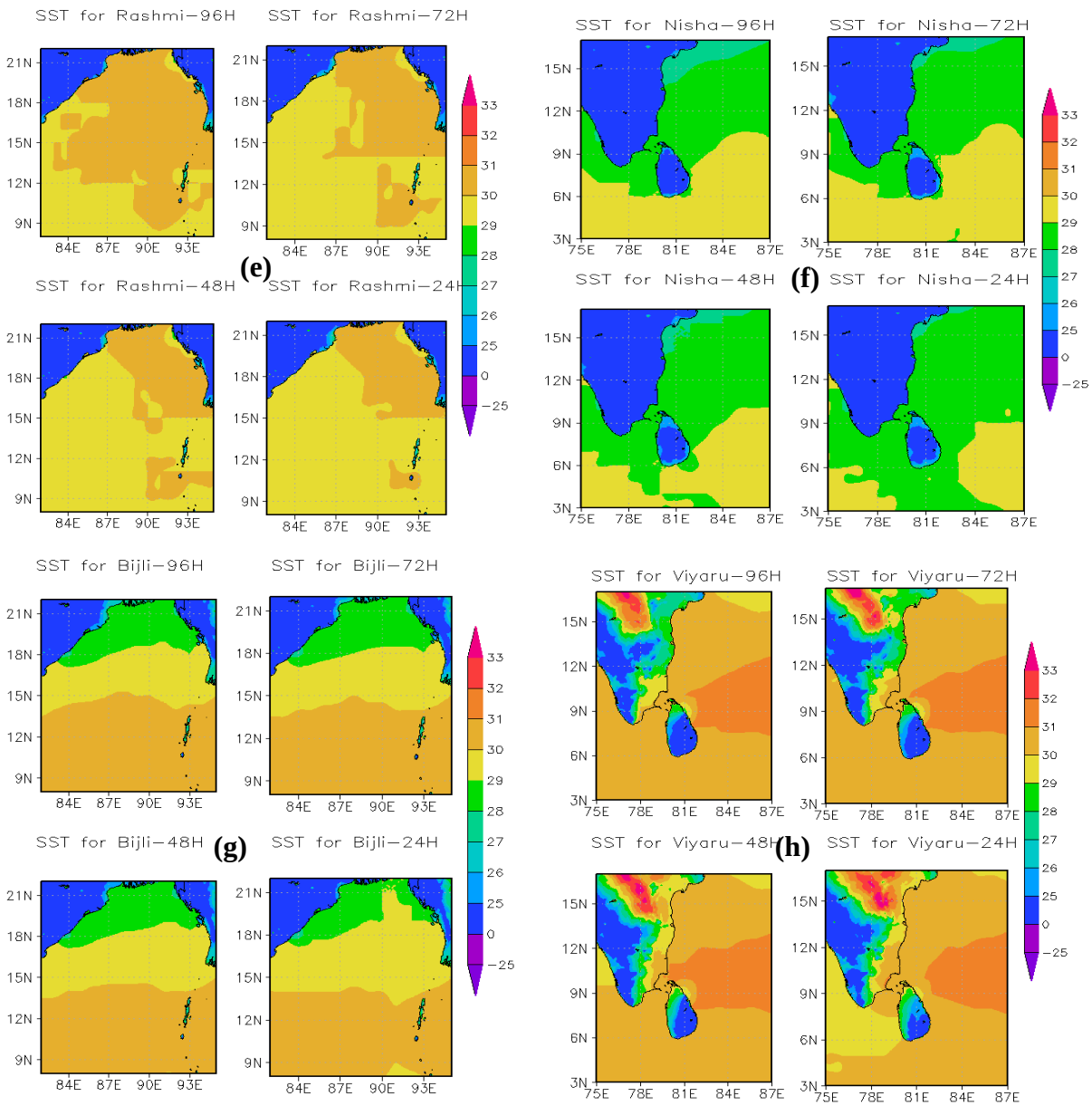


Figure 4.10 (e-h): The spatial distribution of sea surface temperature with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

To test the formation/intensification as cyclonic storm, The spatial distribution of SST for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.10 (i) at time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April

2009 and 03 UTC on 11 May 2013 respectively. These are the observed time of formation as cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, SST are derived for the forecast hours 24 hours with the area (8-22° N, 82-95° E), (3-17° N, 75-87° E), (8-22° N, 82-95°E) and (3-17° N, 85-97 °E) respectively. Ranges of the Maximum SST values for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 29-30, 28-30, 29-31 and 30-32 °C respectively. These values are favorable condition for the cyclone intensification and these values are favorable condition for the cyclone intensification. It is understood that SST more than 26.5°Cis a necessary condition for cyclone formation but not sufficient for condition for cyclone formation.

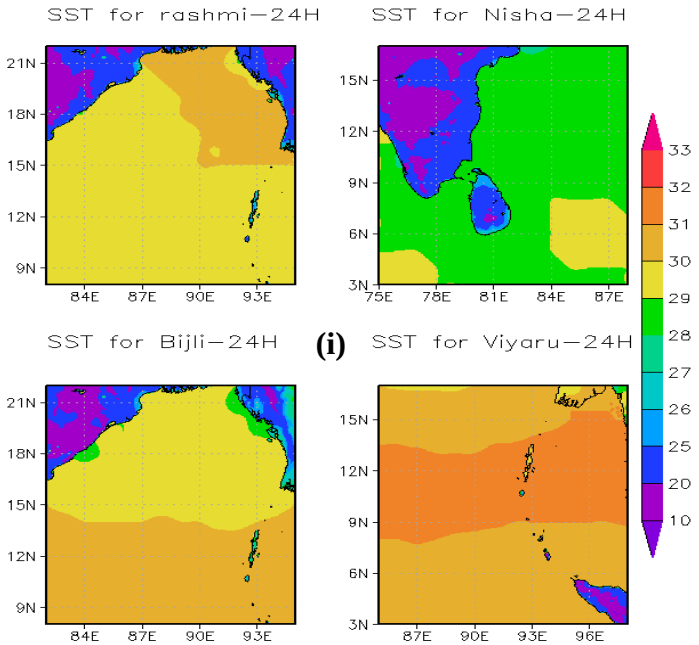


Figure 4.10 (i): The spatial distribution of Sea surface temperature with the forecast time for 4 cyclones.

4.3.2 Mean Sea Level Pressure (MSLP)

Time variation of the Mean sea level pressure (MSLP) for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 for the forecast hours 96, 72, 48 and 24 hours shown in Figure 4.11 (a-d) have a gradually decreasing tendency with little bit oscillating pattern and Ranges of the lowest SLP values are (1009-1002, 1009-1004, 1009-1004 and 1009-1004), (1008-1000, 1009-1003, 1009-1004 and 1009-1005), (998-988, 998-992, 998-993 and 999-

995) and (999-990, 999-991, 996-992 and 996-993)hPa respectively. The Ranges of the values Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are 1009-1002 hPa, 1009-1000, 999-988, 999-990 and 1008-1001 respectively. The Ranges of the lowest values of SLP do not indicate the formation and intensification of low pressure system respectively.

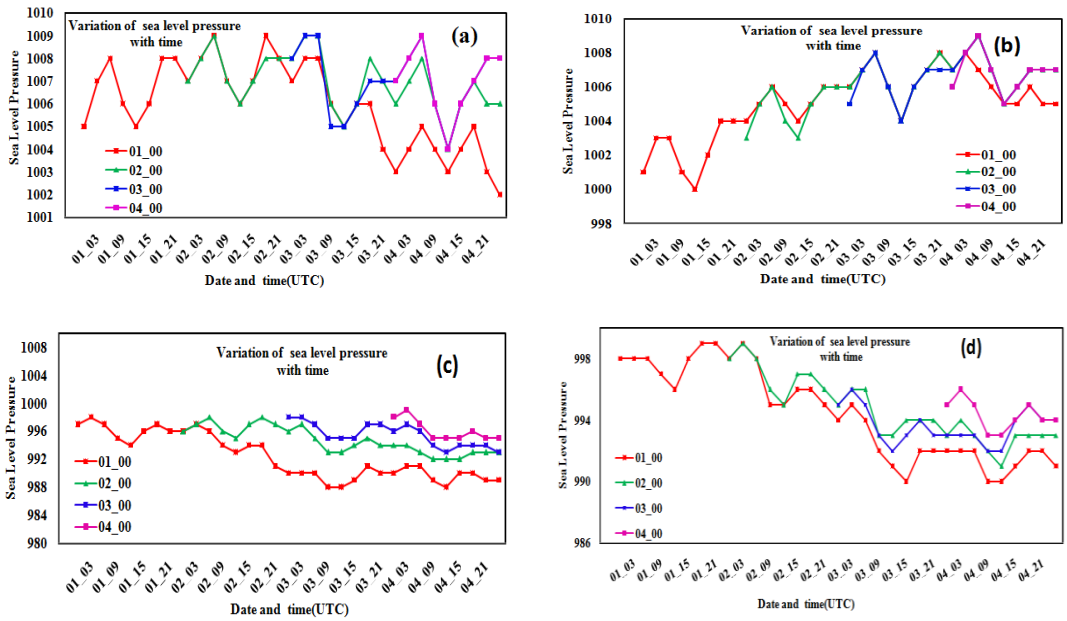


Figure 4.11(a-d): Variation of model simulated mean sea level pressure of Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with time.

Time variation of the observed and model simulated MSLP for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 for the forecast hours 96, 72, 48 and 24 hours are shown in Figure 4.11 (e-h). Model simulated SLPs are more or less than that of observed. Model simulated SLP has a oscillating pattern and Ranges of the lowest values of SLP are (1008-980, 1008-996, 1007-982 and 1006-1000), (1010-982, 1010-992,1008-982 and 1008-998), (1008-940, 1007-972, 1005-1001 and 1005-1001) and (1003-986, 1003-982, 1003-985 and 1001-993) hPa for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 for the forecast hours 96, 72, 48 and 24 hours respectively.

Finally Ranges of the lowest values of SLP for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 1008-980, 1010-982 ,1008-940 and 1003-982 hPa respectively, The Ranges of lowest SLP are larger i.e. pressure fall is larger and center pressure more lower than that of surrounding which indicate for the formation and intensification of low pressure system.

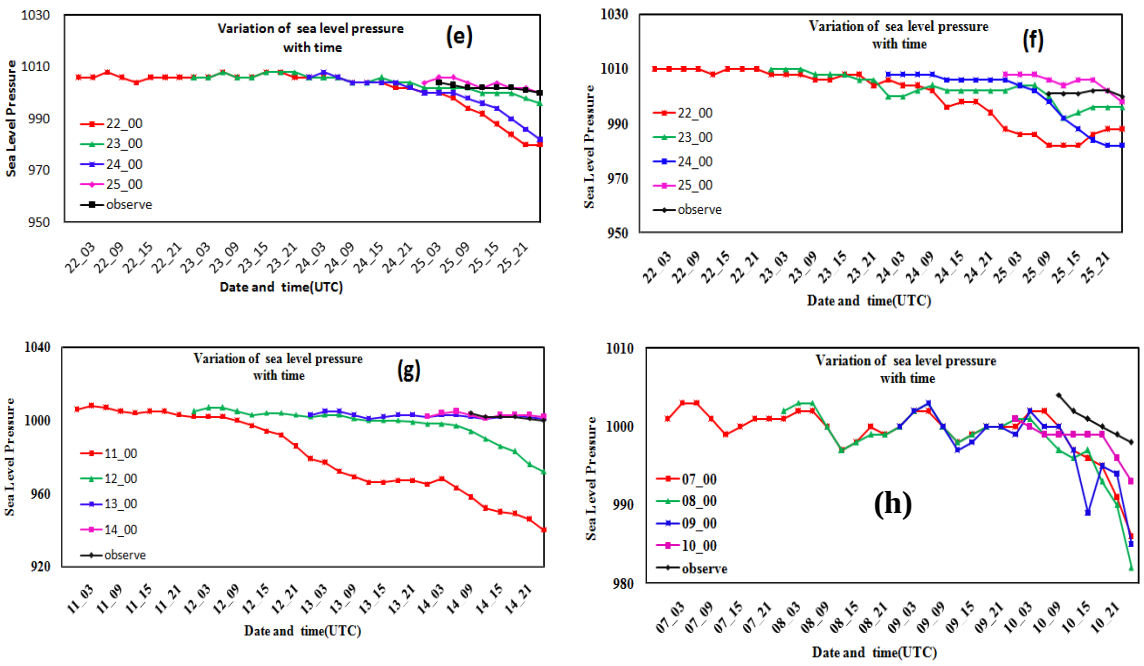


Figure 4.11(e-h): Variation of observed and model simulated Mean sea level pressure of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

