Tropical Cyclone : Intensification and movement

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INDIA METEOROLOGICAL DEPARTMENT

Presentation layout

- ❖ Introduction
- ❖ Cyclone Monitoring
    - ❖ Genesis
    - ❖ Location
    - ❖ Intensity
    - ❖ Movement
- ❖ Conclusions

Cyclone Monitoring, Forecasting and Warning Services

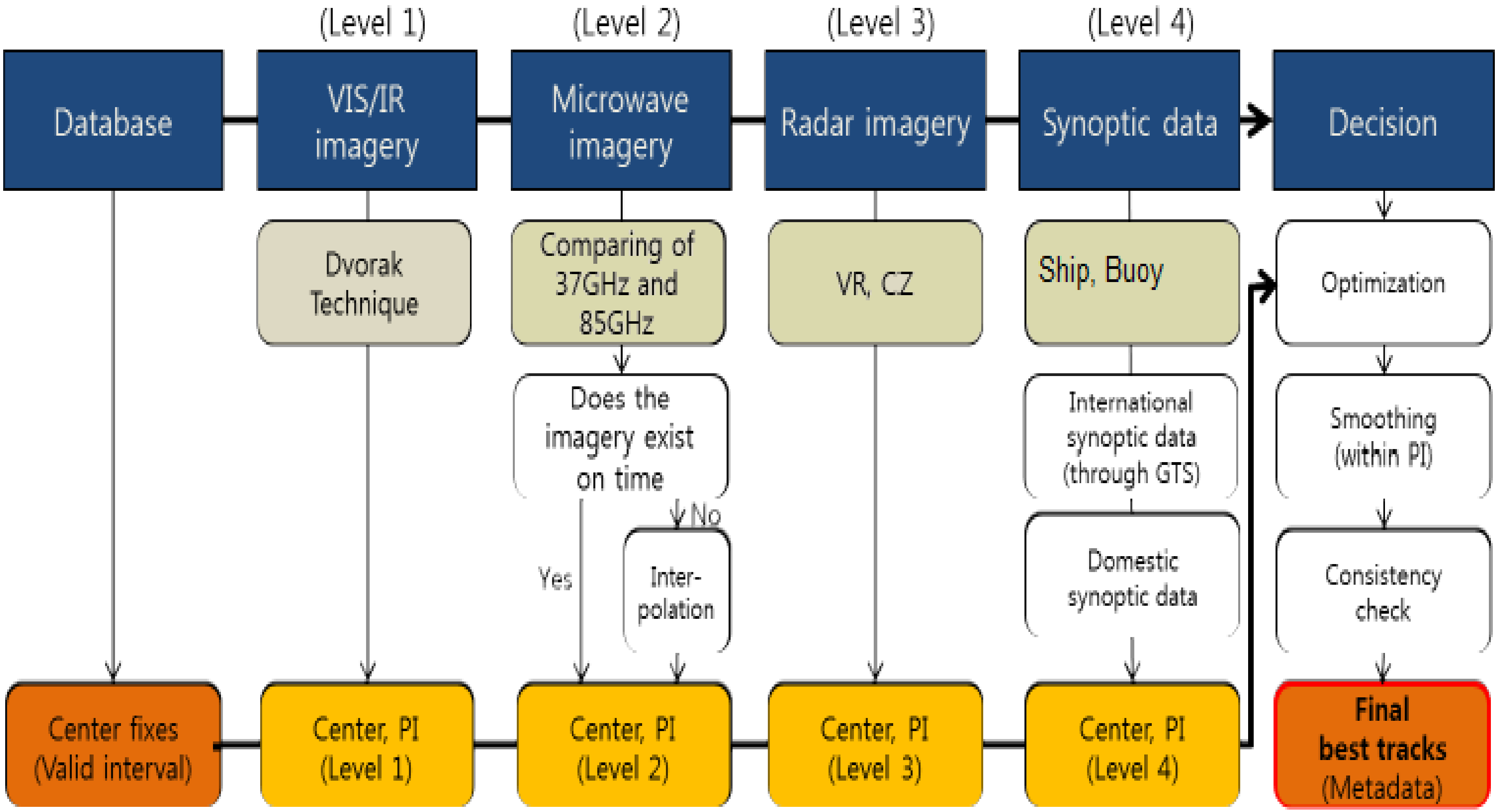
- ❖ **Cyclone Monitoring**
  - ❖ **Genesis, Location, Intensity (wind, pressure), Structure, size**
  - ❖ **Adverse weather (rainfall, storm surge, inundation)**
- ❖ **Cyclone Prediction**
  - ❖ **Location/Track, Intensity, structure/size**
  - ❖ **Adverse weather (Heavy rain, Gale wind, storm Surge, inundation, sea state)**
- ❖ **Warning Bulletins (National/international, user and sector specific, impact based**
- ❖ **Warning dissemination (Redundancy, last mile, disaster managers, Press/media, all stake holders**

Evolution of Cyclonic disturbances Over the Indian Seas

Low pressure system	Maximum sustained winds	
Low	< 17 knots	< 31 kmph
Depression	17 – 27 kts	31 – 51 kmph
Deep Depression	28 – 33 kts	52 – 62 kmph
Cyclone	34 – 47 kts	63 – 87 kmph
Severe Cyclone	48 – 63 kts	88 – 117 kmph
Very Severe Cyclone	64 – 89 kts	118 – 166 kmph
Extremely Severe cyclone	90-119 kts	167-221 kmph
Super Cyclone	120 kts & above	222 kmph & above

System	Pressure deficit (hPa) at the centre
Low	1.0
Depression	1.0 – 3.0
Deep Depression	3.0 – 4.5
Cyclone	4.5-8.5
Severe Cyclone	8.5-15.5
Very Severe Cyclone	15.5-65.6
Super Cyclone	>65.6

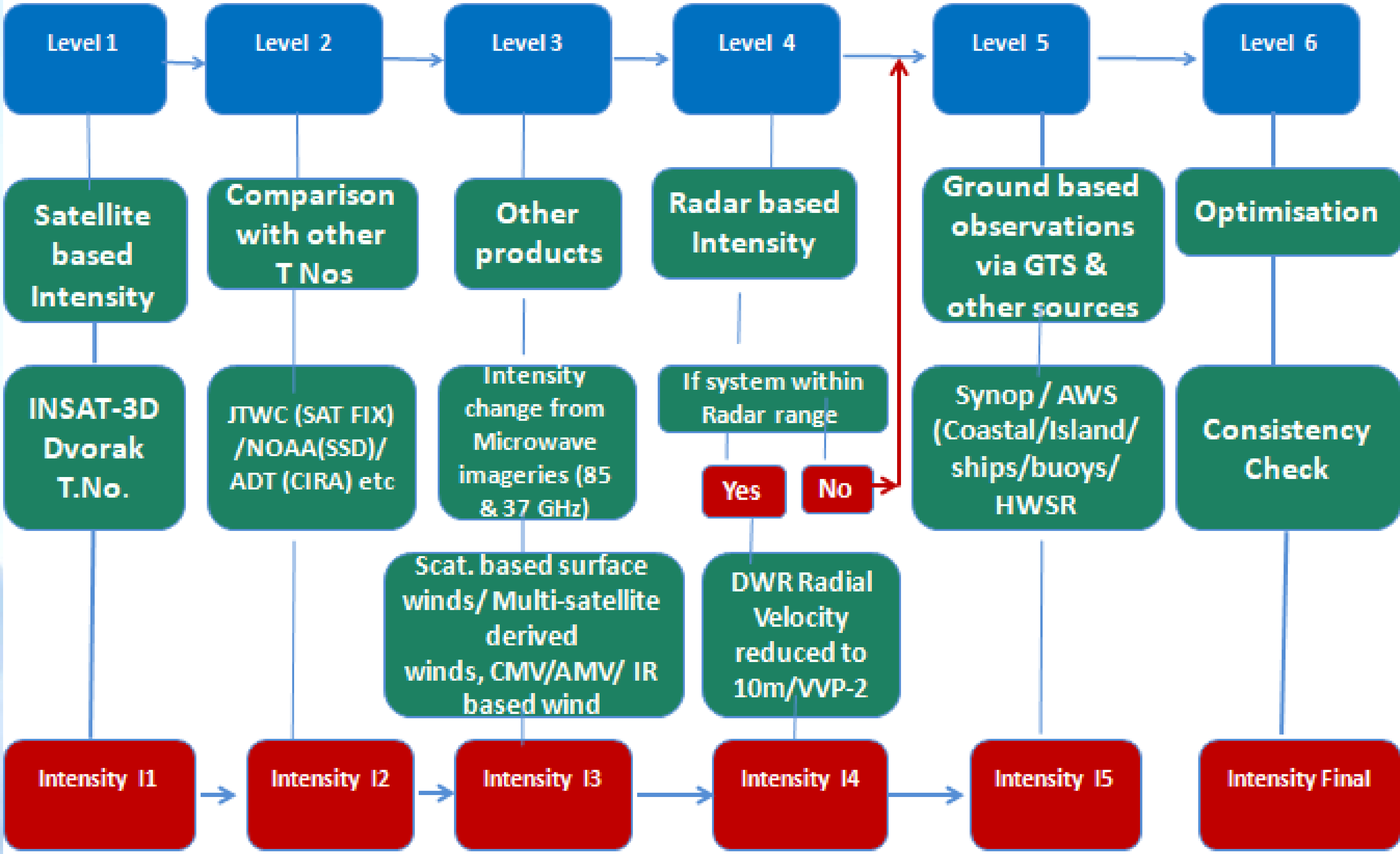
Determination of Centre



Location of Centre:

- When the system is far away from the coast and not within the radar range, satellite position gets more weight, though position is modified some times with availability of ship and buoy observations.
- When the system comes closer to the coast, radar position gets maximum preference followed by the satellite position.
- When the system is very close to coast or over the land surface, the coastal observations get the highest preference followed by radar and satellite observations.
- The average confidence level of locating the centre of the system over the NIO is about 50km.
- The landfall point and time of the TC is determined based on the available hourly coastal observationa and AWS.
- In their absence, the radar observations followed by satellite observation is used for this purpose.

Determination of Intensity



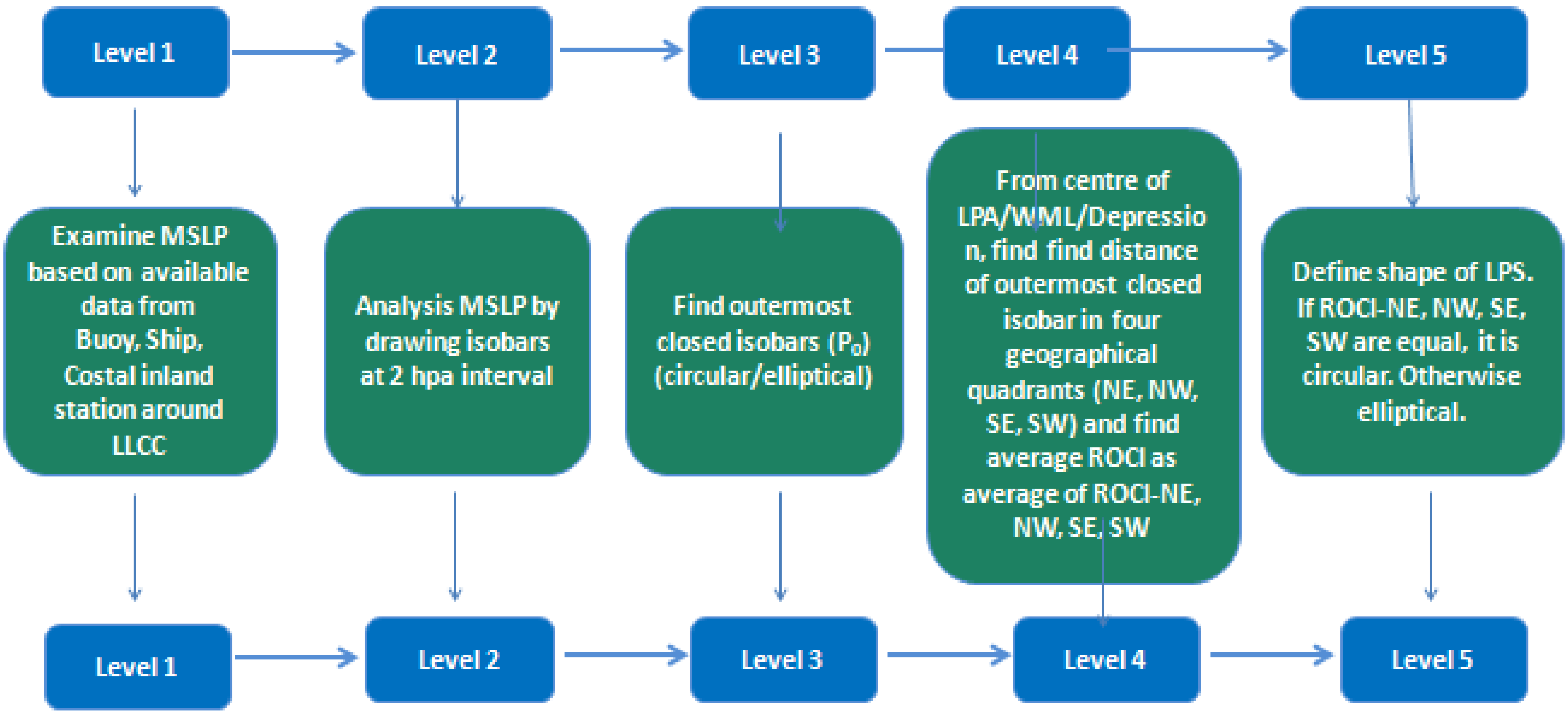
Estimated central pressure (ECP)