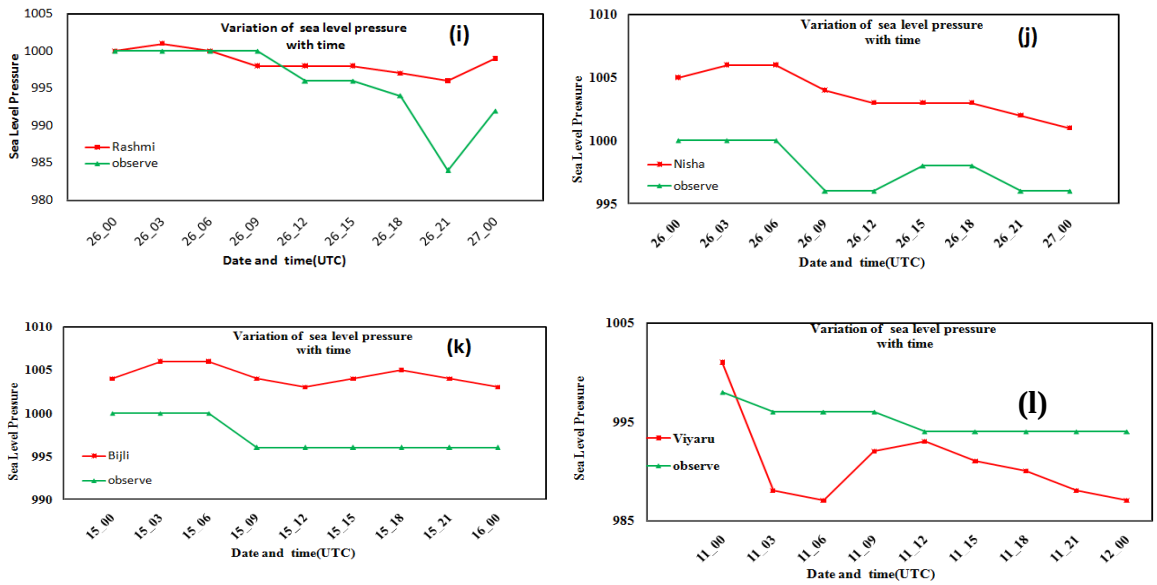


Figure 4.11(i-l): Variation of observed and model simulated mean sea level pressure (MSLP)of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

To test the formation/intensification as cyclonic storm, model is run for further 24 hours using initial conditions 00 UTC on 26 October 2008, 00 UTC on 26 November 2008, 00 UTC on 15 April 2009 and 00 UTC on 11 May 2013 for the TCs Rashmi-2008, Nisha-2008, Bijli-

2009 and Viyaru-2013 respectively and model simulated time variation SLP of TCs along with observed value are shown in Figure 4.11 (i-l). All cases have an oscillating pattern. Ranges of value of SLP for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 996-1000, 1001-1006 ,1003-1006 and 987-1001 hPa respectively, The Ranges of lowest SLP are larger i.e. pressure fall is larger and center pressure more lower than that of surrounding which indicate for the formation and intensification of low pressure system.

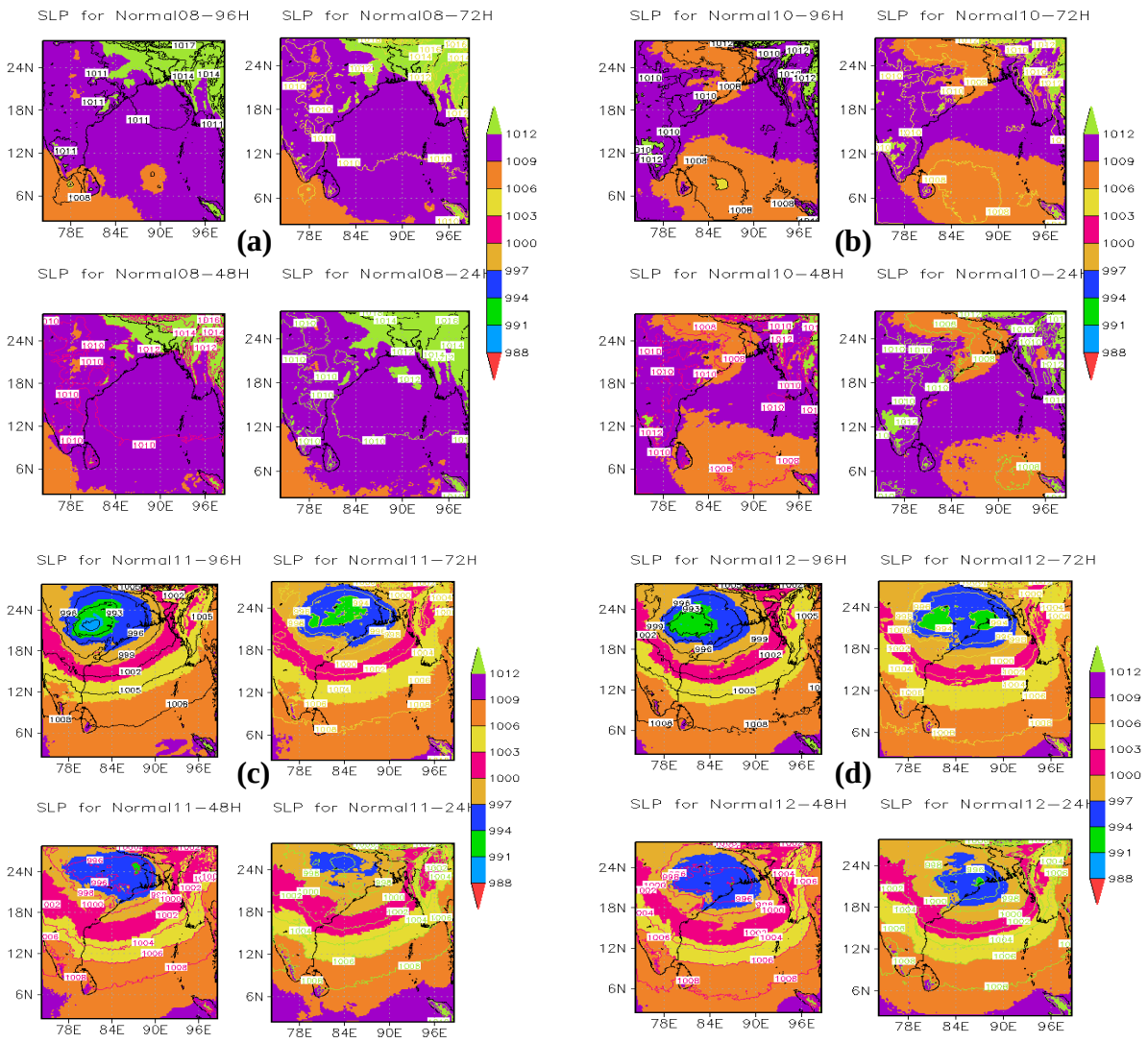


Figure 4.12 (a-d): The spatial distribution of mean sea level pressure with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

The spatial distribution of model simulated MSLP at 00 UTC on 5 April 2008, 00 UTC on 5 April 2010, 00 UTC on 5 August 2011 and 00 UTC on 5 August 2012 for 5normal cases with the forecast hours 96, 72. 48 and 24 hours are plotted in Figure 4.12 (a-d) through the

center (12°N, 85°E) along longitude. MSLP for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are almost same around a significant area and their values are (1004-1012, 1004-1012, 1008-1012 and 1008-1012), (1004-1010, 1006-1010, 1006-1010 and 1006-1010), (1012-997, 1012-997, 1012-997 and 1012-997) and (1012-994, 1012-994 , 1012-994 and 1012-994) hPa respectively. The pressure gradient from the above mentioned normal cases with the forecast hours 96, 72, 48 and 24 hours are (0, 0, 0 and 0), (2, 0, 0 and 0), (0, 0, 0 and 0) and (0, 0, 0 and 0) hPa respectively (Table 4.1). It is noted that pressure gradient are exit for Normal-2011 and Normal-2012 at land which does not contribute anything for the formation of depression at sea. These pressure gradients are measured by observing the closed circle of pressure around the centre of low pressure. Again, the corresponding wind speed are (0, 0, 0 and 0), (19.23, 0, 0 and 0),(0, 0, 0 and 0) and (0, 0, 0 and 0) Knots for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with forecast hours 96, 72, 48 and 24 respectively (Table 4.1). These wind speed are calculated using relation $V_{max}=13.6\sqrt{\Delta P}$ knots.

The Ranges of MSLP for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are 1012-1004, 1010-1004,1012-997 and 1012-994 hPa respectively but the gradient for all normal cases are almost 0 hPa except for the 96 hour forecast of Normal-2010 case which value is 2 hPa. The wind speed for 2 hPa is 19.23 knots. Again, this 2 hPa pressure gradient does not contribute for formation, intensification. It may be for other condition does not favor it to The spatial distribution of model simulated MSLP for 96, 72, 48 and 24 hours for cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with the time at 03 UTC on 25October 2008, 09 UTC on 25 November2008, 09 UTC on 14 April 2009 and 09 UTC on 10May 2013 are shown in Figure 4.11 (e-h) and the values are (997,1001, 997 and 1001), (980, 997, 997 and 1002), (956, 988, 996 and 996) and (1000, 997, 1000 and 1000) hPa respectively. This is the time when cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 initially is formed as a depression according to IMD observed value. It is noted that the observed lowest MSLPs are1004, 1001, 1004 and 1004 hPa at the (8-22° N, 82-95° E), (3-17° N, 75-87° E), (8-22° N, 82-95 °E) and (3-17° N, 85-97 °E) for cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. Whereas simulated positions for the formation of depression are {(17.5°N, 90.5°E), (15.00°N, 83.00°E), (16.5°N, 86.00°E) and (18.00°N, 86.00°E)}, {(10.5°N, 85.00°E), (8.5°N, 81.00°E), (9.00°N, 81.00°E) and (8.5°N,

81.00°E°)}, {(14.5°N, 86.00°E), (12.00°N, 86.00°E), (11.00°N°, 86.00°E) and (12.00°N, 87.00°E)} and {(6.00°N, 93.00°E), (5.00°N, 93.00°E), (6.00°N,93.00°E) and (5.00°N,93.00°E)}for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 96, 72, 48 and 24 hours forecast respectively. Simulated positions for the formation of depression of cyclones are different from that of the observed. Model simulated lowest MSLP are largely differing from the observed lowest pressure. The pressure gradient estimated from the afore mentioned lowest MSLP value are (11, 4, 11and 2), (27, 10, 11 and 2), (44 , 14, 2 and 1) and (4, 7, 4and 7) hPa for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 96, 72, 48 and 24 hours forecast respectively (Table 4.1). So, the corresponding wind speed are (45.10, 27.2, 45.10 and 14.61), (70.67, 43.00, 45.10 and 14.61), (90.21, 50.89, 27.2and 13.6) and (27.2, 35.98, 27.2 and 35.98) Knots for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 96, 72, 48 and 24 hours forecast respectively (Table 4.1). As we know, according to the TC classification, wind speed 17-27 Knot is necessary for the formation of the depression state of the cyclone.

For the simulation of cyclone Rashmi-2008 , model predict the event as CS, Deep depression, CS and low with 96, 72, 48 and 24 hour forecast at 03 UTC on 25October 2008. So, 96, 72 and 48 hour forecast over predict the system and 24 hours forecast under predict the system. It is noted that at 03 UTC on 25 October 2008, according to IMD, system was as depression. It may be written that model at least captured the event but could not estimate it intensity.

For the simulation of cyclone Nisha-2008, model predict the event as VSCS, CS, CS and low with 96, 72, 48 and 24 hour forecast at time 09 UTC on 25 November 2008. So, 96, 72, 48 and 24 hour forecast over predict the system and 24 hours forecast under predict the system. It is noted that at time 09 UTC on 25 November 2008, according to IMD, system was as depression. It may be written that model at least captured the event but could not estimate it intensity.

For the simulation of cyclone Bijli-2009, model predict the event as VSCS,SCS, Deep depression and low with 96, 72, 48 and 24 hour forecast at time 09 UTC on 14 April 2009. So, 96, 72, 48 and 24 hour forecast over predict the system and 24 hours forecast under predict the system. It is noted that at time 09 UTC on 14 April 2009, according to IMD, system was as depression. It may be written that model at least captured the event but could not estimate it intensity.

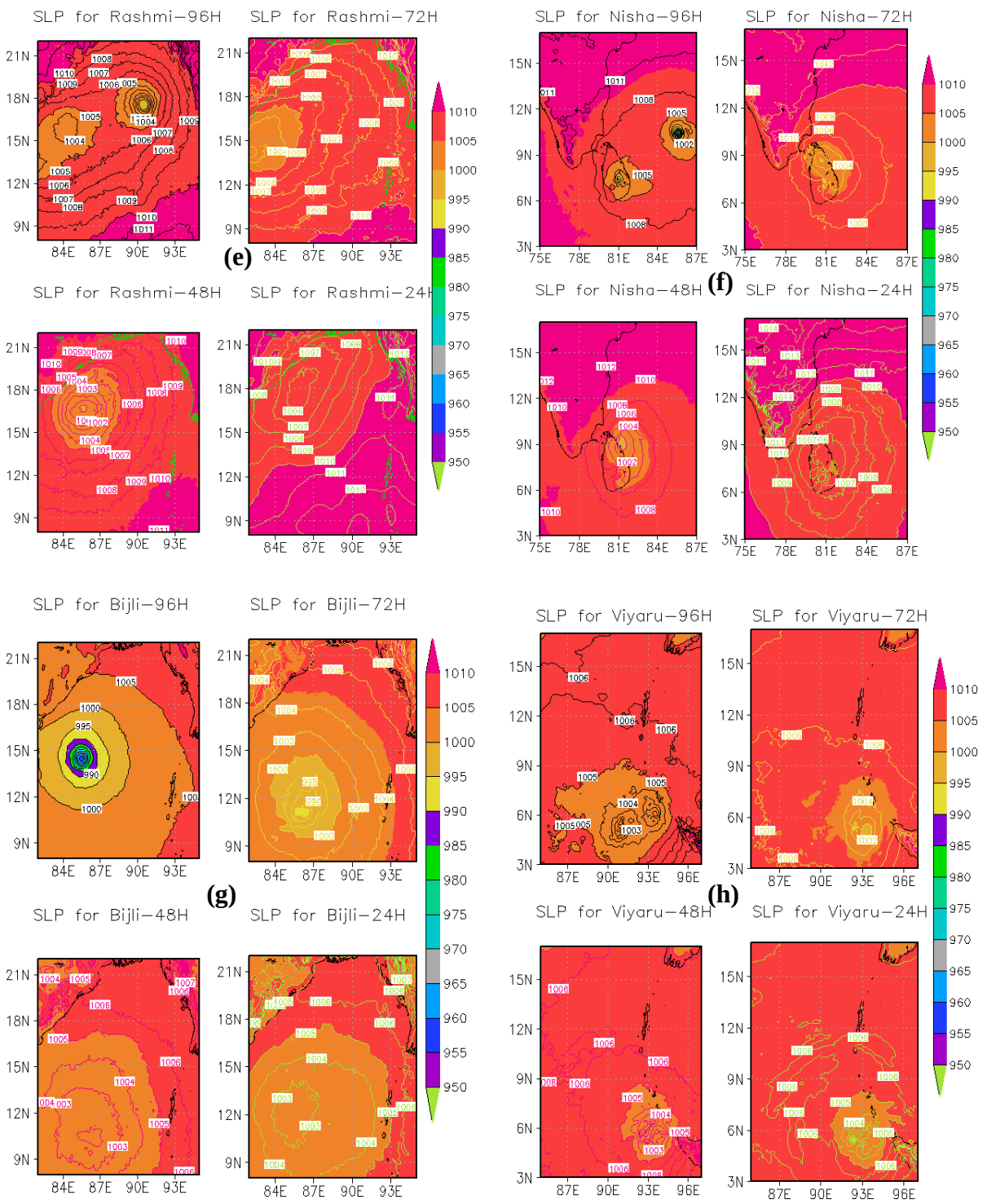
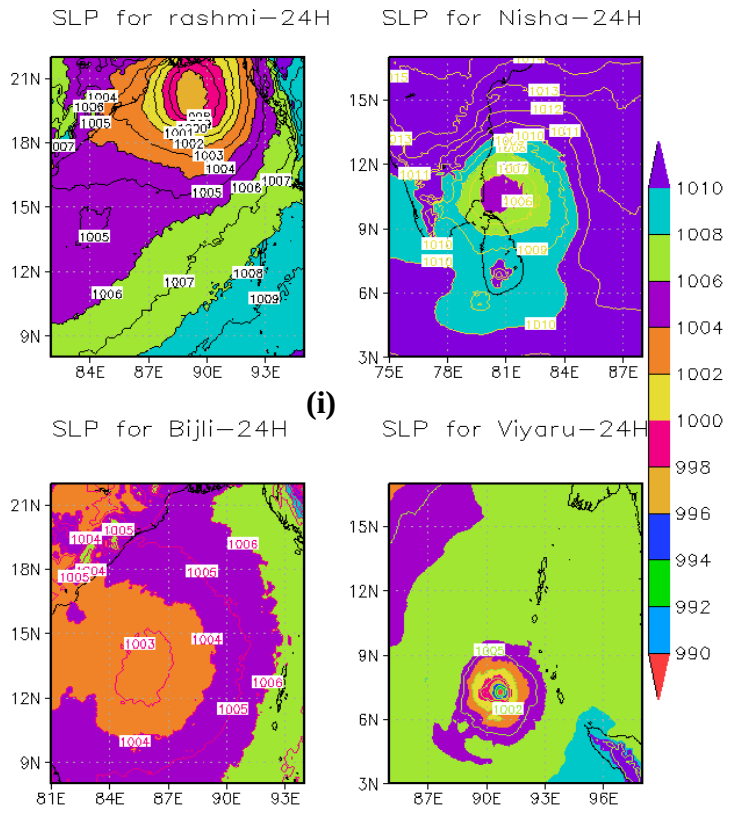


Figure 4.12 (e-h): The spatial distribution of mean sea level pressure with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

For the simulation of cyclone Viyaru-2013, model predict the event as Deep depression, CS, Deep depression and CS with 96, 72, 48 and 24 hour forecast at time 09 UTC on 10May 2013. So, 96, 72, 48 and 24 hour forecast over predict the system. It is noted that at time 09 UTC on 10May 2013, according to IMD, system was as depression. It may be written that model captured the event with higher intensity. From Figure 4.11 (e-h), it is clear to us that MSLP shows a decreasing trend at the beginning of cyclone formation. Model predicts the formation of events with more or less intensity than that of observed. From the Figure 4.11 (e-h), the value of SLP is lowest at sea surface where as from the Figure 4.11 (a-d), the value of pressure is lowest at earth surface which does not contribute to form depression at sea.



(i)

Figure 4.12 (i): The spatial distribution of mean sea level pressure with the forecast time for 4 cyclones.

To test the formation/intensification as cyclonic storm, The spatial distribution MSLP for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.12 (i) at time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009 and 03 UTC on 11 May 2013 respectively. These are the observed time of formation as

Table 4.1: Derived pressure changed and wind speed

Name of cyclones	Initial Date/Time (UTC)	Forecasting hours	ΔP	Vmax=13.6 √Δ P knots
Normal-2008	01 April/0000	96	0	0
	02 April/0000	72	0	0
	03 April/0000	48	0	0
	04 April/0000	24	0	0
Normal-2010	01 April/0000	96	2	19.23
	02 April/0000	72	0	0
	03 April/0000	48	0	0
	04 April/0000	24	0	0
Normal-2011	01 August/0000	96	0	0
	02 August/0000	72	0	0
	03 August/0000	48	0	0
	04 August/0000	24	0	0
Normal-2012	01 August/0000	96	0	0
	02 August/0000	72	0	0
	03 August/0000	48	0	0
	04 August/0000	24	0	0
Rashmi-2008	22 October/0000	96	11	45.10
	23 October/0000	72	4	27.20
	24 October/0000	48	11	45.10
	25 October/0000	24	2	19.23
	26 October/0000	24	4	27.20
Nisha-2008	22 November/0000	96	27	70.67
	23 November/0000	72	10	43.00
	24 November/0000	48	11	45.10
	25 November/0000	24	2	19.23
	26 November/0000	24	6	33.31
Bijli-2009	11 April/0000	96	44	90.21
	12 April/0000	72	14	50.89
	13 April/0000	48	2	19.23
	14 April/0000	24	1	13.60
	15 April/0000	24	2	19.23
Viyaru-2013	07 May/0000	96	4	27.20
	08 May/0000	72	7	35.98
	09 May/0000	48	4	27.20
	10 May/0000	24	7	35.98
	11 May/0000	24	13	49.00

cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, SLP are derived for the forecast hours 24 hours with the area (8-22° N, 82-95° E), (3-17° N, 75-87° E), (8-22° N, 82-95 °E) and (3-17° N, 85-97 °E) respectively. Ranges of the SLP values for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 998-996, 1006-1003, 1003-1000 and 992-990 hPa with 24 hours forecast time respectively. Simulated positions for the formation of

depression of cyclones are different from that of the observed. Model simulated lowest MSLP are largely differing from the observed lowest pressure. The pressure gradient estimated from the afore mentioned lowest MSLP value are 4, 6, 2 and 13 hPa for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 24 hours forecast time respectively (Table 4.1). So, the corresponding wind speeds are 27.2, 33.31, 19.23 and 49 knots for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 24 hours forecast respectively (Table 4.1). As we know, according to the TC classification, wind speed 34-48 Knot is necessary for the formation of cyclonic storm. So, the values of WS for cyclones Nisha-2008 and Viyaru-2013 with 24 hours forecast satisfy the condition for cyclonic storm. According to values of SLP from Figures 4.11(i-l), cyclone Rashmi intensified to cyclonic storm later than the observed time. Similarly, situation is also observed according to values of wind from Figures 4.2(i-l). Unfortunately, 24 hours forecast could not simulate the cyclonic storm for the cyclone Bijli. It may be possible run with different initial conditions with long time.

4.3.3 Vertical Profile of Relative Humidity

The Vertical distribution of RH at 00 UTC on 5 April 2008, 00 UTC on 5 April 2010, 00 UTC on 5 August 2011 and 00 UTC on 5 August 2012 for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 respectively with 96, 72. 48 and 24 hours are plotted in Figure 4.13 (a-d) through the center (12°N, 85°E). Model simulated maximum RH exist not full area up to 900 hPa level and the values are 90-100 % for all forecast time for all normal cases. 60 % or less RH exist in the upper levels (900-500,900-600, 900-250 and 900-200) hPa for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 respectively with all forecast time. Model simulated maximum RH does not cover full area up to a considerable height and it indicates normal weather in lower level. So, no depression is formed in any forecast time.