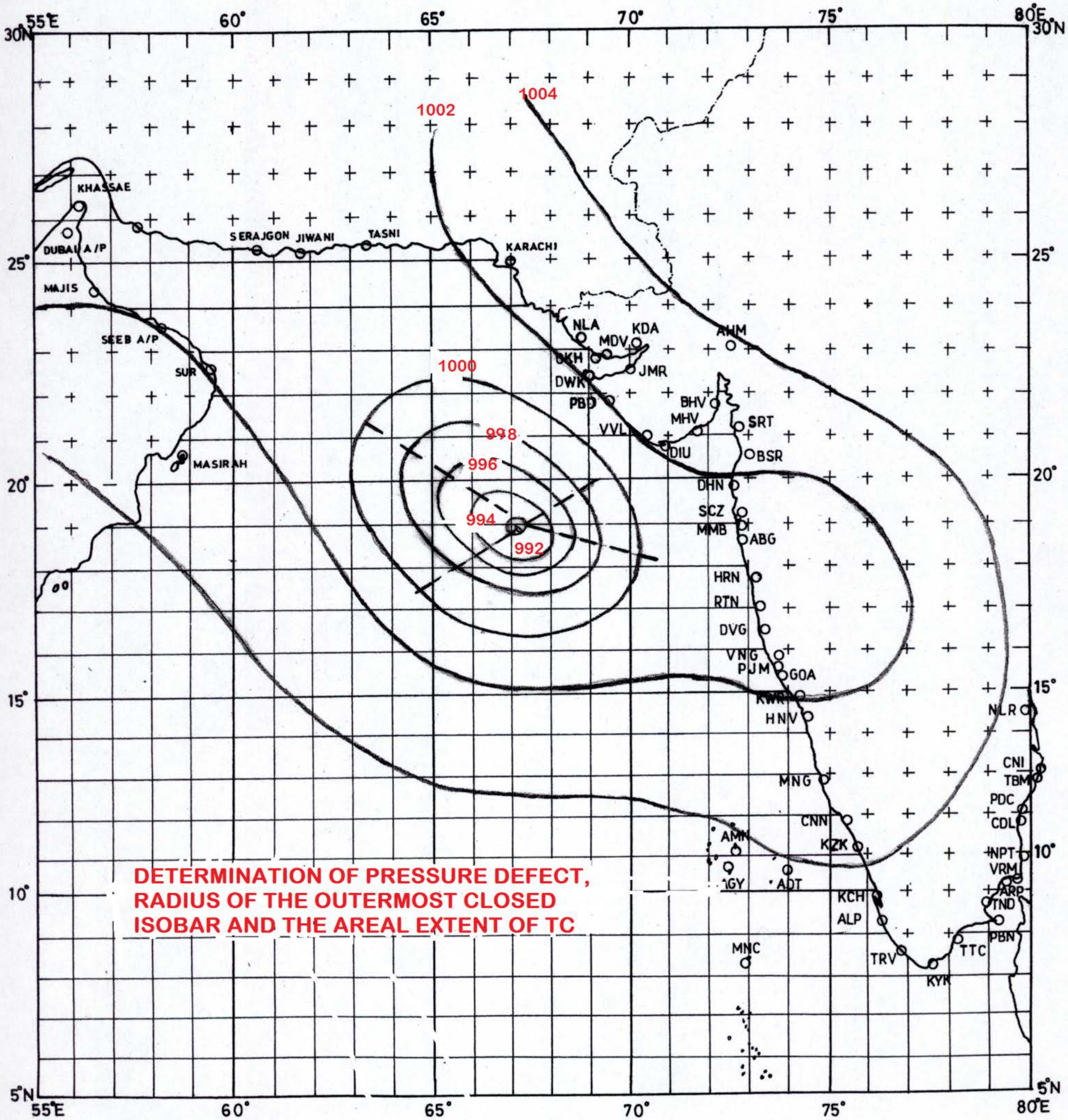
Level 1 → **Level 2** → **Level 3** → **Level 4** → **Level 5**

- **Level 1:** Examine MSLP based on available data from Buoy, Ship, Costal inland station around LLCC
- **Level 2:** Analysis MSLP by drawing isobars at 2 hpa interval
- **Level 3:** Find outermost closed isobars (P_0) (circular/elliptical)
- **Level 4:** From P_0 and ΔP Find ECP
- **Level 5:** Compare ECP with nearest buoy/ship/island/costal data to optimise ECP

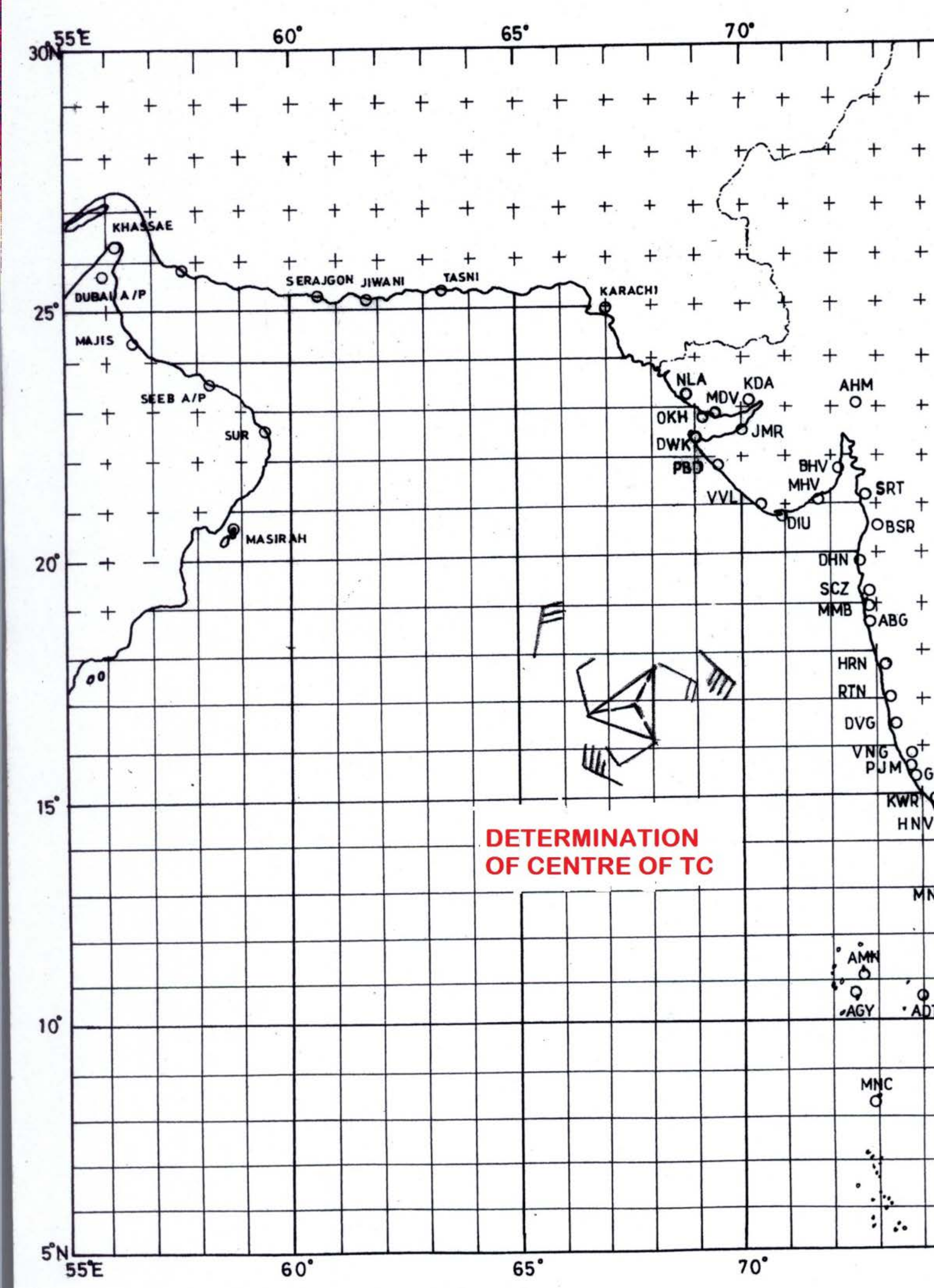
Level 1 → **Level 2** → **Level 3** → **Level 4** → **Level 5**

Shape and size (Radius of Outermost closed isobar (ROCI) of Low pressure system





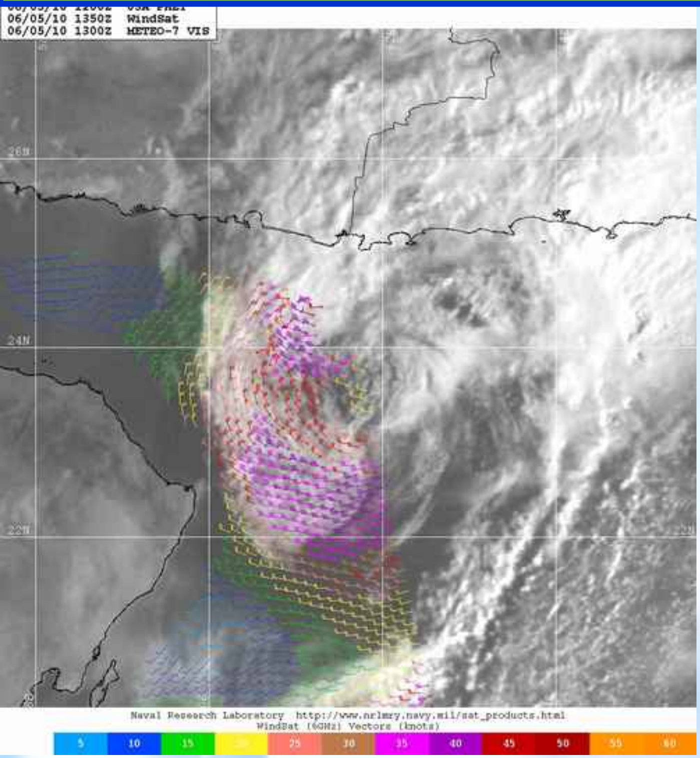
DETERMINATION OF PRESSURE DEFECT, RADIUS OF THE OUTERMOST CLOSED ISOBAR AND THE AREAL EXTENT OF TC

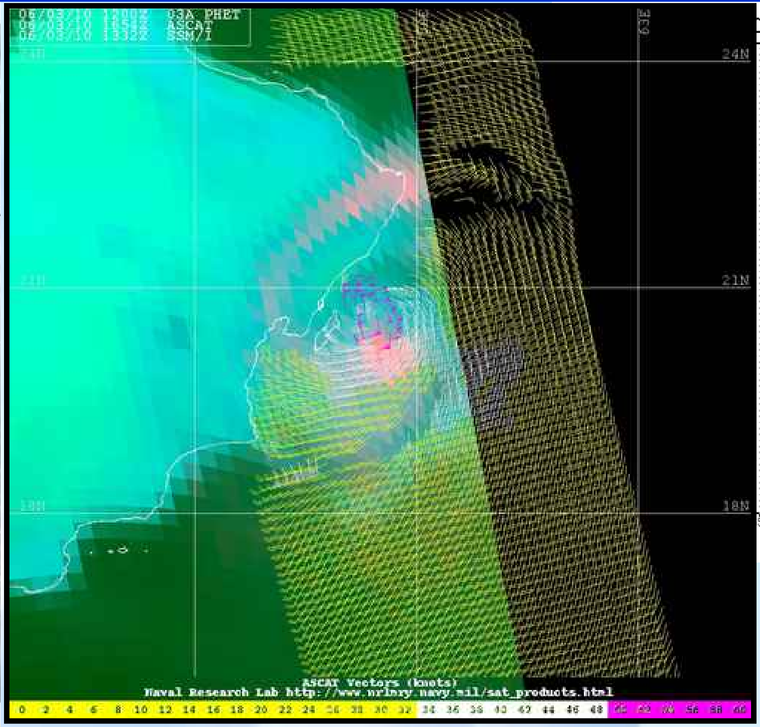


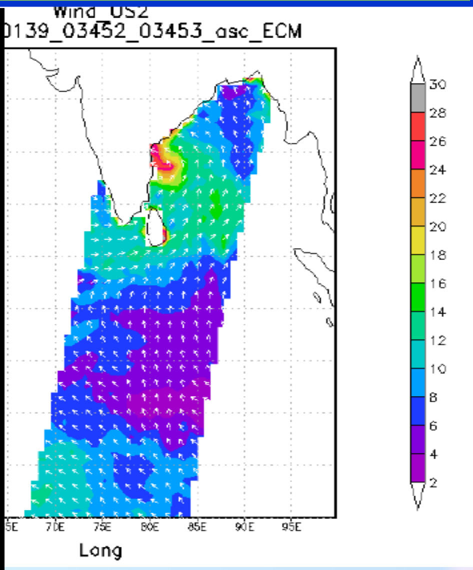
(a) Synoptic position

(Centre of the system is determined by considering the centroid of the wind distribution at the surface level. In the pressure field, the location of lowest mean sea level pressure is considered as the centre of the system.