The Vertical distribution of RH at 03 UTC on 25 October 2008, 09 UTC on 25 November 2008, 09 UTC on 14April 2009 and 09 UTC on 10May 2013 of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 for 96, 72. 48 and 24 hours are plotted in Figure 4.13 (f-i) through the center {(17.5 °N, 90.5 °E) (14.22 °N, 85 °E), (16.5 °N, 83.8 °E) and (18.0 °N, 82.8 °E)},{(10.5 °N, 85.3 °E) (8.5 °N, 79.8 °E), (9.0 °N, 80.8 °E) and (7.5 °N, 83.0 °E)}, {(14.5 °N, 85.9 °E) (11.0 °N, 87 °E), (10.5 °N, 82.0 °E) and (12.0°N, 82.5 °E)} and {(6.0 °N, 94.0 °E) (5.5 °N, 92.5 °E), (5.5 °N, 93.0 °E) and (5.5 °N, 92.2 °E)} respectively. This

is the observed time of formation of depression of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 according to IMD observed value. Maximum RH is 90-100 % and lies up to the level (1000-700, 1000-600, 1000-500 and 1000-450), (1000-350, 1000-400, 1000-400 and 1000-800), (1000-350, 1000-400, 1000-400 and 1000-800) and (1000-300, 1000-350, 1000-350 and 1000-400) hPa for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with forecast hours 96, 72, 48 and 24 respectively. At least 60% RH exit up to 200 hPa for all run. Considerable values of RH exist from surface up to 200 hPa level and it indicates the favorable situation for the formation of depression of the above mentioned cyclones.

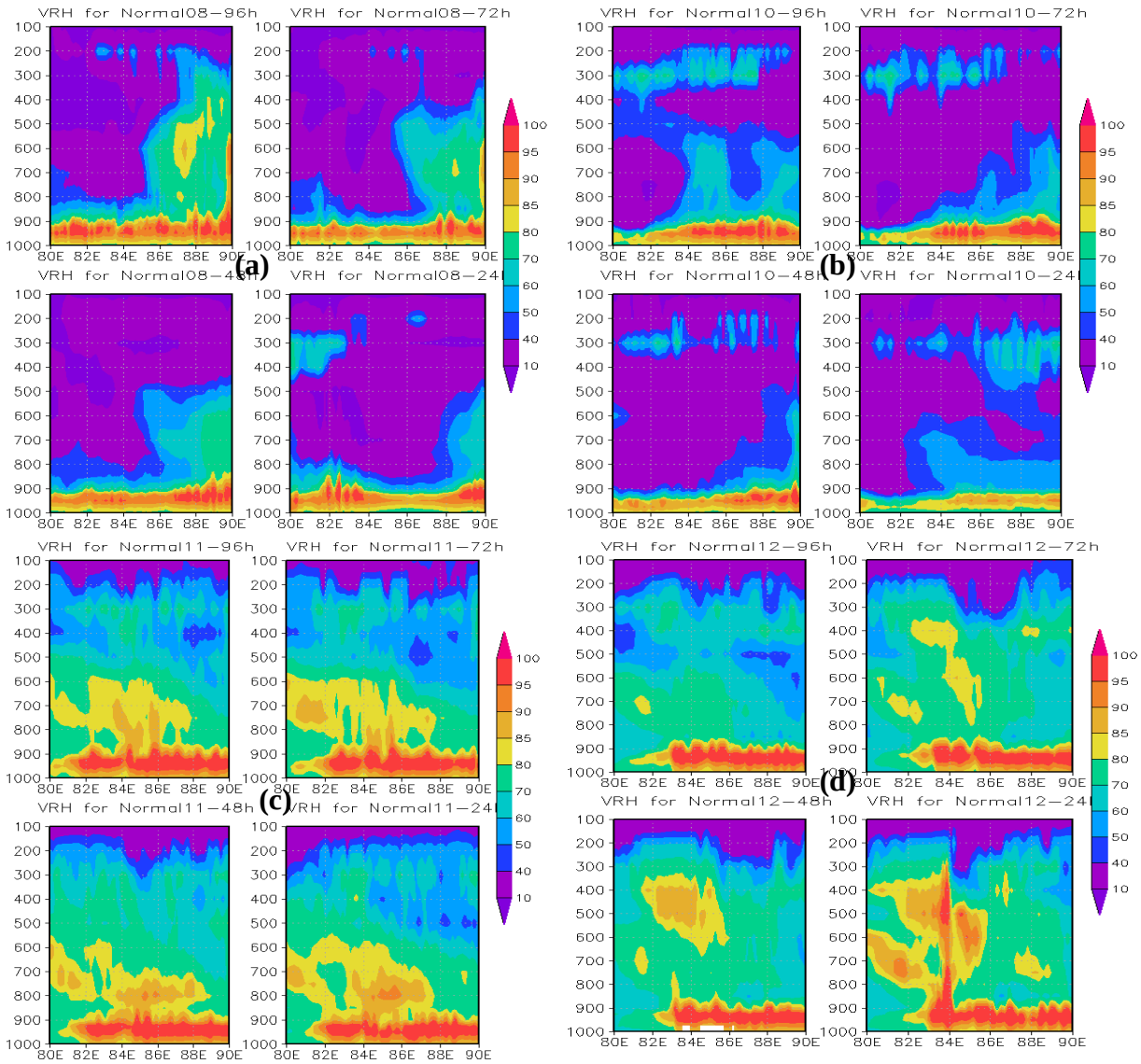


Figure 4.13 (a-d): The vertical distribution of relative humidity with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

As the cyclone intensity is low, Relative humidity's value for normal and cyclones are almost same. But a few differences are found in their existence up to higher levels with large area. The value of relative humidity is observed between 90-100% for both cyclonic and normal cases. The level of remarkable amount of relative humidity is observed at 1000-900 hPa and 1000-300 hPa for normal and cyclone cases respectively. So, high relative humidity from surface to higher level with large area is favorable for the formation of depression. Model could simulate the formation of the depression.

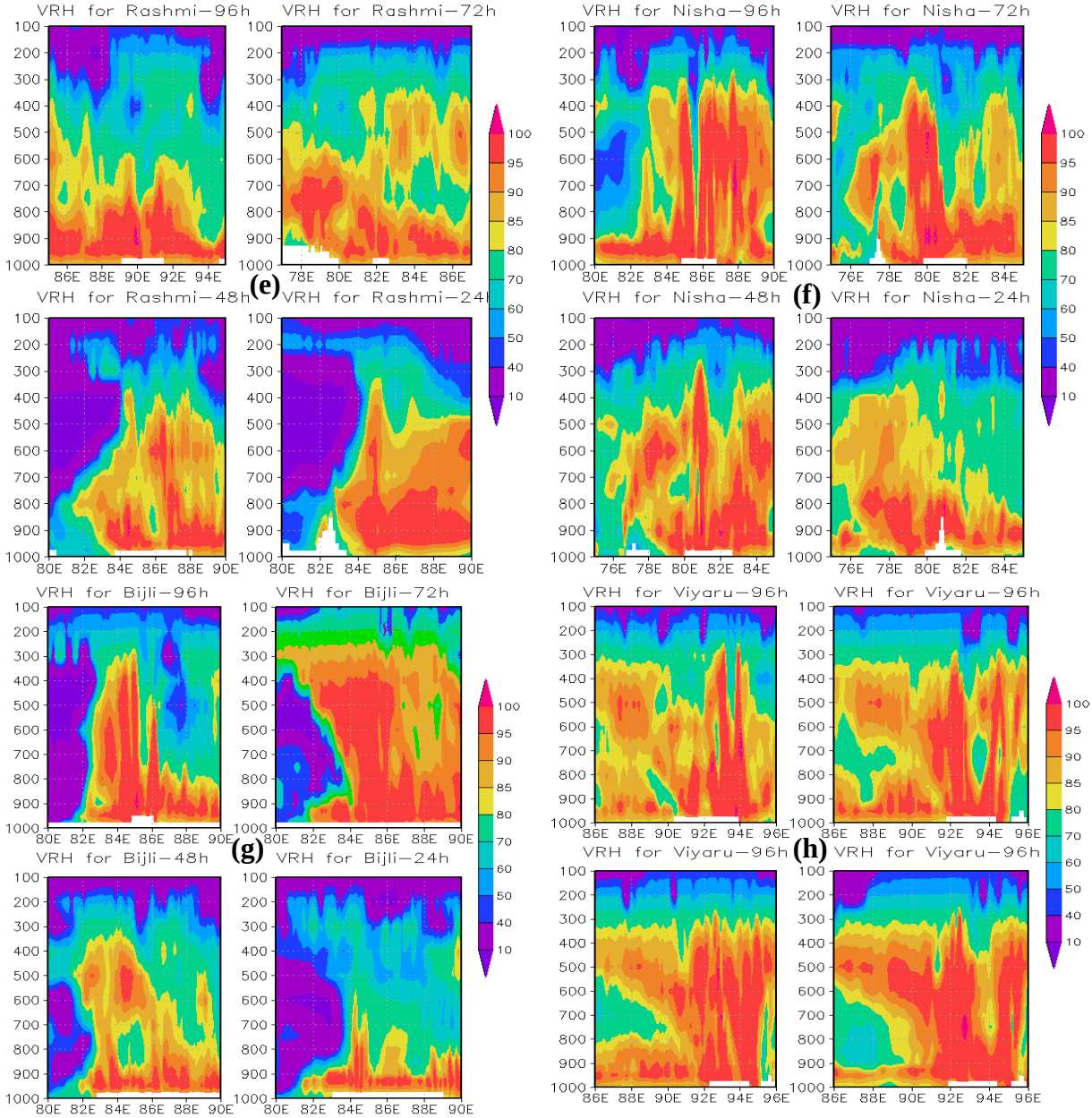


Figure 4.13 (e-h): The spatial distribution of relative humidity with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

To test the formation/intensification as cyclonic storm, the vertical distribution of RH for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.13 (i) at time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009 and 03 UTC on 11 May 2013 respectively. These are the observed time of formation as cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively. For cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, RH are derived for the forecast hours 24 hours through the centre (20.5° N, 85-95° E), (10.5° N, 75-85° E), (13.5° N, 80-90 °E) and (7.5° N, 85-95 °E) respectively. Maximum RH is 90-100 % and lies up to the level 1000-800, 1000-600, 1000-900 and 1000-400 hPa for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively with forecast hours 24. At least 50% RH exit up to 500-100, 250-100, 350-100 and 200-100 hPa for all run. Considerable values of RH exist from surface up to 500 hPa level and it indicates the favorable situation for the formation of cyclonic storm of the above mentioned cyclones.

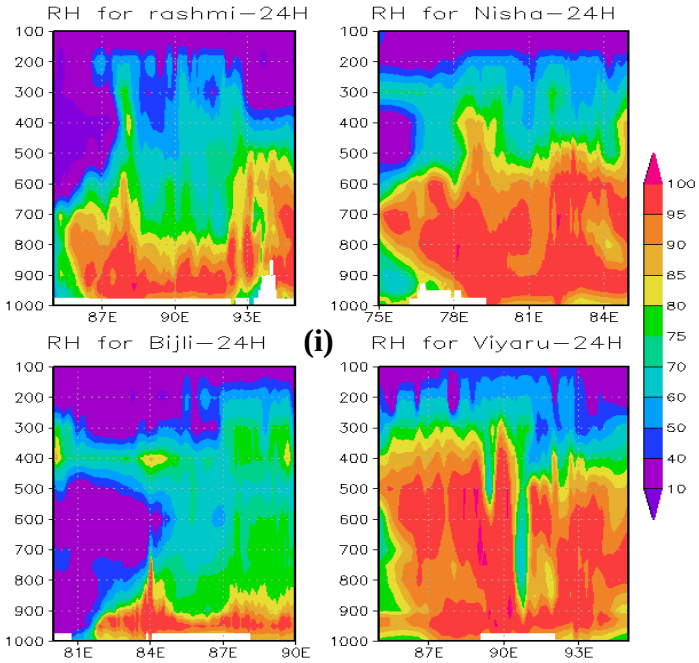


Figure 4.13 (i): The vertical distribution of relative humidity with the forecast time for 4 cyclones.