Centre based on surface wind







Scatterometry products

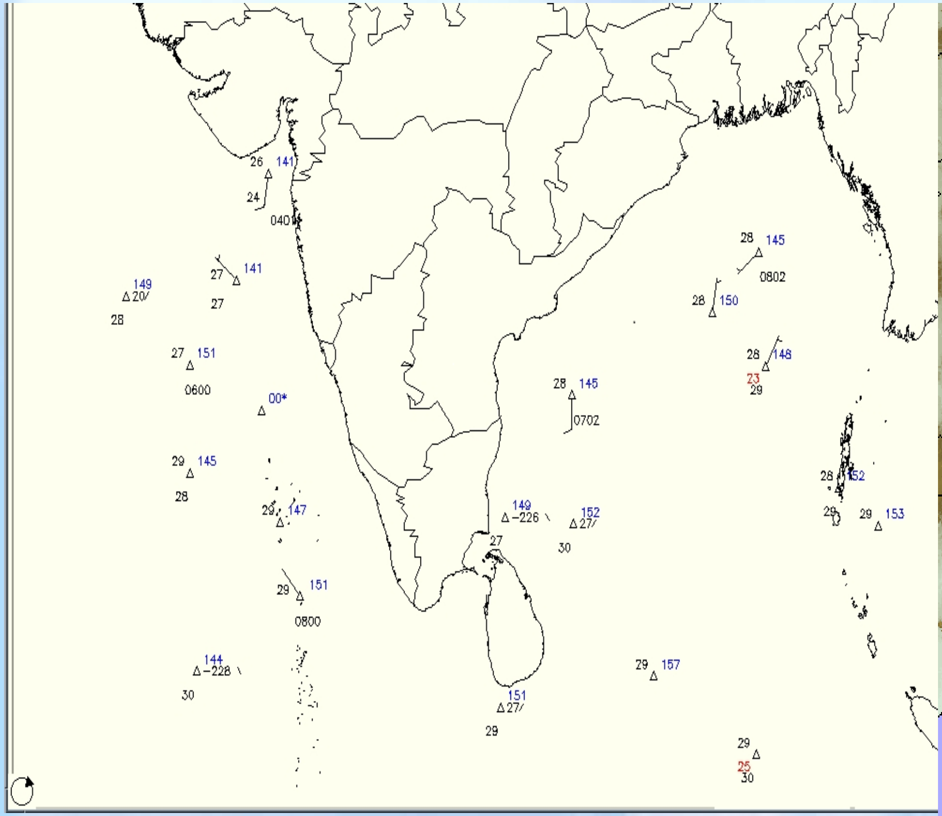
(only once/twice daily, rain contamination and unability to measure more than 50 knots, Less swath)

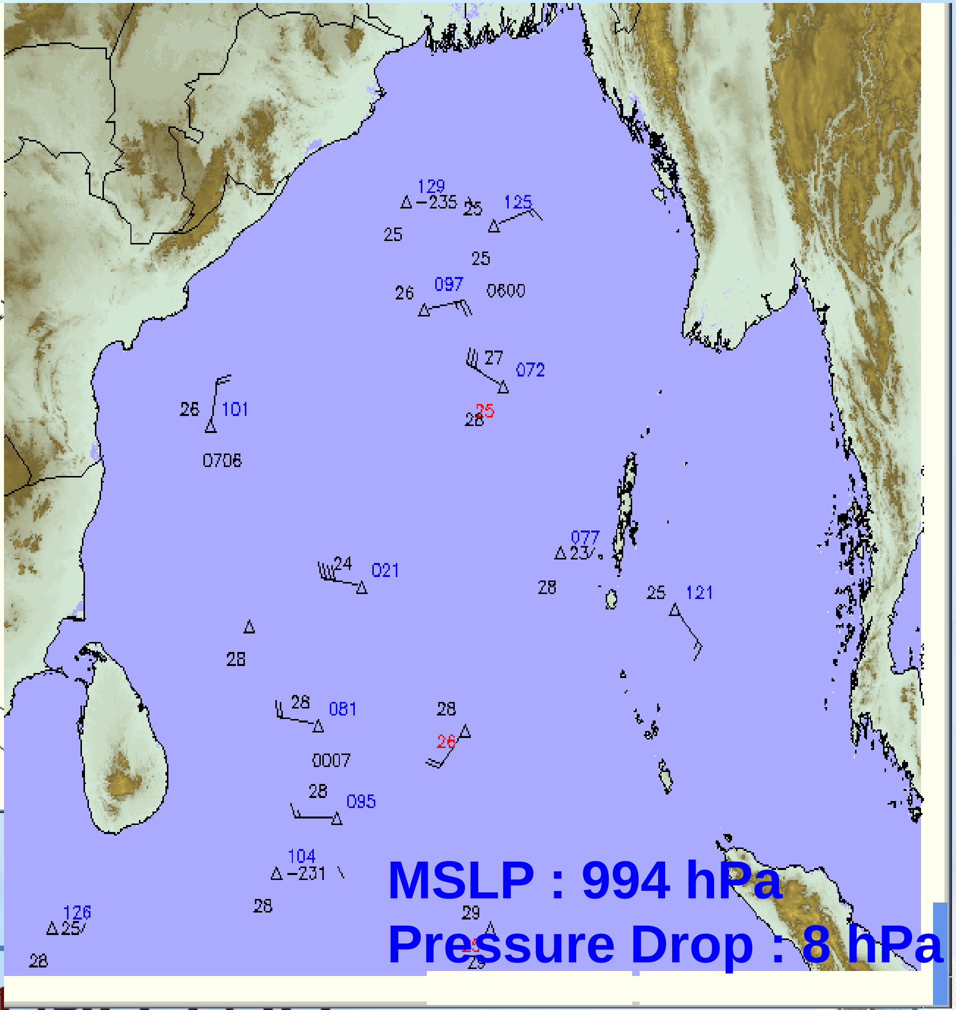
Ships

Buoys

Buoy and ships observations for MSLP and wind centre

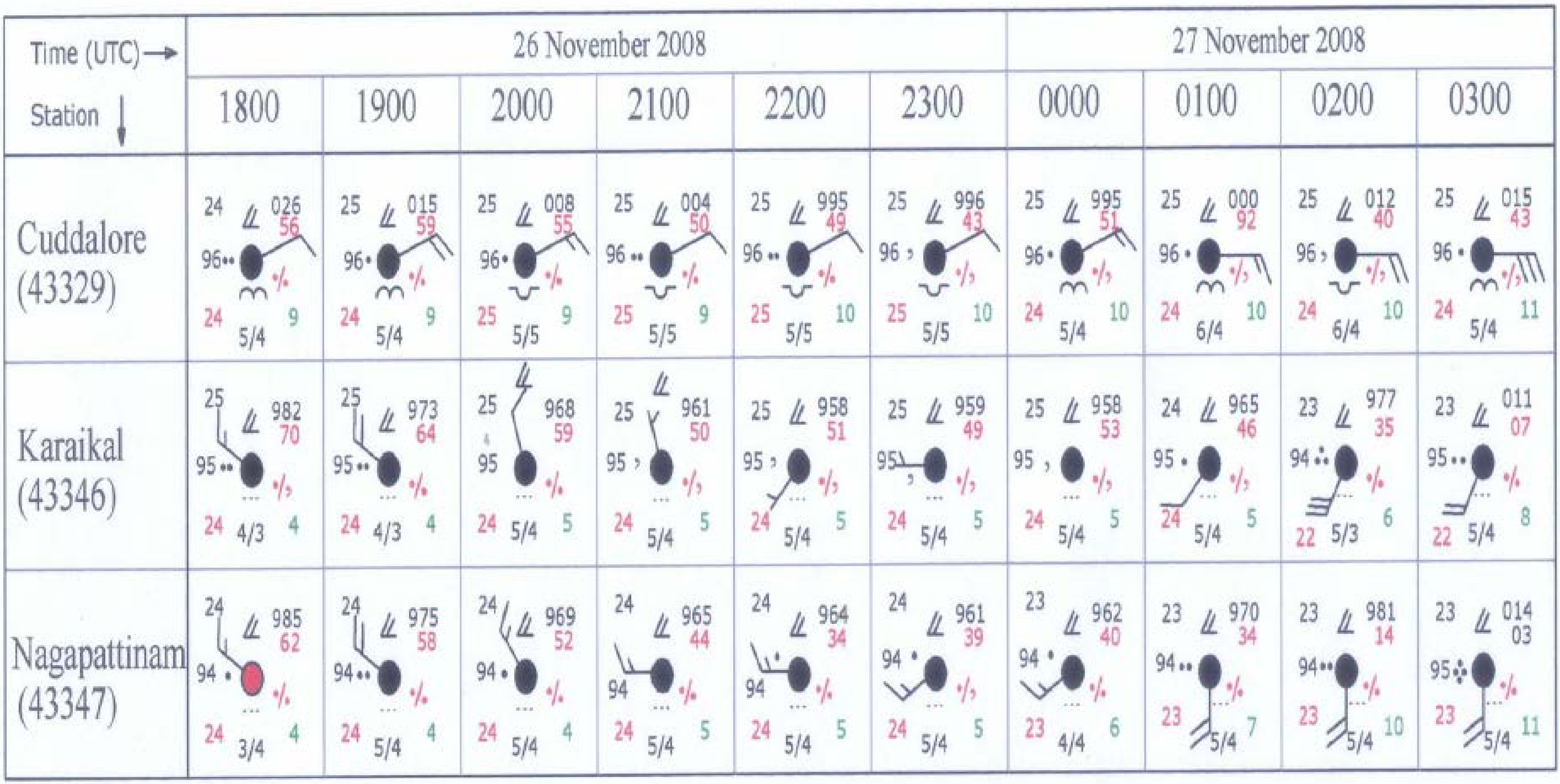
27 Dec 2011: 03UTC
CS: 12.0N/87.0E, 40Knots





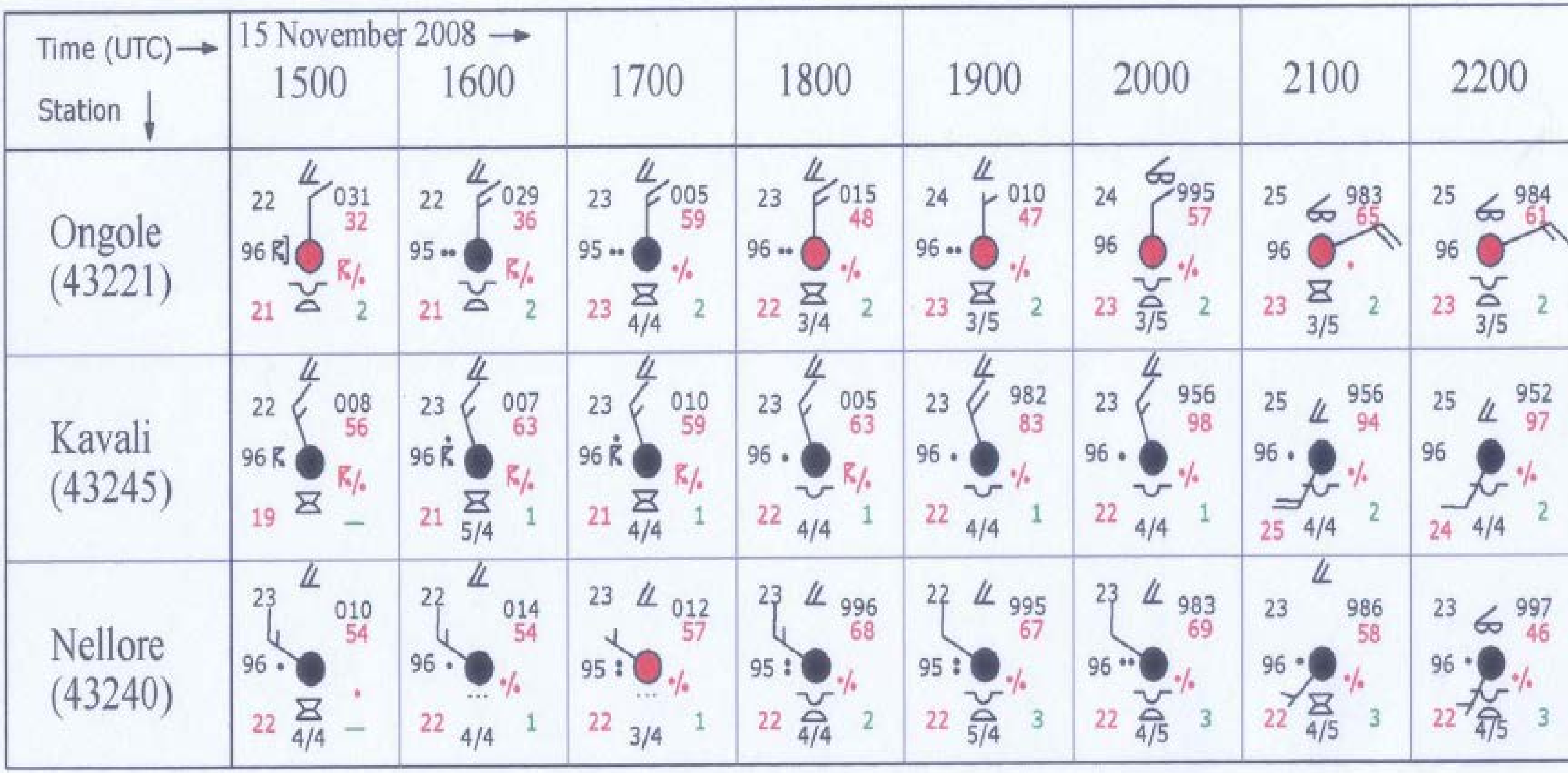
Coastal observations for MSLP and wind centre