4.3.4 Convective Available Potential Energy (CAPE)

Time variation of Convective Available Potential Energy (CAPE) in case of Normal-2008, Normal-2010, Normal-2011 and Normal-2012 for the forecast hours 96, 72, 48 and 24 hours

are shown in Figure 4.14 (a-d). CAPE have a gradually decreasing tendency with little bit oscillating pattern and Ranges of the maximum CAPE values are (5500-3200, 5800-3300 , 5800-3500 and 5000-3900), (6100-4000, 5900-4200, 5600-4400 and 6400-4300), (4700-2800 , 4300-2800, 4400-2800 and 3800-3000) and (4900-2900,4200-2700, 4200-2900 and 4700-2700) J/Kg for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with the forecast hours 96, 72, 48 and 24 hours respectively.

Ranges of the values of CAPE values for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are 5800-3200, 6400-4000, 4700-2800 and 4900-2700 J/Kg respectively. The Ranges of CAPE are bigger and it was favorable condition for formation but it could not form low depression. It may be due to other conditions does not satisfy.

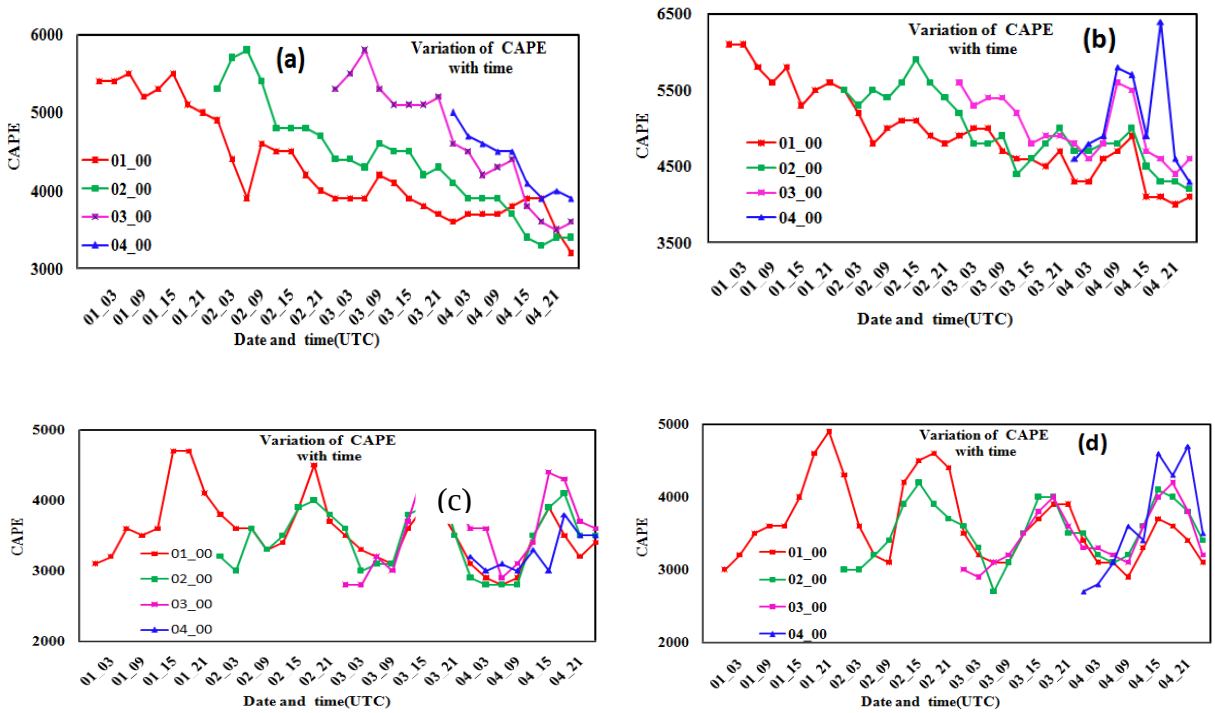


Figure 4.14 (a-d): Variation of model simulated convective available potential energy of Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with time.

Time variation of CAPE in case of the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 for the forecast hours 96, 72, 48 and 24 hours Figure 4.14 (e-h) have a oscillating pattern and Ranges of the lowest values of CAPE are (4300-3200, 4000-3000, 3900-3100 and 4100-2800), (3900-2700, 3600-2400,3300-2500 and 3400-2400), (6100-3800

, 6200-3700, 6000-3900 and 6000-4200) and (7600-3700, 7400-4800, 7400-5600 and 7400-5800)J/Kg respectively.

Finally Ranges of the values of CAPE for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 4300-2800, 3900-2400, 6200-3700 and 7600-3700 J/Kg respectively. The CAPE value more than 2500 J/Kg indicates the extremely unstable situation. So these values indicate the formation of low pressure system as depression.

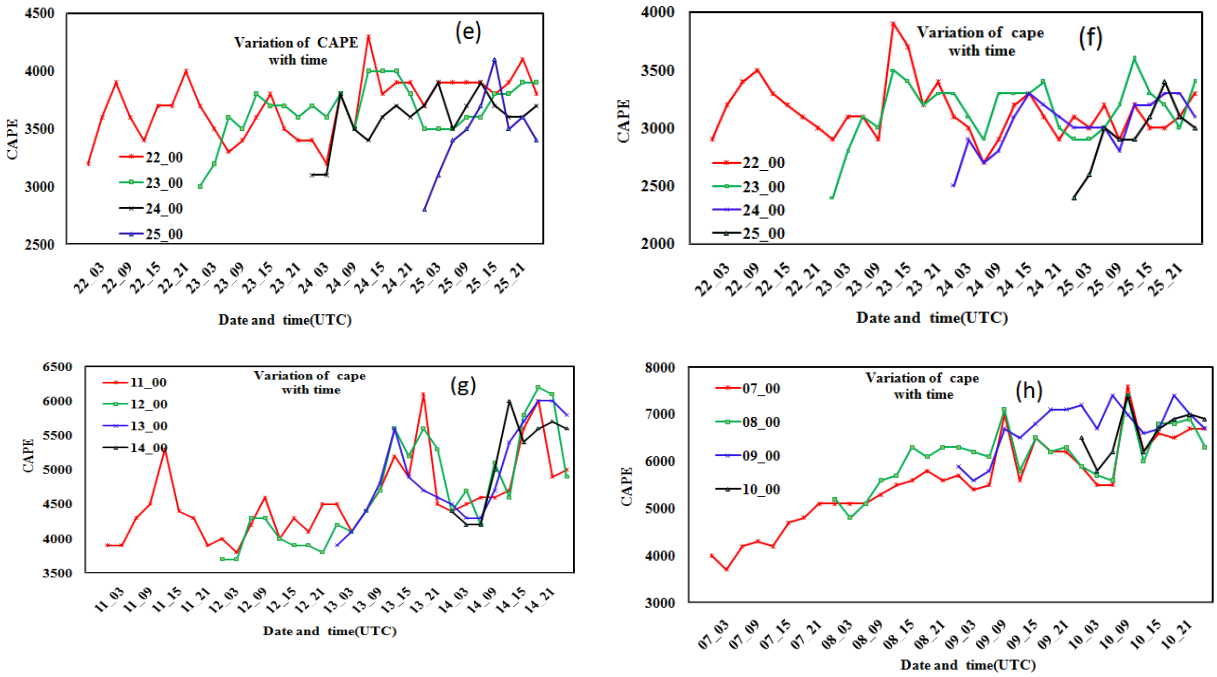


Figure 4.14 (e-h): Variation of model simulated convective available potential energy of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

To test the formation/intensification as cyclonic storm, model is run for further 24 hours using initial conditions 00 UTC on 26 October 2008, 00 UTC on 26 November 2008, 00 UTC on 15 April 2009 and 00 UTC on 11 May 2013 for the TCs Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively and model simulated time variation of CAPE of TCs along with observed value are shown in Figure 4.14 (i). All cases have an oscillating pattern. Ranges of values of CAPE for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 2900-3700, 2400-3000, 3700-5400 and 3900-5200 J/Kg respectively. The CAPE value more than 2500 J/Kg indicates the extremely unstable situation. So these values indicate the formation of low pressure system as cyclonic storm.

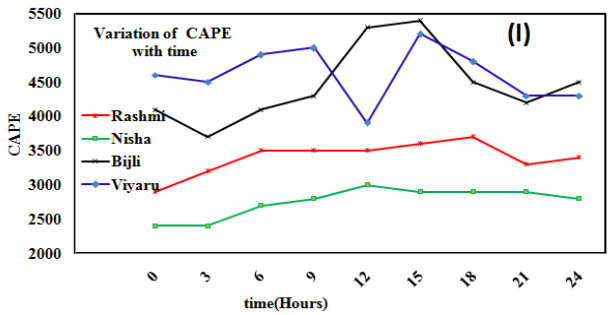


Figure 4.14 (i): Variation of model simulated convective available potential energy of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

The Vertical distribution of CAPE at 00 UTC on 5 April 2008, 00 UTC on 5 April 2010, 00 UTC on 5 August 2011 and 00 UTC on 5 August 2012 normal case for 96, 72. 48 and 24 hours are plotted in Figure 4.15 (a-d) through the center (12 °N, 85 °E). Maximum CAPE (1950, 1700, 1700 and 2200), (2850, 2850, 2850 and 2150), (2650, 2650, 2650 and 2650) and (3150, 3150, 3150 and 3150) J/kg lies at level 1000-900, 1000 - 950, 1000 - 975 and 1000 – 975 hPa for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with 96, 72, 48 and 24 forecast hours respectively. The CAPE value is absent above 900 hPa level. This value of CAPE at the lower level is not considered as the favorable situation for the formation of depression.

The Vertical distribution of CAPE at 03 UTC on 25 October 2008, 09 UTC on 25 November 2008 , 09 UTC on 14April 2009 and 09 UTC on 10May 2013of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 for 96, 72. 48 and 24 hours are plotted in Figure 4.15 (e-h) through the center {(17.5 °N, 90.5 °E) (14.22 °N, 85 °E), (16.5 °N, 83.8 °E) and (18.0 °N, 82.8 °E)},{(10.5 °N, 85.3 °E) (8.5 °N, 79.8 °E), (9.0 °N, 80.8 °E) and (7.5 °N, 83.0 °E)}, {(14.5 °N, 85.9 °E) (11.0 °N, 87 °E), (10.5 °N, 82.0 °E) and (12.0°N, 82.5 °E)} and {(6.0 °N, 94.0 °E) (5.5 °N, 92.5 °E), (5.5 °N, 93.0 °E) and (5.5 °N, 92.2 °E)} respectively. This is the observed time of formation of depression of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. Maximum CAPE are (3300, 3050, 3050 and 2800), 2400, 2600 and (3200, 3200, 3200 and 3450) J/kg lies at 950 hPa for all forecast hours. CAPE values 500, 400, 500 and 500 or more lies from surface to upper level (750, 650, 800 and 850), (750, 780, 850 and 800), (400, 750, 800 and 880) and (400, 800, 800 and 700) hPa for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 96, 72. 48 and 24 forecast hours

respectively. These values up to higher level are considered as the favorable situation for the formation of depression.

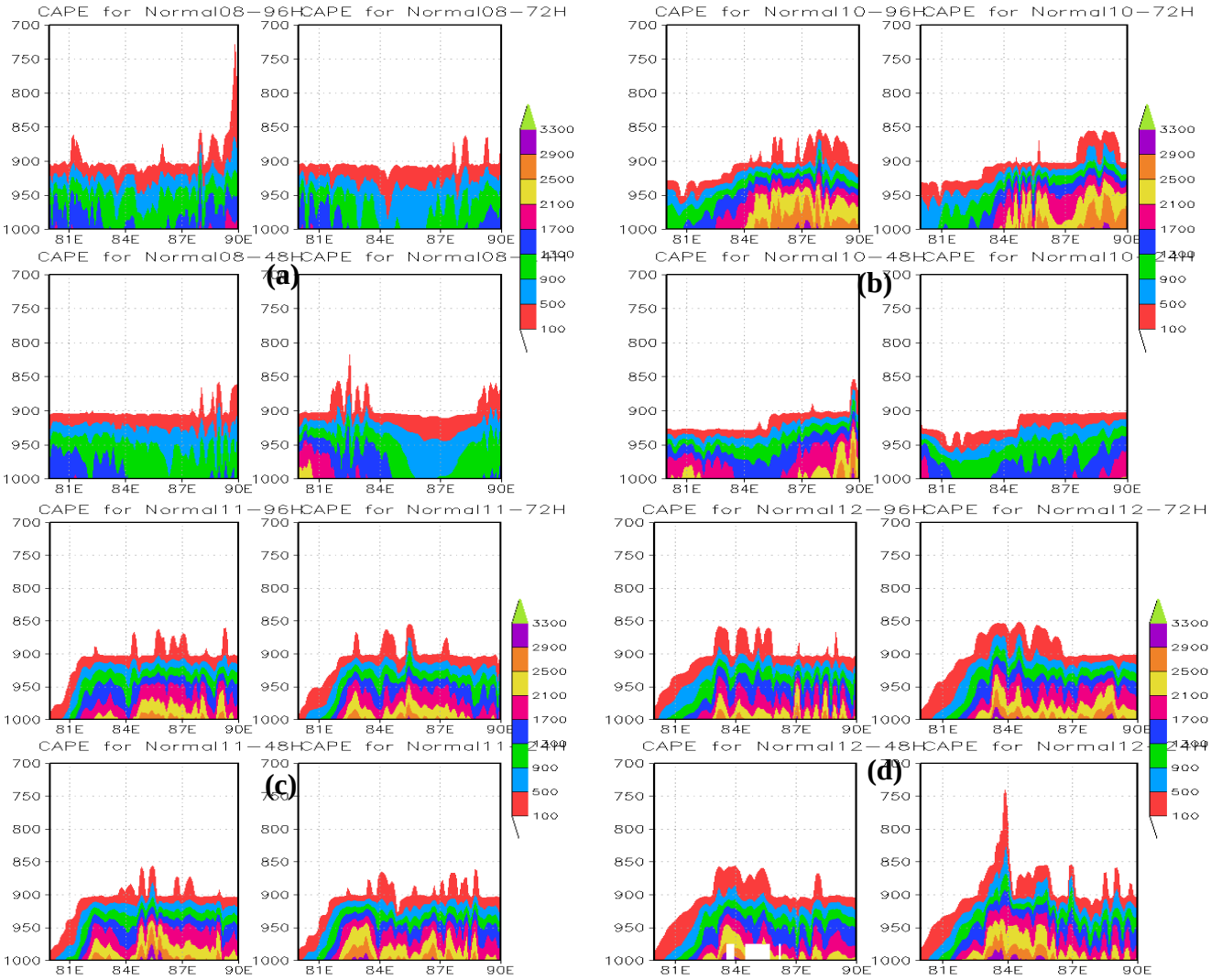


Figure 4.15 (a-d): The vertical distribution of convective available potential energy with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

Values of CAPE are almost same for cyclone and normal cases. Since cyclone has low intensity. Only few differences are found in their presence at lower and upper level. The CAPE is presence in the levels 1000-700 and 1000-900 hPa for normal and cyclone cases respectively. Again, the maximum value of CAPE is 3150 and 3450 J/Kg for normal and cyclones cases respectively.

To test the formation/intensification as cyclonic storm, the vertical distribution of CAPE for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.15 (i)

at time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009 and 03 UTC on 11 May 2013 respectively.

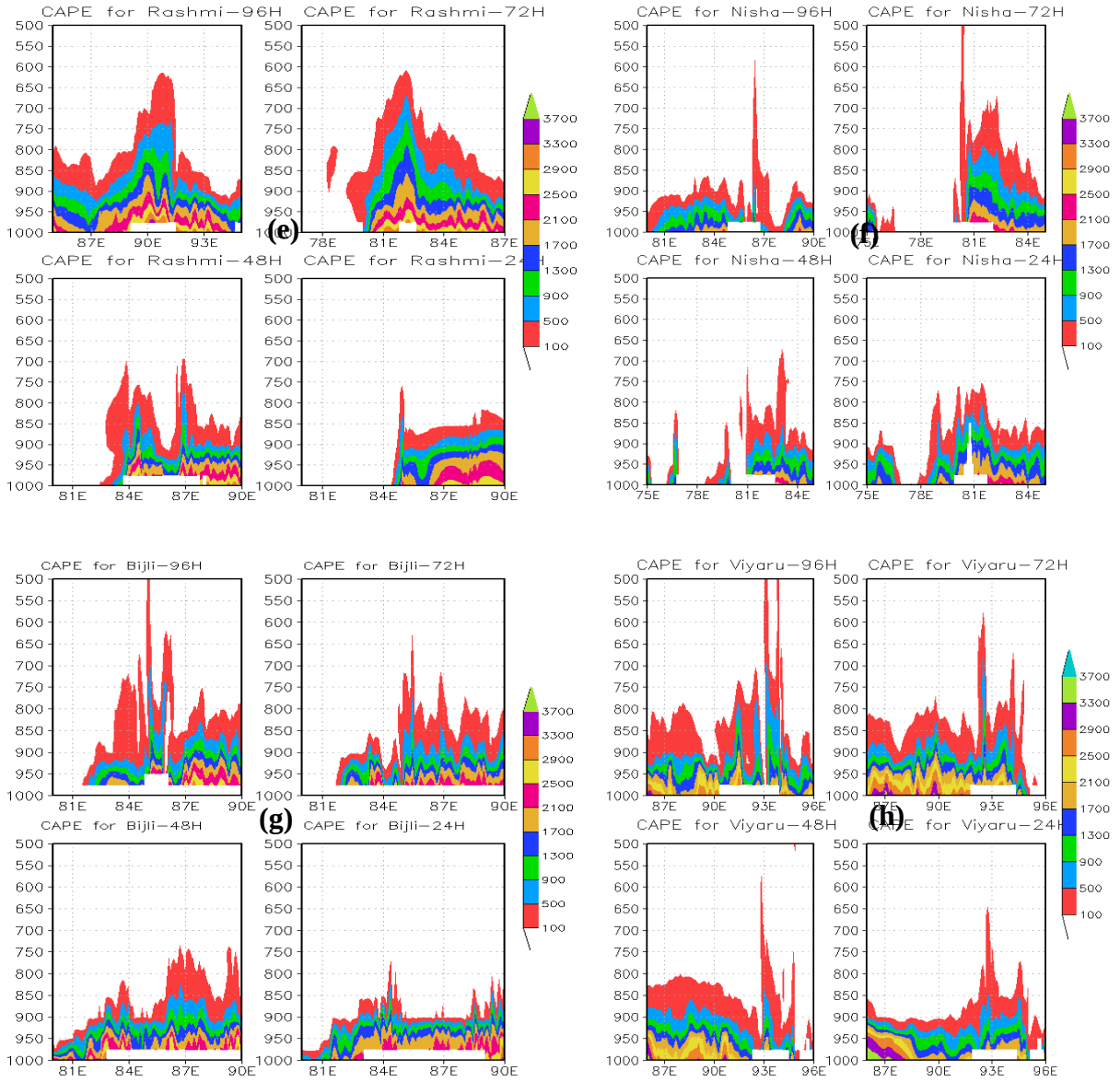


Figure 4.15 (e-h): The vertical distribution of convective available potential energy with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

These are the observed time of formation as cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013, CAPE are derived for the forecast hours 24 hours through the centre (20.5° N, 85-95° E), (10.5° N, 75-85° E), (13.5° N, 80-90 °E) and (7.5° N, 85-95 °E) respectively.

Ranges of the Maximum CAPE are 2850, 2250, 3150 and 3150 J/Kg lies at 1000-950 hPa for 24 hours forecast time for all cyclones. CAPE values 450 J/Kg or more lies from surface to upper level 900 hPa for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 24 forecast time. These values up to higher level are considered as the favorable situation for the formation of cyclonic storm. It is noted that CAPE values is necessary for the formation but not intensification.

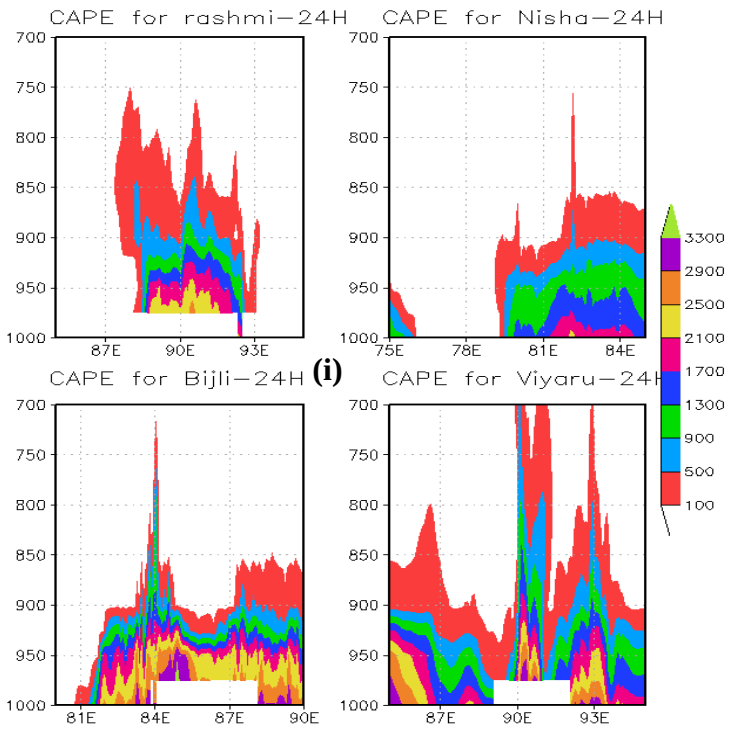


Figure 4.15 (i): The vertical distribution of Convective Available Potential Energy with the forecast time for 4 cyclones.

4.3.5 Convective Inhibition (CIN)

Time variation of The Convective Inhibition (CIN) in case of Normal-2008, Normal-2010, Normal-2011 and Normal-2012 for the forecast hours 96, 72, 48 and 24 hours shown in Figure 4.16 (a-d) have a gradually decreasing tendency with little bit oscillating pattern and Ranges of the highest CIN values are (150-600, 170-570, 190-620 and 260-510), (240-680, 230-660, 260-600 and 310-630), (100-310, 90-280, 120-270 and 100-230) and (50-350, 70-310, 90-350 and 130-340) J/Kg respectively.

Ranges of the values for highest CIN values Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are 150-620, 230-680, 90-310 and 50-350 J/Kg respectively. The Ranges of highest CIN is bigger and its do not indicate the formation and intensification of depression.

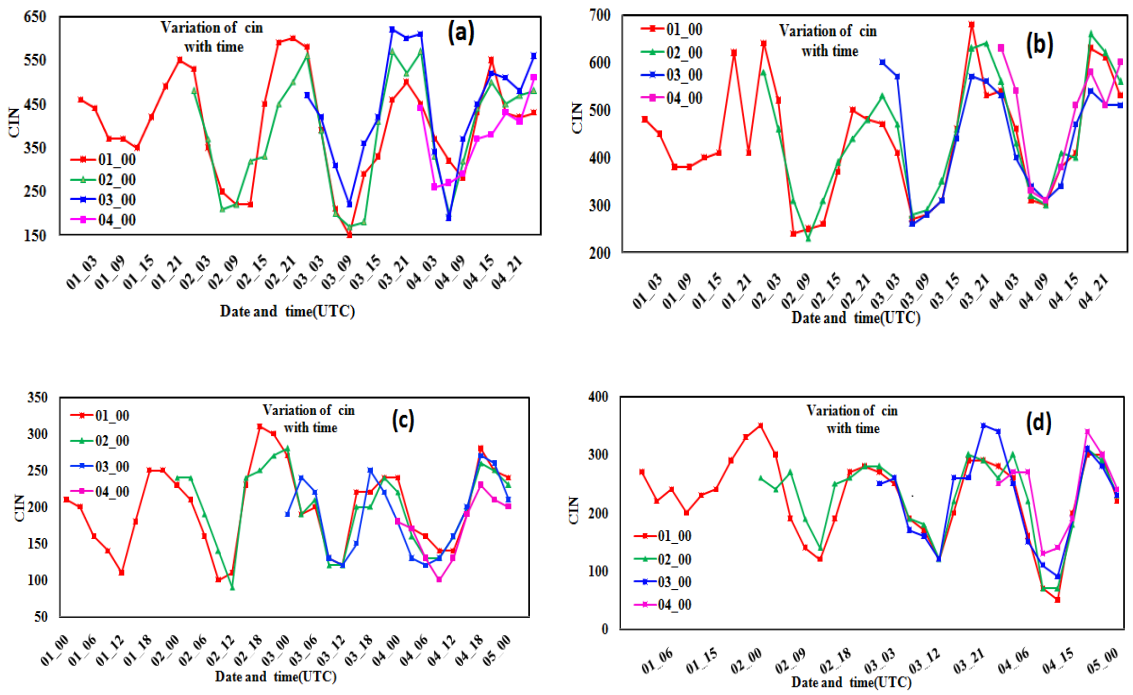


Figure 4.16 (a-d): Variation of model simulated convective inhibition of Normal-2008, Normal-2010, Normal-2011 and Normal-2012 with time.