Hourly Observations of NISHA cyclonic storm during 25-27 November 2008

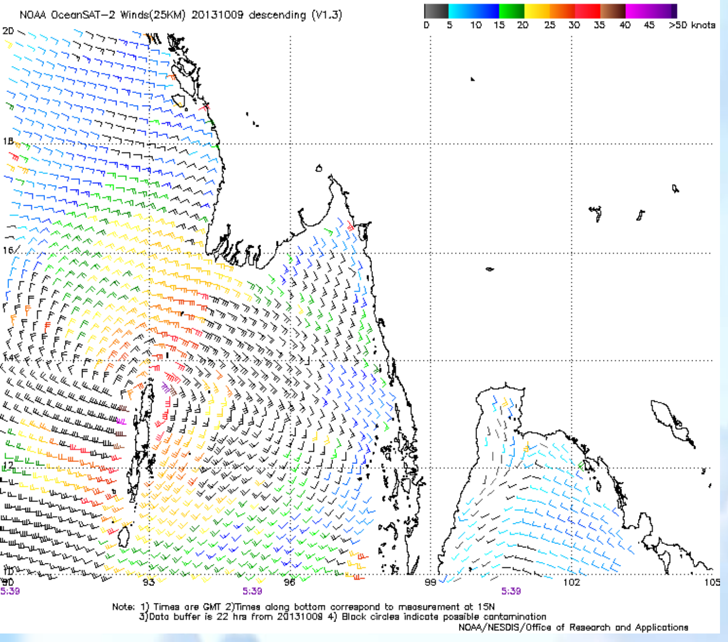


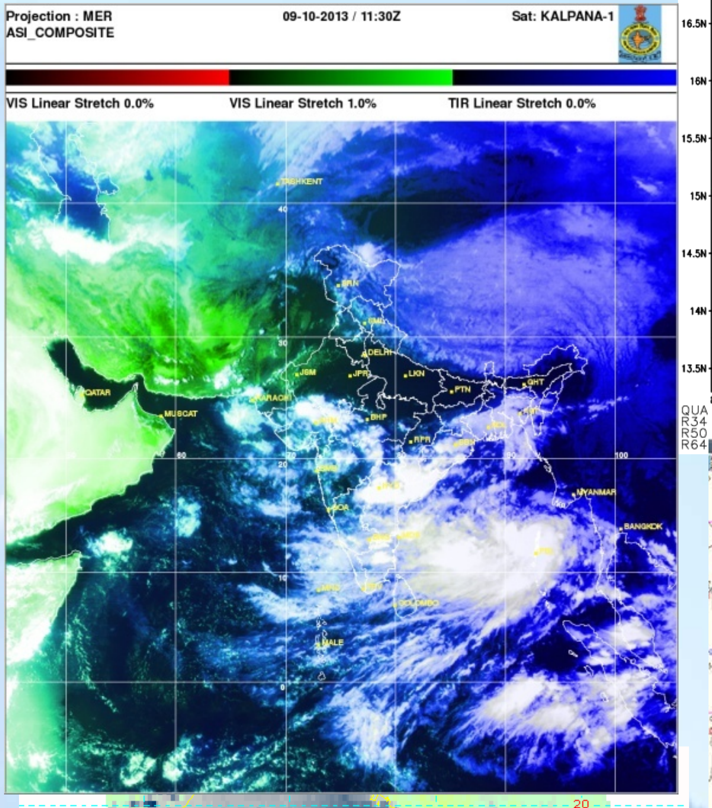
Utility of Coastal Hourly Observations for landfall point and time

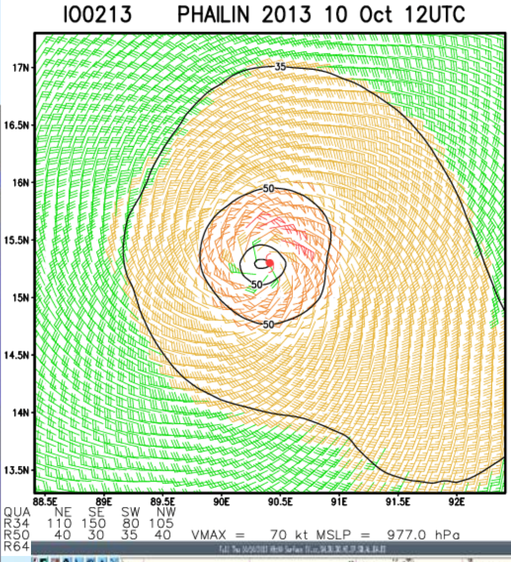
Hourly Observations of KHAIMUK cyclonic storm during 13-16 November 2008

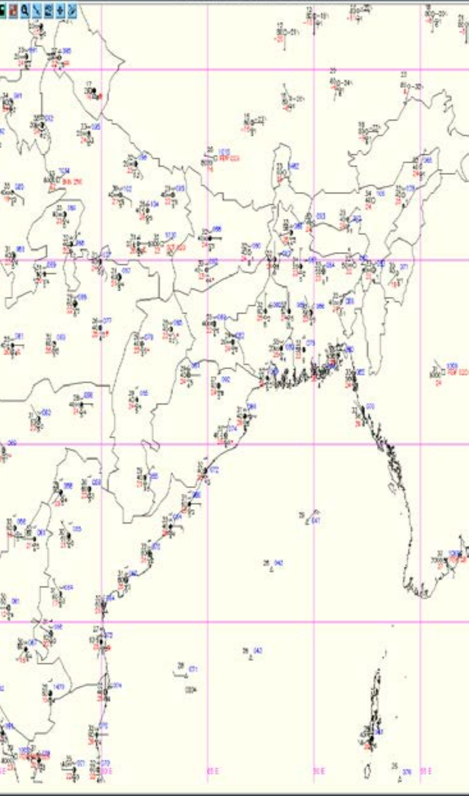


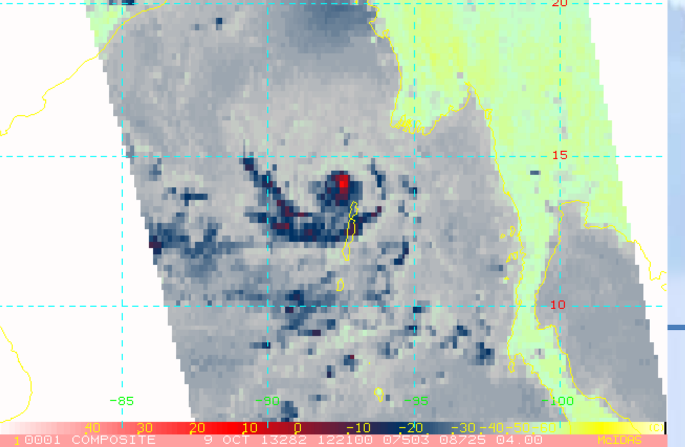
Current Status of location estimation is mostly satellite driven











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Location of Centre:

(b) Satellite

- In the initial stage, the centre is determined, from the centre of the low cloud lines (IMD, 2003).
- Similar is the case in shear pattern, when the convection lies away from the centre.
- As the system intensifies and acquires the banding pattern, the centre is determined from the banding feature using logarithmic spiral.
- In the CDO pattern, the centre of CDO is the centre of the system.
- In the eye pattern, the centre determination is easier and accurate as it is same as the centre of the eye of the cyclone.

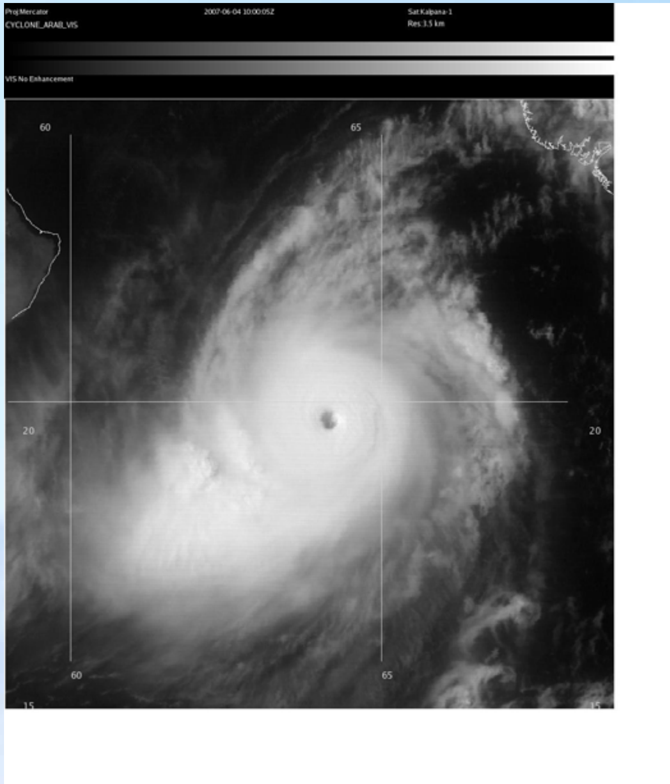
Visible imagery for cyclone monitoring

Helps better in monitoring the centre and intensity of cyclone, as

- **It filters out the high clouds**
- **It has better resolution (2 km) compared to IR (8 km)**

Limitations

- **It is available only during day time**
- **It can not measure convection quantitatively**



SUPER CYCLONE GONU
DATE: 04062007
INTENSITY T6.0
CENTRE 19.6N/64.3E

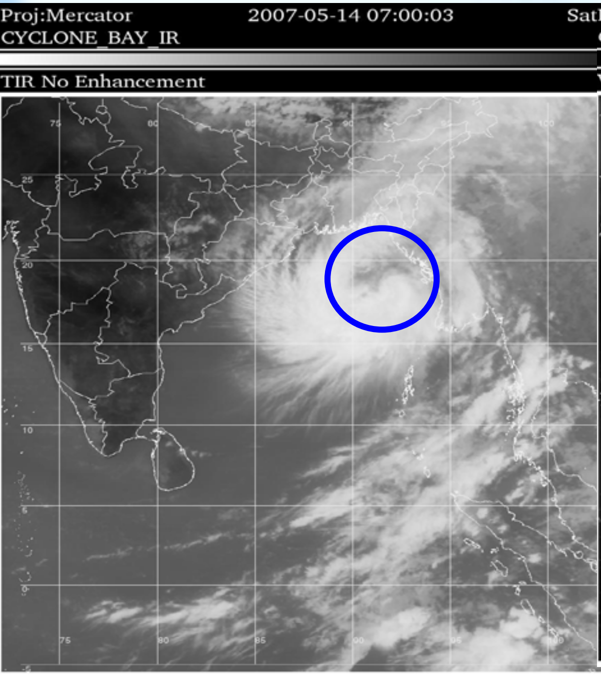
IR imagery for cyclone monitoring

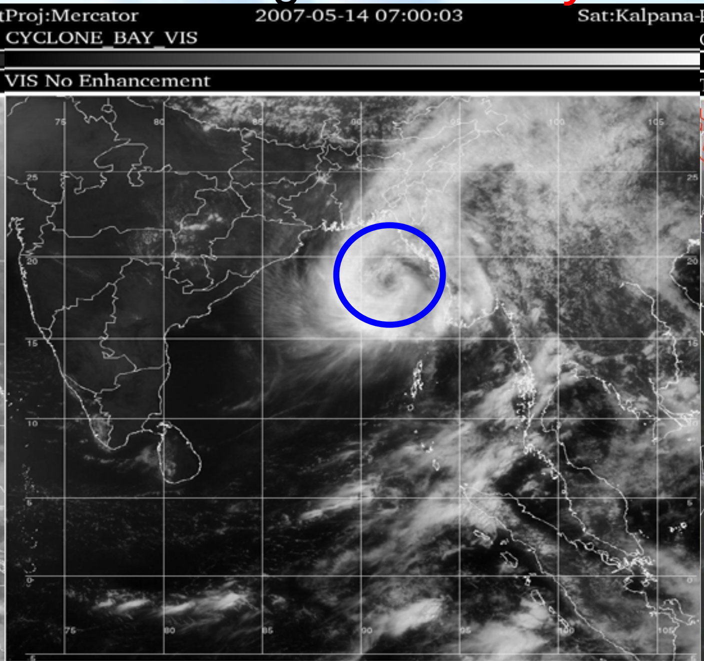
- **IR imagery is available for continuous monitoring round the clock**
- **It is essential to compare the IR imagery with Visible imagery for better understanding of cyclone**