Time variation of CIN in case of the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 for the forecast hours 96, 72, 48 and 24 hours shown in Figure 4.16(e-h) have a oscillating pattern and Ranges of the lowest values of CIN are (130-250, 90-270 , 100-260 and 70-220), (100-200, 90-190,90-200 and 90-200), (170-420, 170-380, 200-440 and 190-430) and (190-430, 150-420, 140-430 and 170-450) J/kg respectively.

Finally Ranges of the lowest values of CIN for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 70-270, 90-200,170-440 and 140-450 J/kg respectively. The Ranges of lowest CIN is larger which does not confirm for the formation and intensification of low pressure system. The formation of depressions is responsible for other factors related to formation.

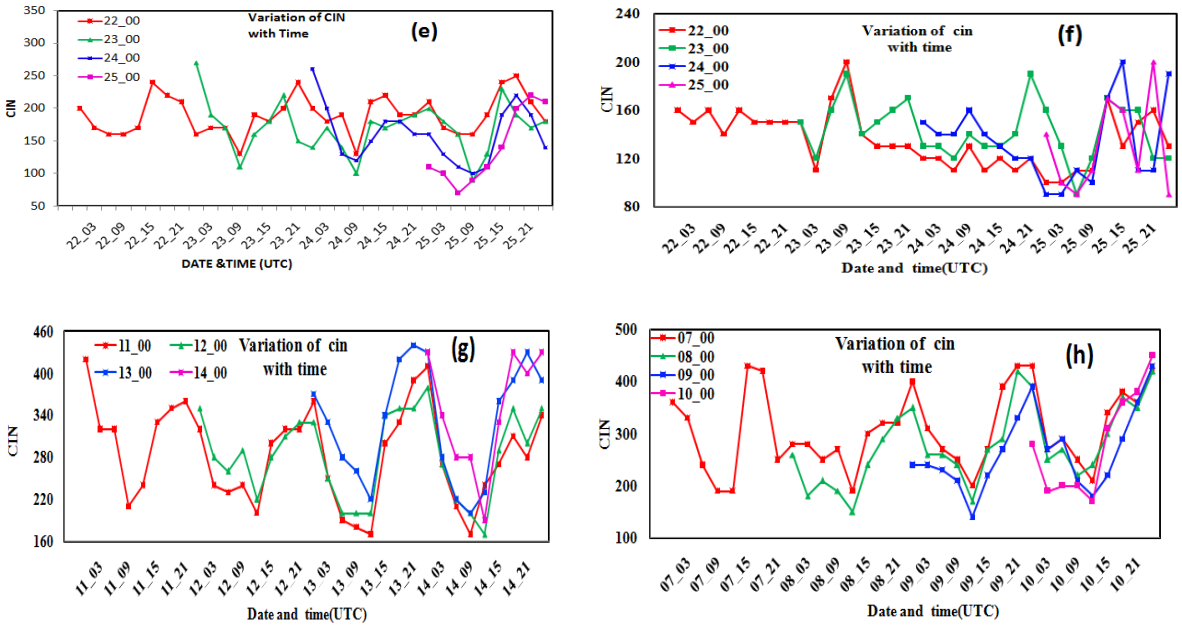


Figure 4.16 (e-h): Variation of observed and model simulated convective inhibition of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

To test the formation/intensification as cyclonic storm, model is run for further 24 hours using initial conditions 00 UTC on 26 October 2008, 00 UTC on 26 November 2008, 00 UTC on 15 April 2009 and 00 UTC on 11 May 2013 for the TCs Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 respectively and model simulated time variation CIN of TCs along with observed value are shown in Figure 4.16 (i). All cases have an oscillating pattern. Ranges of lowest values of CIN for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 66-120, 60-120, 120-320 and 100-200 J/kg respectively. The Ranges of lowest CIN is larger which does not confirm for the formation and intensification of low pressure system. The formation of cyclonic storm is responsible for other factors related to intensification.

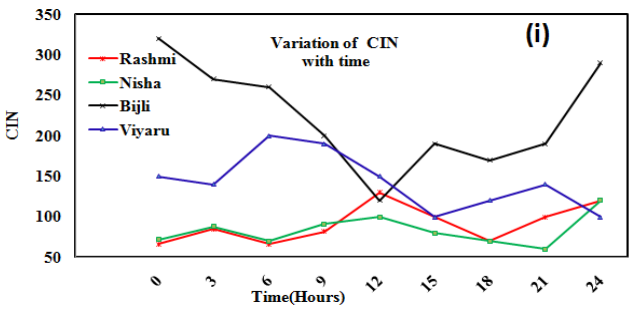


Figure 4.16 (i): Variation of observed and model simulated convective inhibition of TC Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with time.

The Vertical distribution of CIN at 00 UTC on 5 April 2008, 00 UTC on 5 April 2010, 00 UTC on 5 August 2011 and 00 UTC on 5 August 2012 normal cases for 96, 72. 48 and 24 hours are plotted and shown in Figure 4.17 (a-d) through the center (12N°, 85°E). Maximum CIN (70-80, 60-70, 10-20 and 20-30), (145-160,120-130,105-120 and 50-65), (50-65,50-65,65-75 and 65-75) and (65-90,65-90,90-100 and 125-135) J/kg lies at900 hPa for 96, 72, 48 and 24 forecast hours respectively. The CIN value is absent above 900 hPa. This value of CIN at the lower level is not considered as the favorable situation for the formation of depression.

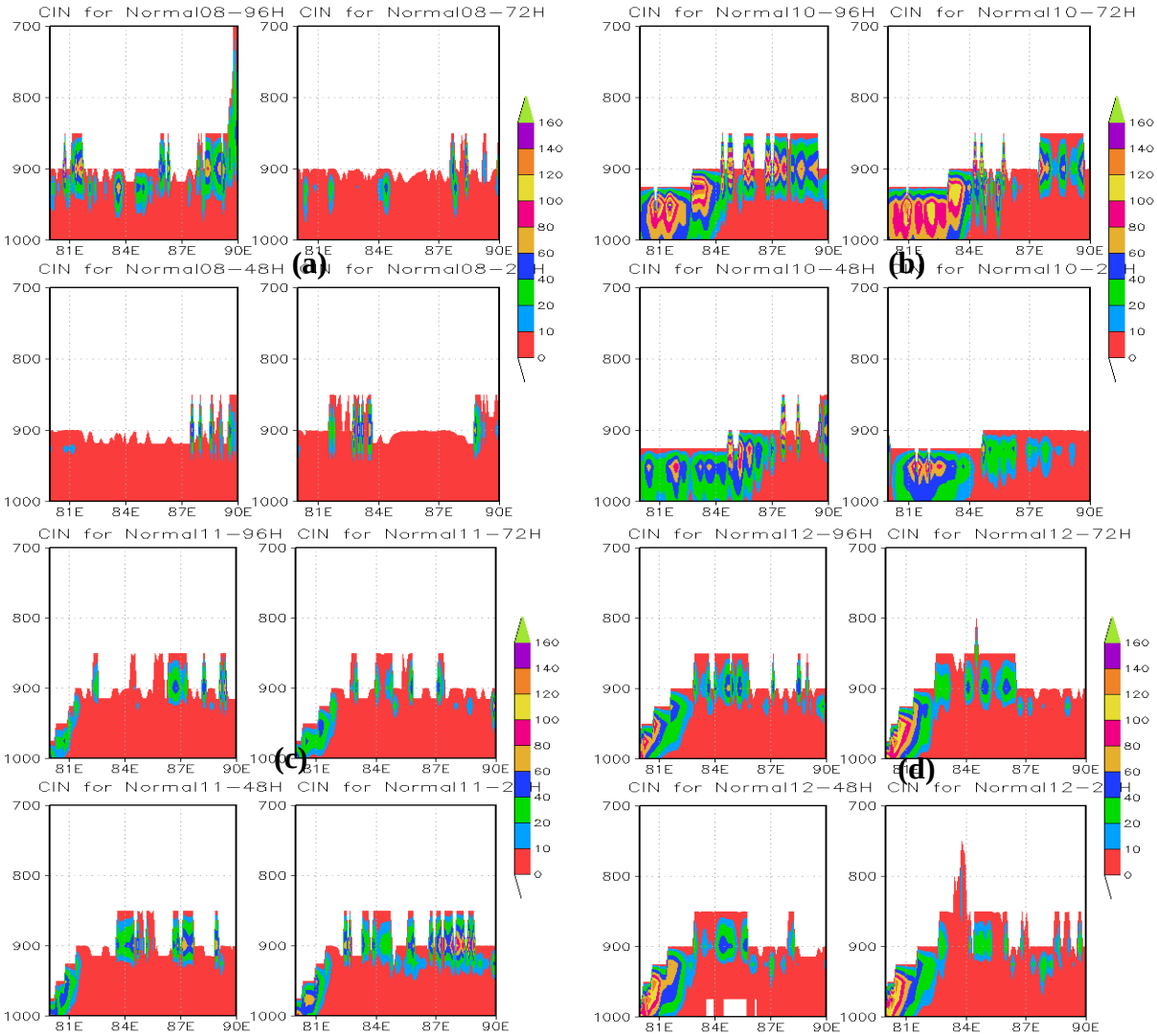


Figure 4.17 (a-d): The vertical distribution of convective inhibition with the forecast hours 96, 72, 48 and 24 hours for 4 normal cases.

The Vertical distribution of CIN at 03 UTC on 25 October 2008,09 UTC on 25 November 2008, 09 UTC on 14April 2009 and 09 UTC on 10May 2013 for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 96, 72. 48 and 24 hours are shown in Figure 4.17 (f-i)through the center{(17.5 °N, 90.5 °E) (14.22 °N, 85 °E), (16.5 °N, 83.8 °E) and

(18.0 °N, 82.8 °E)},{(10.5 °N, 85.3 °E) (8.5 °N, 79.8 °E), (9.0 °N, 80.8 °E) and (7.5 °N, 83.0 °E)}, {(14.5 °N, 85.9 °E) (11.0 °N, 87 °E), (10.5 °N, 82.0 °E) and (12.0°N, 82.5 °E)} and {(6.0 °N, 94.0 °E) (5.5 °N, 92.5 °E), (5.5 °N, 93.0 °E) and (5.5 °N, 92.2 °E)} respectively.