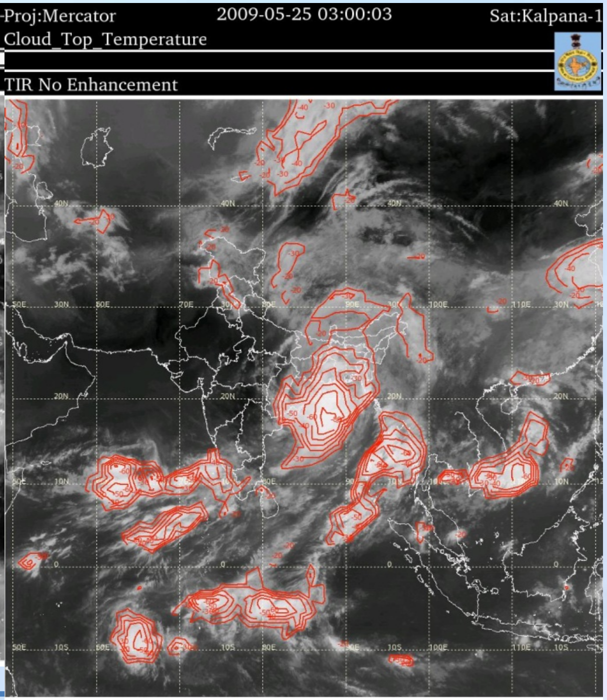
IR imagery clear shows that the cyclone is of curved band pattern

VIS gives a false signature of Eye

IR with CTT

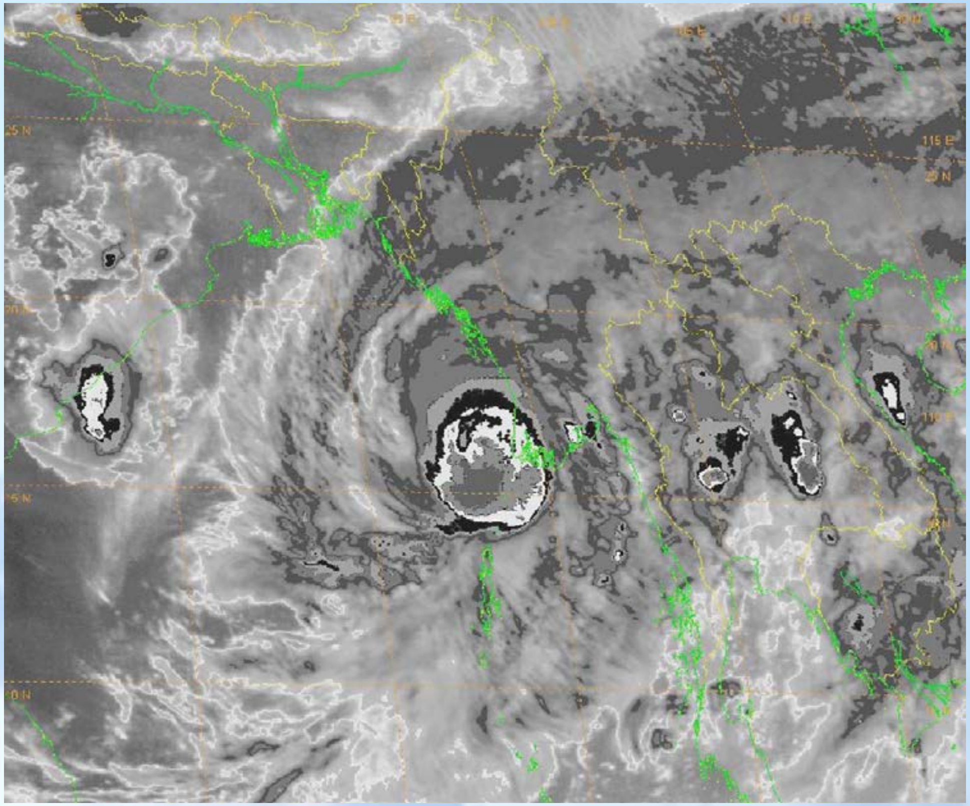






Enhanced IR Imagery for cyclone monitoring

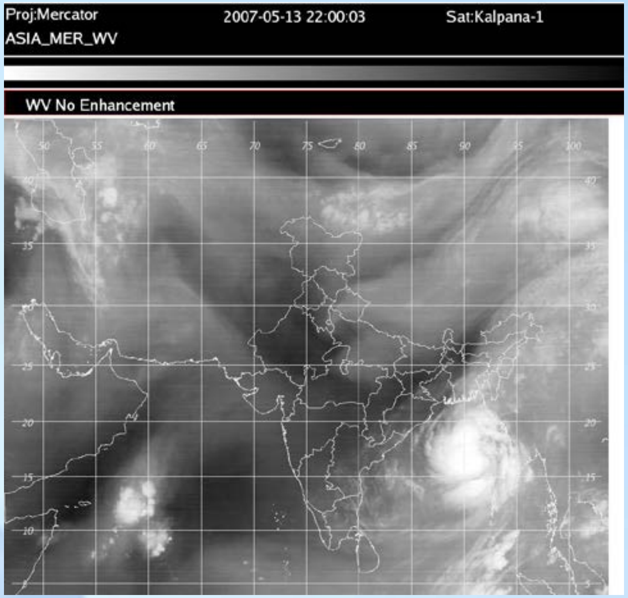
- Based on cloud top temperature ranges in different shades
- Helps in better identification of location and intensity
- Enhanced IR imageries are used in Dvorak Technique



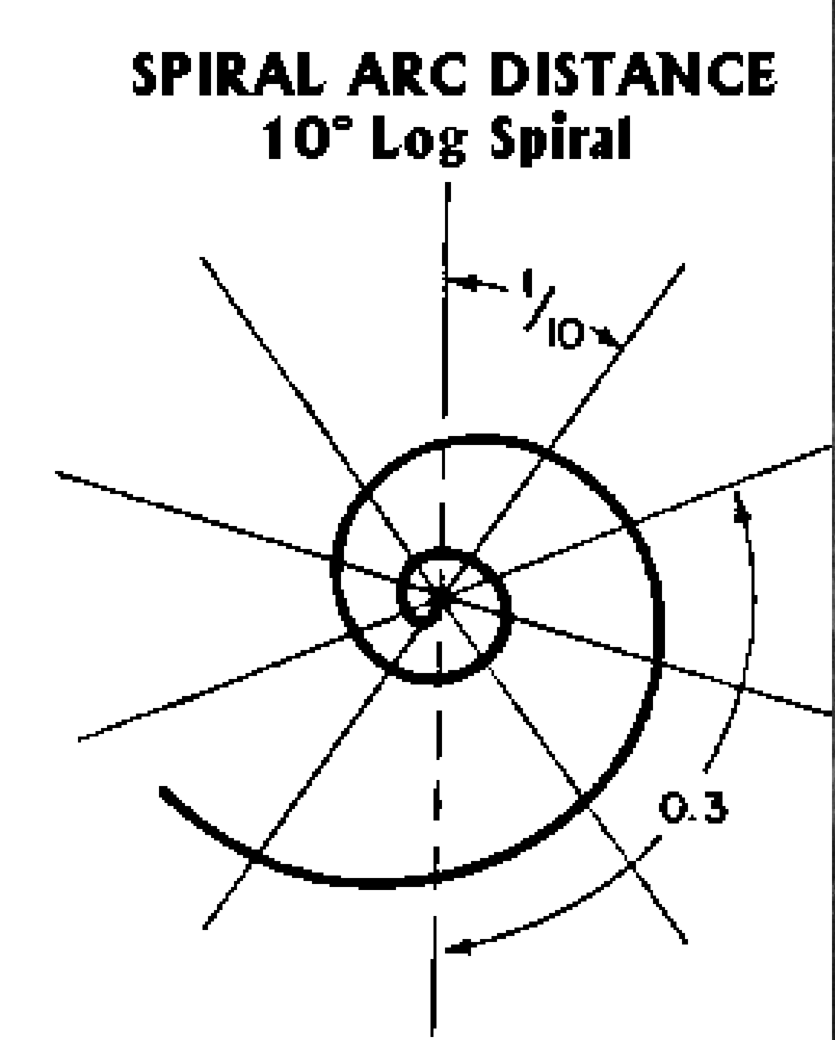
04Z EIR imagery of TC Mala (28-04-06)

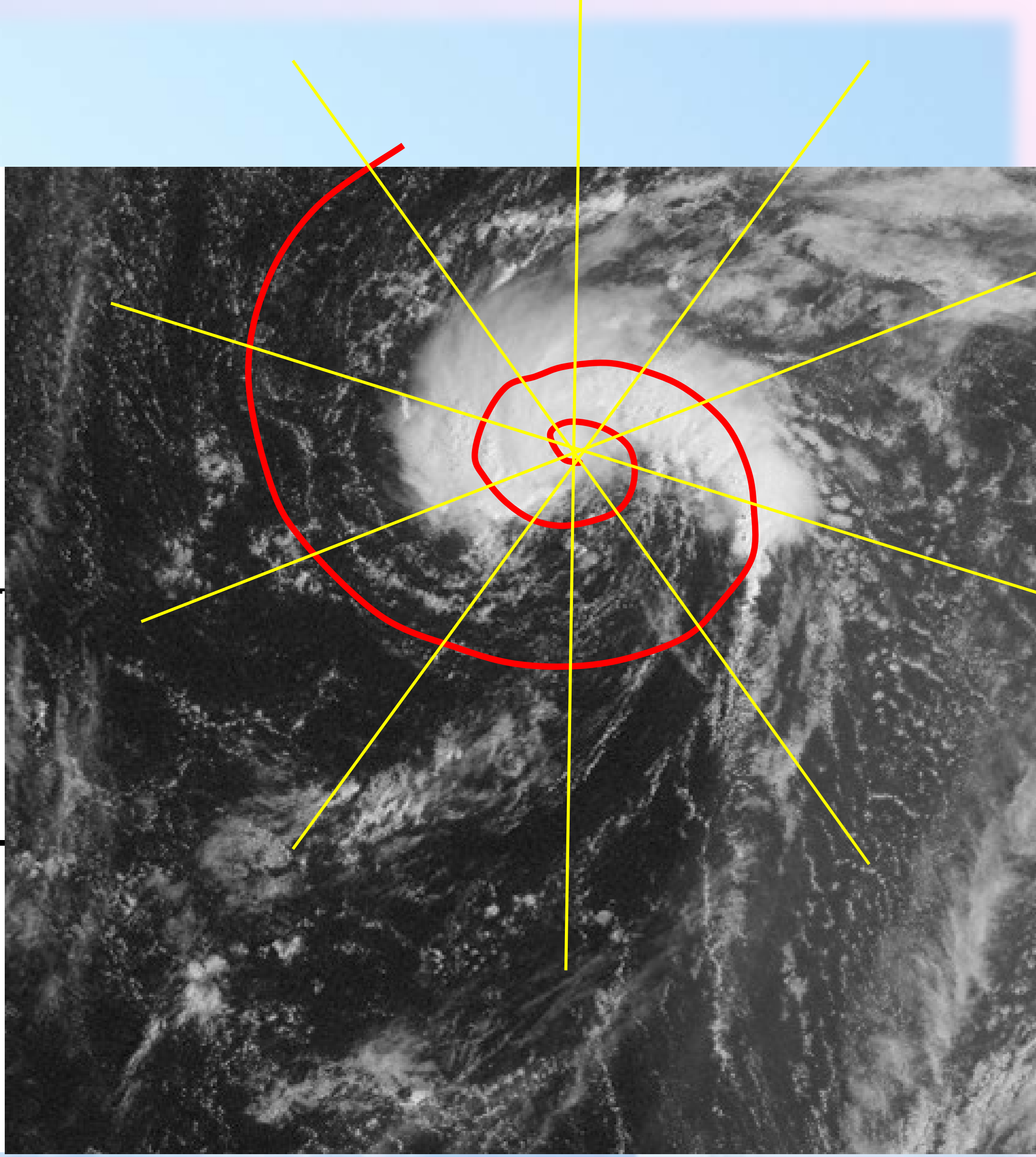
Water Vapour imagery for cyclone monitoring

- Water vapour imagery mainly helps in the following
- Movement of cyclone with
  - Location of westerly trough
  - outflow
  - Ridge
- Middle and upper tropospheric humidity
- It does not provide centre and intensity



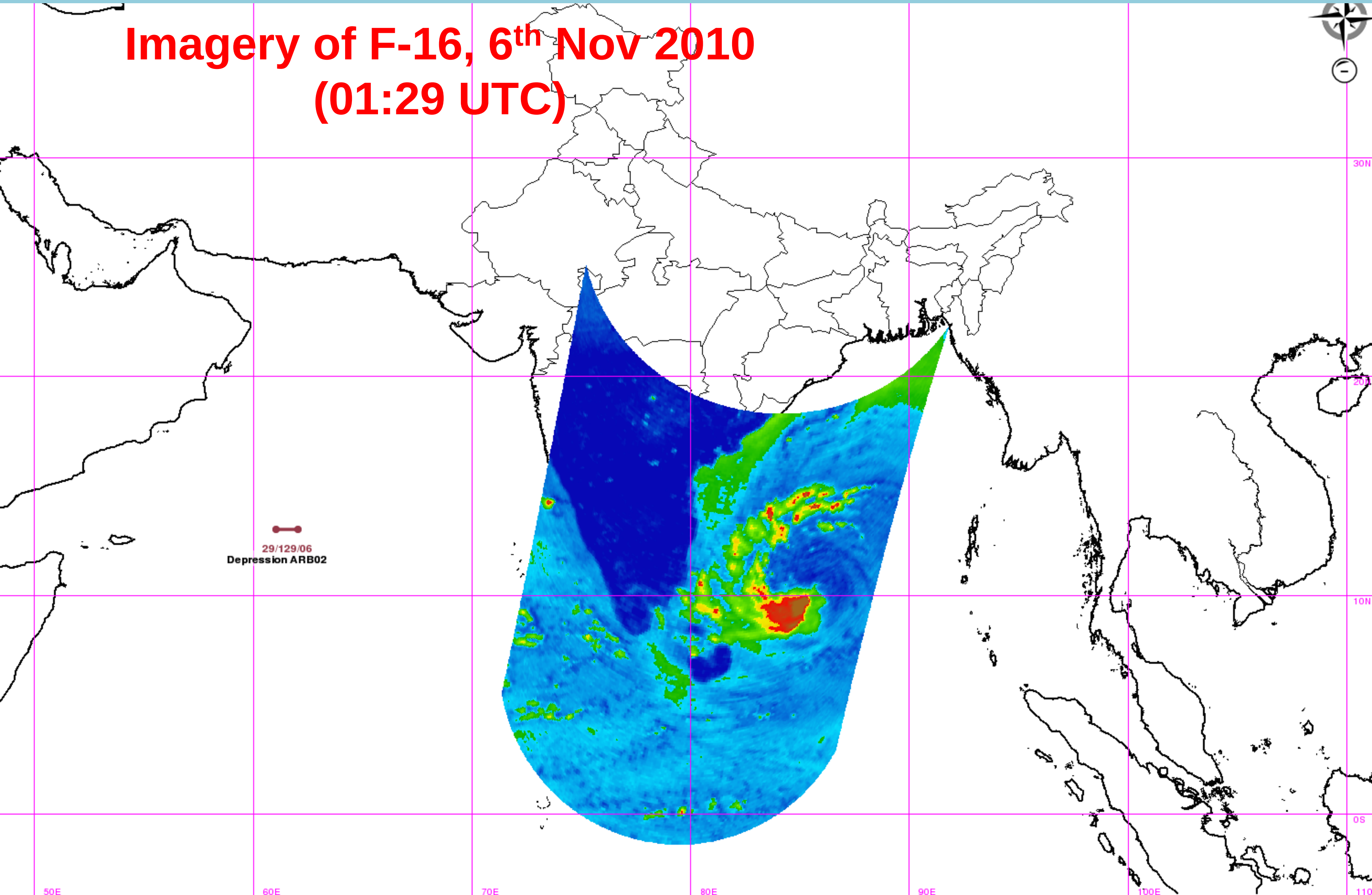
Role of westerly trough in Akash


SPIRAL ARC DISTANCE
10° Log Spiral
1/10
0.3

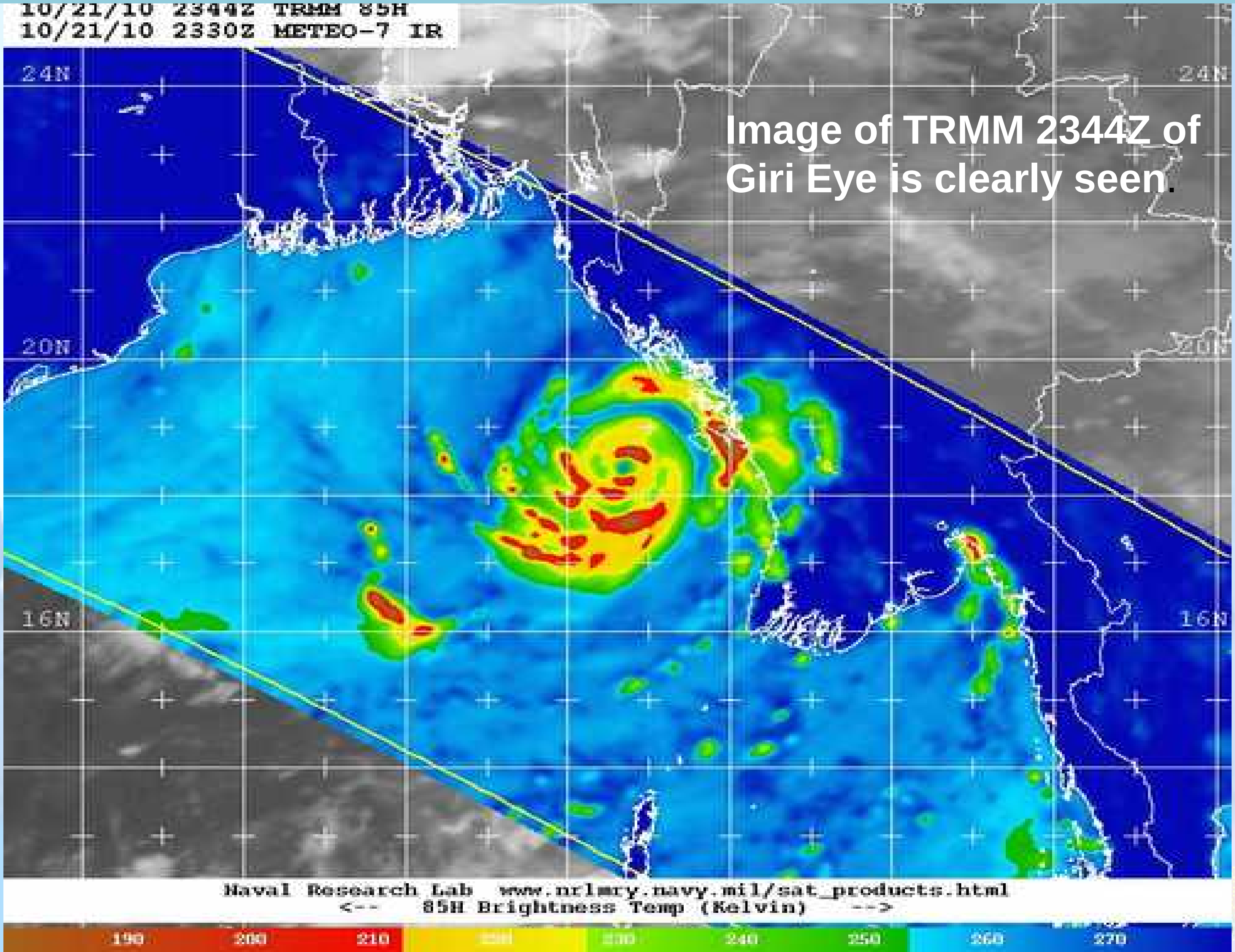


Banding pattern

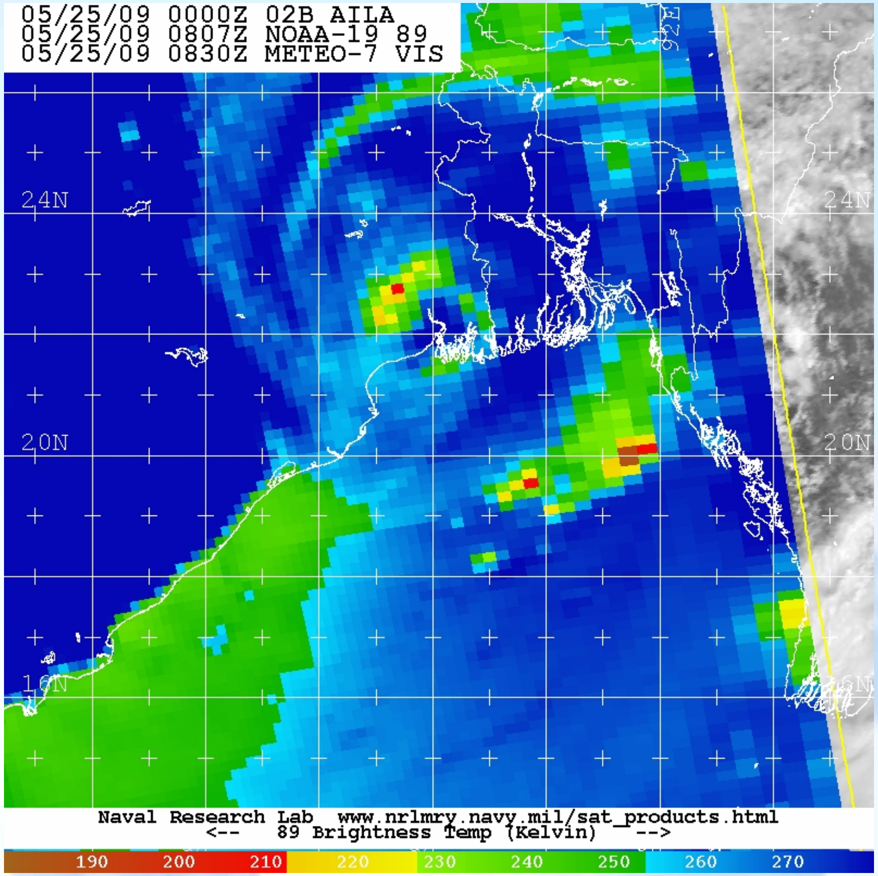
Imagery of F-16, 6th Nov 2010 (01:29 UTC)

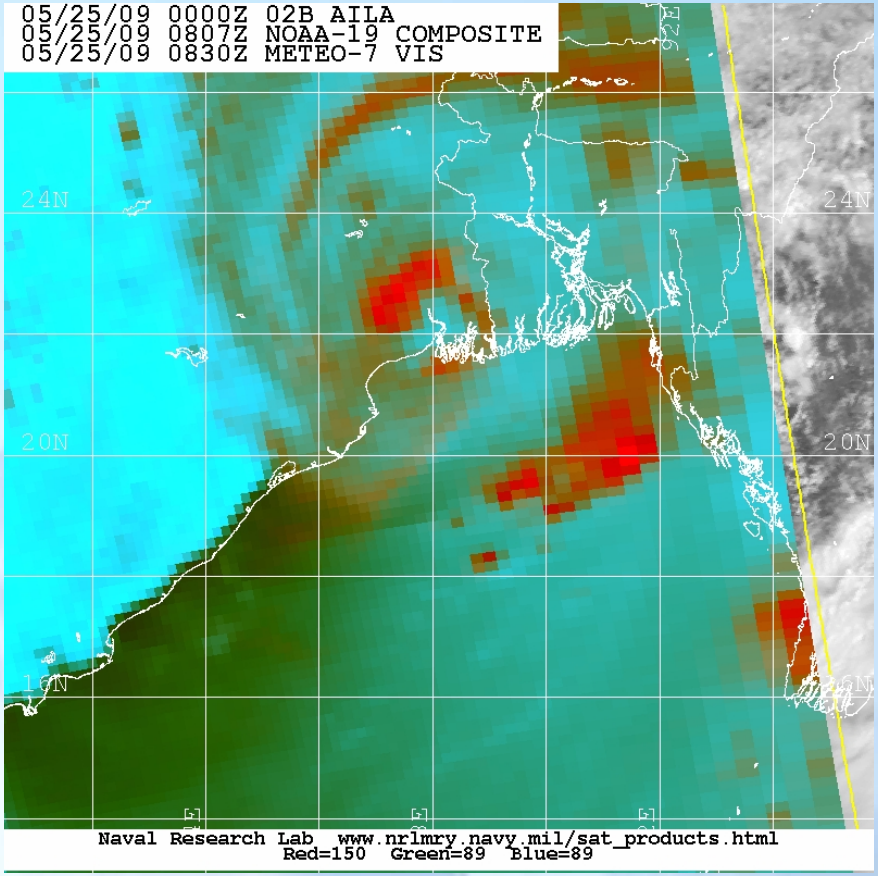


Eye pattern


10/21/10 2344Z TRMM 85H
10/21/10 2330Z METEO-7 IR
24N
20N
16N
Image of TRMM 2344Z of Giri Eye is clearly seen.
Naval Research Lab www.nrlmry.navy.mil/sat_products.html
<-- 85H Brightness Temp (Kelvin) -->
190
200
210
240
250
260
270