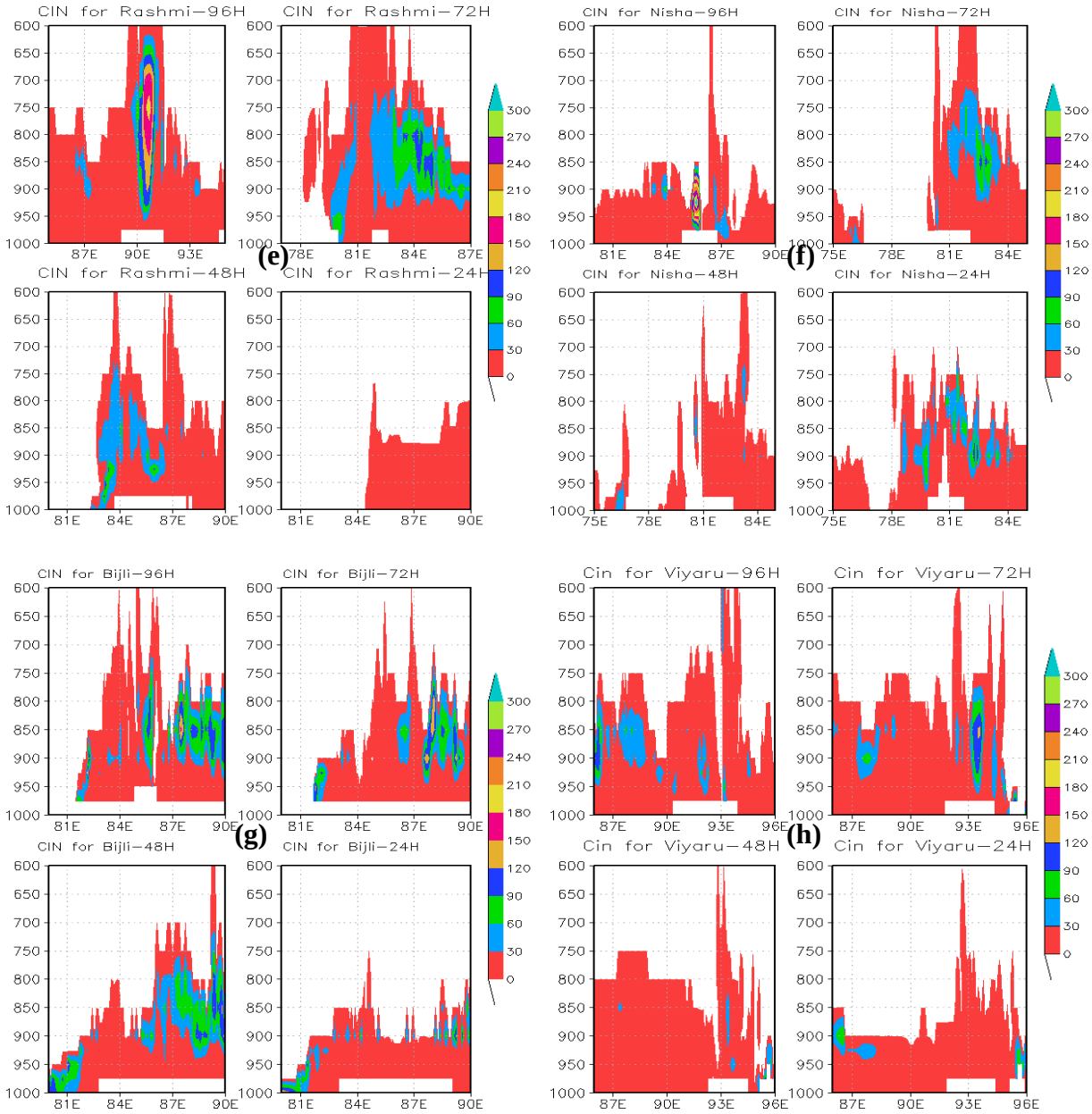


Figure 4.17 (e-h): The vertical distribution of convective inhibition with the forecast hours 96, 72, 48 and 24 hours for 4 cyclones.

Above mentioned time are the observed time of formation of depression of cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. Maximum CIN are (175, 110, 70 and 5), (295, 120, 60 and 90), (145, 110, 110 and 95) and (105, 105, 75 and 105)J/Kg and lies at (750, 800, 900 and 900), (900, 850, 750and 850), (850, 900, 900 and 900) and (900,800, 900

and 900) hPa for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 96, 72, 48 and 24 hours. Again, At the higher levels, CIN are (100, 10, 30 and 0.5), (30, 10, 10 and 10), (20, 10, 30 and 20) and (10, 15, 15 and 15) J/kg and lies at levels (650, 650, 650, 750), (800, 650, 650, 750), (750, 700, 700, 800) and (400, 800, 800, 850) hPa for 96, 72. 48 and 24 forecast hours respectively. At the lower levels, CIN are (20, 10, 20 and 0.5), (30, 20, 10 and 10), (20, 20, 10 and 20) and (10, 10, 25 and 20) J/Kg and lies at levels 975, 975, 950 and 950 hPa for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 96, 72, 48 and 24 hours respectively. These lower values of CIN at lower level are consider as the favorable situation for the formation of depression. The highest maximum CIN value shows for Normal causes while lowest maximum value indicates cyclone.

As the cyclone intensity is low, the CIN values for normal and cyclone cases are close to each other. But there is a difference of their existence in different levels. CIN values lies between levels 1000-600 and 1000-850 hPa for cyclone and normal cases respectively.

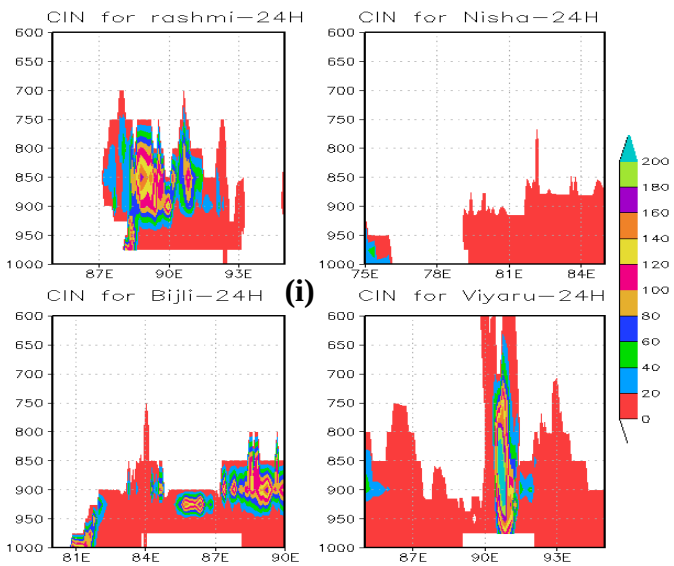


Figure 4.17 (i): The vertical distribution of convective inhibition with the forecast time for 4 cyclones.

To test the formation/intensification as cyclonic storm, the spatial distribution of CIN for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are shown in Figure 4.17 (i) at time 12 UTC on 26 October 2008, 03 UTC on 26 November 2008, 12 UTC on 15 April 2009 and 03 UTC on 11 May 2013 respectively. These are the observed time of formation as cyclonic storm of cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013. For cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 CIN are derived for the

forecast hours 24 hours with the area (20.5° N, 85-95° E), (10.5° N, 75-85° E), (13.5° N, 80-90 °E) and (7.5° N, 85-95 °E) respectively. Ranges of the Maximum CIN values for Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 160-180, 40-60, 160-180 and 200 J/Kg and lies at 850, 975, 900 and 950-800 hPa for the cyclones Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 with 24 hours forecast respectively. At the lower levels, the values are around 20 J/Kg in most of the area. These lower values of CIN at lower level are consider as the favorable situation for the formation of cyclonic storm.

CHAPTER V

Conclusions

On the basis of the present study, the following conclusions can be drawn:

- Model simulated average value of WS in cases of cyclones is more than that of non cyclone cases. Again, circular shape is observed in all cases of cyclones. Difference of values in WS between cyclone and normal is less because cyclone has weak intensity. Model simulates the depression and cyclonic stage with more and less intensity almost for all cyclones.
- Using four normal cases, model simulated positive VWS exist with negative value in the area with larger latitude and in almost cases vertical wind shear is found at earth surface for normal cases. So, expression does not form. The value of VWS for cyclone is relatively greater than that of normal cases that causes depression and intensify to cyclonic storm.
- The values of HW with cyclone are higher whereas for normal it is very poor. The maximum of HW for normal and cyclone lies in the levels between 300 to 100 hPa and 1000-400 hPa respectively. The value of VHW for cyclone is higher than that of normal cases. These higher values cause depression and intensify to cyclonic storm.
- Almost VVW value is negative for normal causes. On the hand, the value of VVW for cyclone is positive / negative. The value of VVW for cyclone is relatively greater than that of normal causes. Model could simulate the formation of the depression and intensify to cyclonic storm for cyclone cases for their higher value.
- Values of RV for Normal-2008, Normal-2010, Normal-2011 and Normal-2012 are 8-240×10^{-5},13-180×10^{-5},12-110×10^{-5} and 14-120×10^{-5} s^{-1} respectively and relative vorticity (RV) for cyclone Rashmi-2008, Nisha-2008, Bijli-2009 and Viyaru-2013 are 13-210×10^{-5}, 11-260×10^{-5} ·9-150×$10^{-5}$and 10-180×10^{-5} s^{-1} respectively . So, Highest value of RV at the low level for with cyclone that's liable to cyclone formation and intensifies to cyclonic storm.
- The values of RV for normal and cyclone cases are between -22.5 to 25 ×10^{-5} and -75 to 315×10^{-5} s^{-1} respectively. For normal cases the value is found at upper level and for

cyclone the value is found at lower level. The highest value of relative vorticity is observed between 300 to 100 and 1000 to 400 hPa for normal and cyclone cases respectively. Again, the value of relative vorticity is higher for cyclone than that of normal causes. Higher value of RV at the lower level is considered as the favorable situation for the formation of depression and intensifies to cyclonic storm.

- SST is found almost more than 26.5 °C in The BoB in all of the cyclones cases which is favorable for cyclone formation. These values are favorable condition for the cyclone intensification and these are more than the values obtained from normal cases. It is understood that SST more than 26.5°C is a necessary condition for cyclone formation but not sufficient for condition for cyclone formation. Finally, it is observed that the average value of SST for cyclone is higher than that of normal cases. For all cyclone and normal cases SST is highest at sea surface and the lowest value of SST at sea surface is 26.5°C.
- MSLP shows a decreasing trend during cyclone formation. Model predicts the formation of events with different intensity. Model also intensifies the events with different intensity. The value of SLP is lower for cyclone than the normal cases. The lowest average value of SLP is (1012-994) and (1010-940) hPa for Normal cases and cyclone respectively. The formation and intensification of cyclone is understood from the change of pressure i.e. number of closed circle of pressure.
- As the cyclone intensity is low, relative humidity's value for normal and cyclones are almost same. But a few differences are found in their existence up to higher levels with large area. The value of relative humidity is observed between 90-100% for both cyclonic and normal case. The highest humidity value is observed at 1000-900 hPa for normal case and 1000-300 hPa for cyclone case. So, high relative humidity up to higher level with large area is favorable for the formation of depression and intensifies up to cyclonic storm.
- The highest maximum CAPE value is observed for cyclone while lowest maximum value indicates Normal cases. As the cyclone intensity is low, the CAPE value is close between Normal cases and cyclone. But there is a difference of levels for the existence of CAPE between Normal and cyclone cases. The levels values for cyclone and Normal cases are 1000-650 and 1000-900 hPa respectively.

- The highest maximum CIN value is observed for Normal cases while lowest maximum value indicates cyclone cases. As the cyclone intensity is low, the CIN value is close to between Normal cases and cyclone. But there is a difference of levels between Normal cases and cyclone. The levels values for cyclone and Normal cases are 1000-600 and 1000-850 hPa respectively.

Finally, the followings may be noted

- Circular shape of wind is observed in cyclone cases without exception.
- Maximum value of VWS and VVW are greater for cyclone cases than normal cases.
- Maximum value of VHW and RV are observed in surface to 400 hPa level for cyclone and 300 to 100 hPa for without cyclone cases.
- No significant different in SST for both cyclone and non cyclone cases.
- Close circle of SLP are observed in cyclone cases.
- Maximum value of RH, CAPE and CIN are observed from surface to upper level (1000-300, 1000-700, 1000-600 hPa) for cyclone cases compared to non cyclone cases (1000-900, 1000-900, 1000-850 hPa).

So, it may be concluded that WRF model could simulate the formation of low intensity of TC up to cyclonic storm even with 96 hours ahead of time. The study may be useful for forecasting of low intensity cyclones.

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