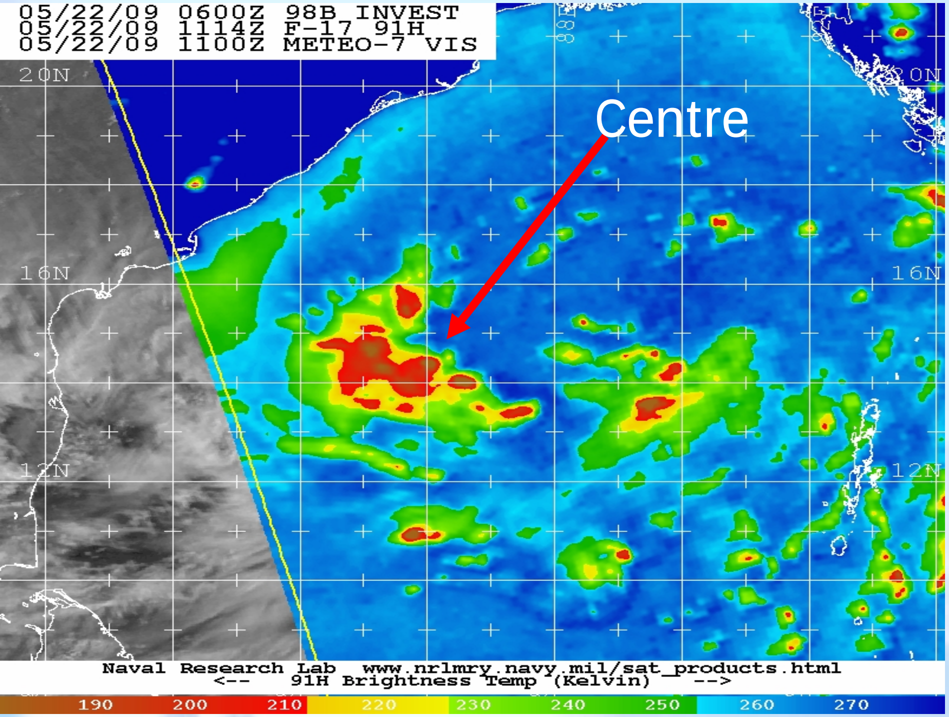
Utility of superimposed image of NOAA 19 and Meteosat7

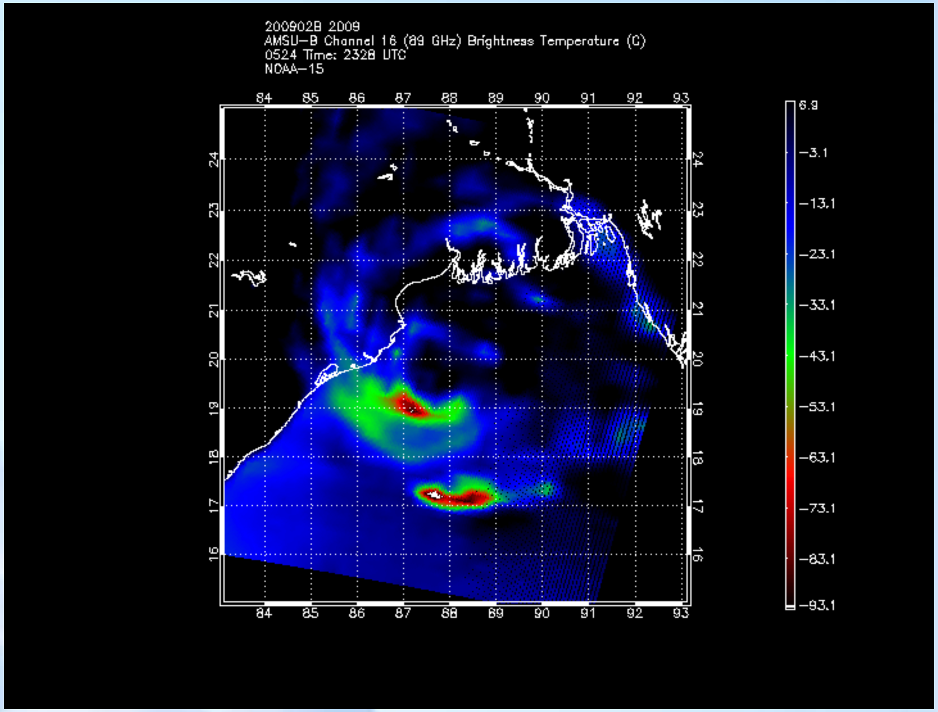




- These images are helpful to locate the centre of system

Utility of brightness temperature for cyclone monitoring





- These images are helpful to locate the centre in the initial stage
- The product is extensively available in US Navy site

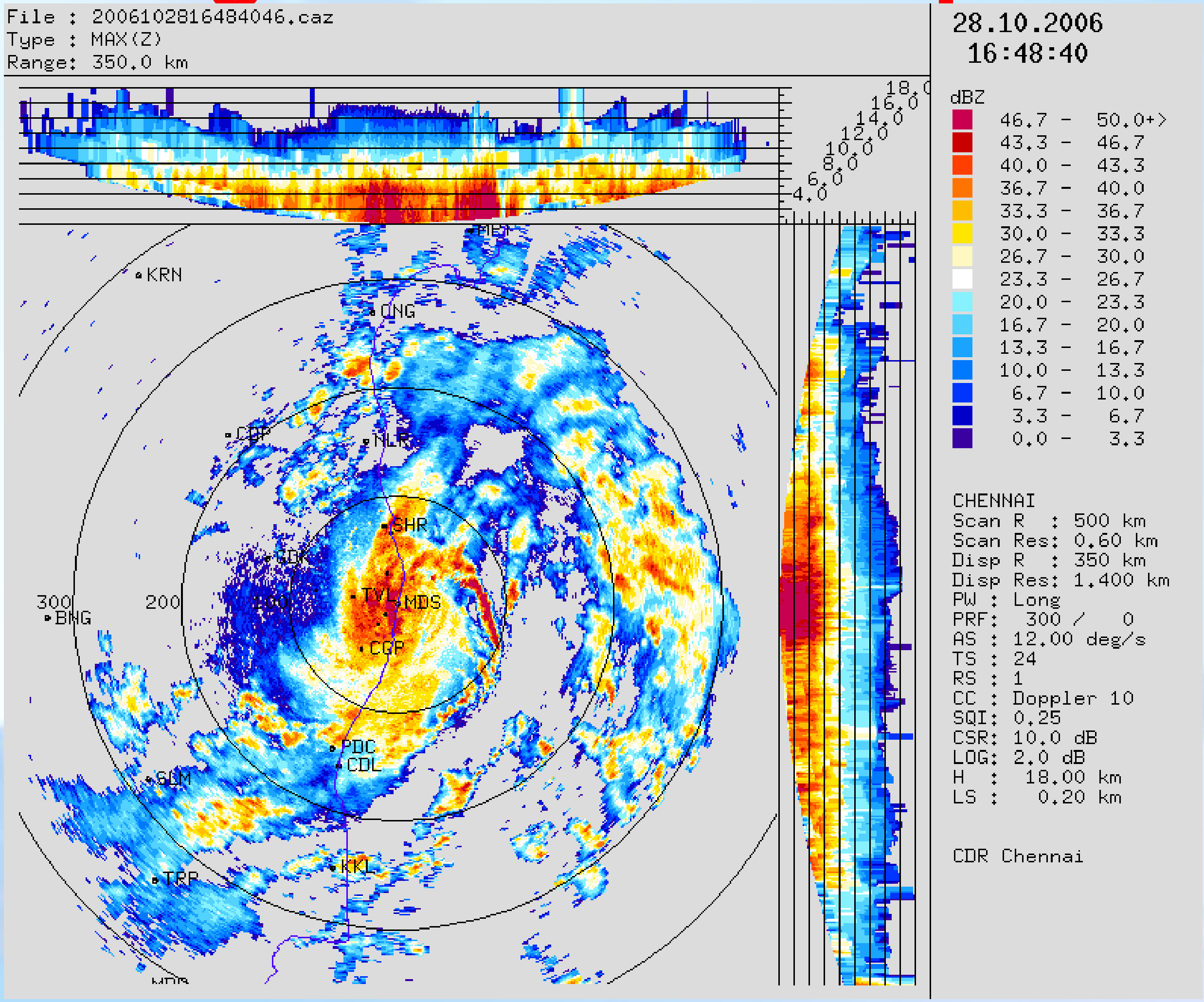
Cyclone centre fixing using Doppler Weather Radar

1. Initial Centre fixing is essential for accurate model predictions.
2. Required for accurate short range forecasts
3. Multiple circulations within the centre can be detected
4. Cloud centre is generally located accurately but may not be the cyclone centre
5. Satellite centre is different from Radar centre in some cases
6. Vortex tilt can be seen in radar data

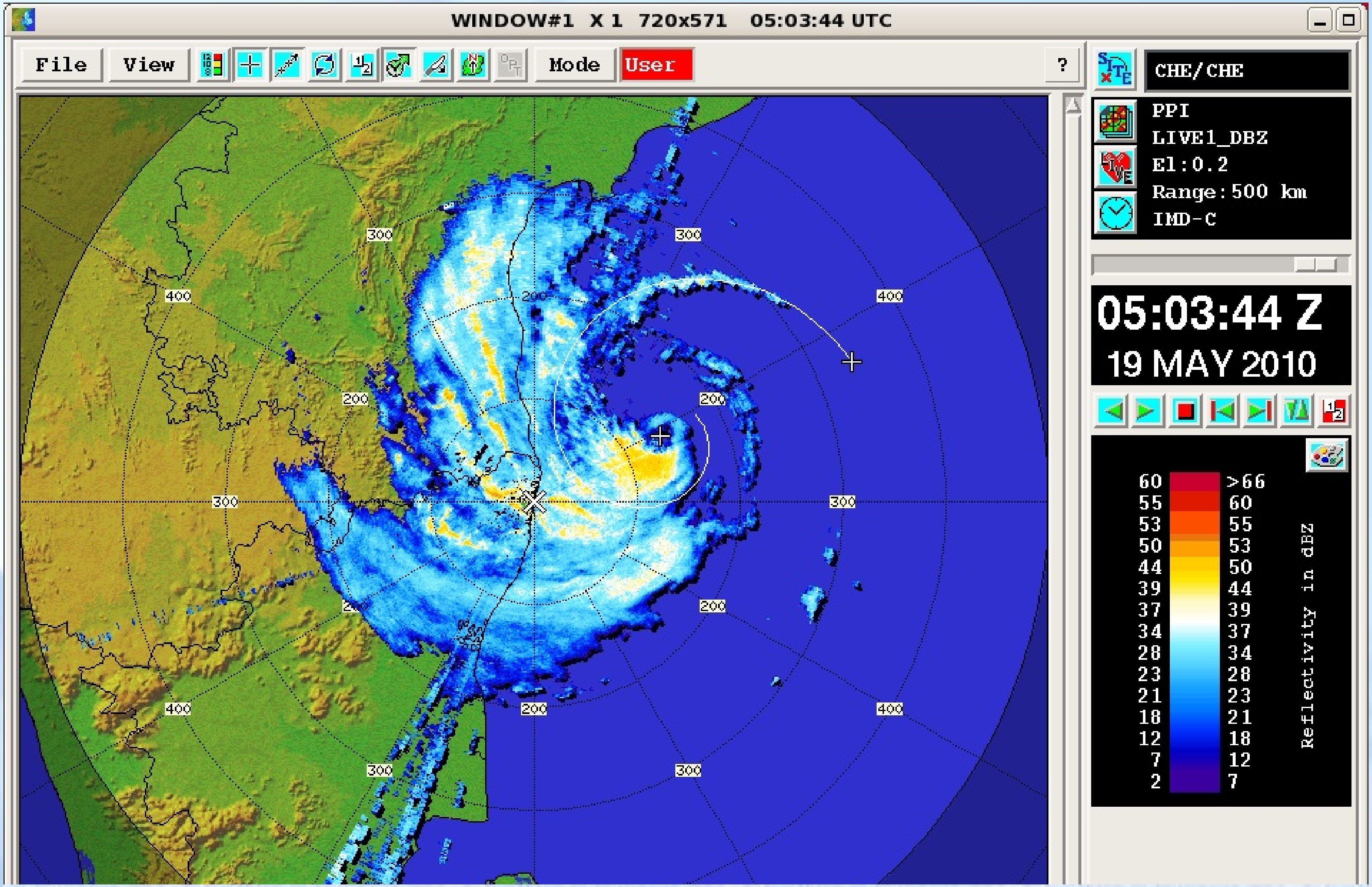
Center fixing by Radar

- Eye or the centre is derived from a continuous and logical sequence of observations.
- Geometric centre of the echo-free area -centre.
- If the wall cloud not completely closed, centre is found by sketching the smallest circle or oval superimposed on inner edge of existing portion of wall cloud.
- When wall cloud is not developed fully but centre of circulation is identifiable its reported similar to eye.

Cyclonic Spiral bands
Fitting centre with spirals

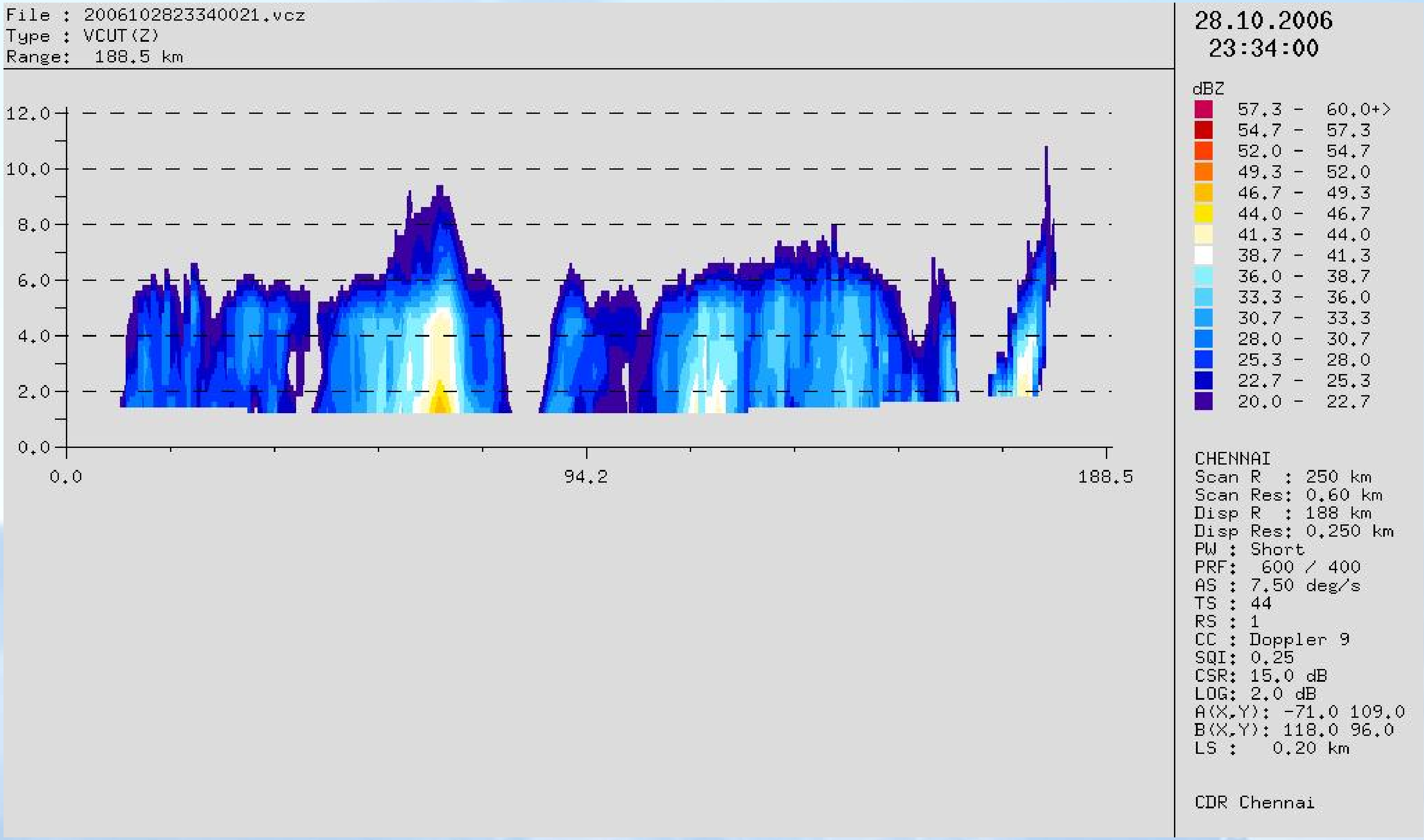


Center fixing in eye pattern

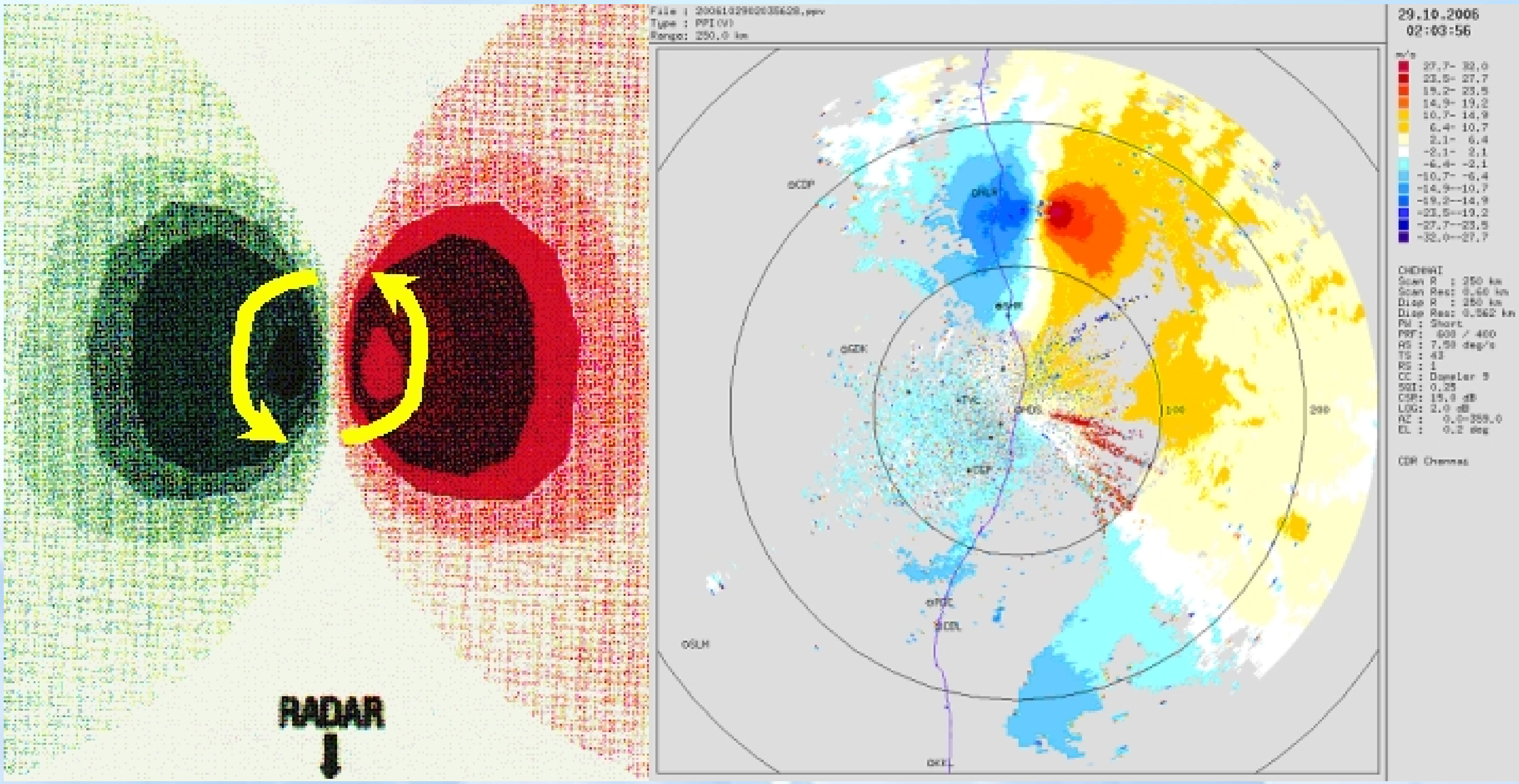


Radar Cyclone center: 13.6325ºN 81.4065ºE

Cyclone centre using V-Cut



Centre from Radial Velocity Couplet



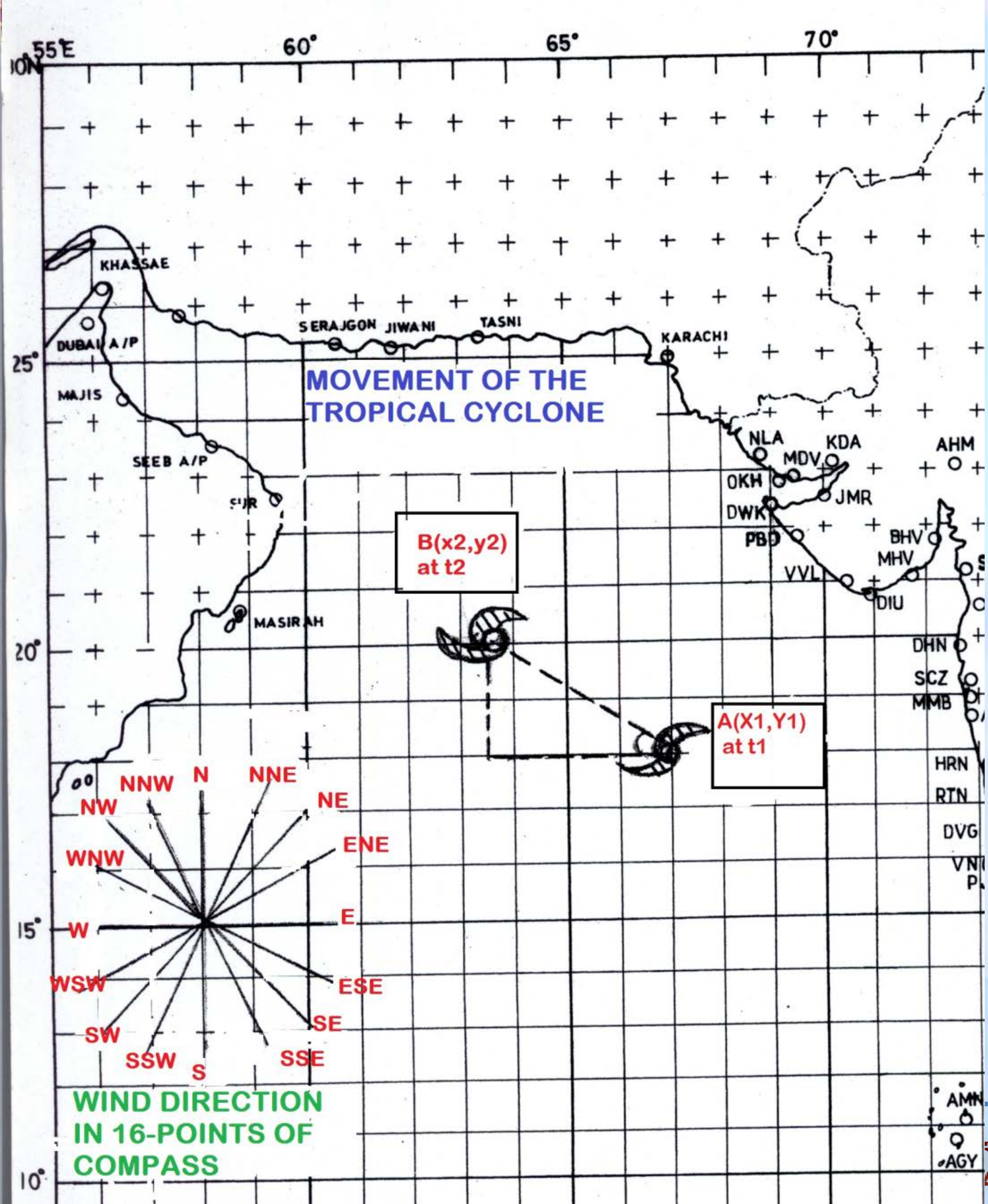
Location estimation error

- It is about is about 55 km over the sea areas (standard error of satellite estimation).
- Location error of a depression is more than a TC.
- According to Elsberry (2003), the errors in determining the TC centre over the northwest Pacific Ocean can be upto 50 km by satellite fixes, 20-50 km by radar observations and by about 20 km by aircraft reconnaissance.

Landfall Location estimation error

- **Landfall point estimation error is 140 km or more prior to 1891 for west coast and more than 105 km for east coast. It reduced to about 100 km by the end of 1940 for both the coasts and to 55 km by the end of 1960. It further reduced to about 25 km by 2010 mainly due to installation of coastal AWS during late 2000s.**
- **Landfall time estimation error may be about half an hour since 1974 with introduction of coastal hourly observations and CDRs. During 1960-1974, it may be at least one and a half hour with the three hourly observations.**

Movement of Tropical Cyclones



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Methods for Estimating Intensity

- Beaufort Scale (0-12: Calm to hurricane)
- Anemometers – Biases in Early Instruments
- Pressure-Wind Relationships
- Utilizing Size (Radius of Maximum Wind) Information
- Storm Surge
- Wind-caused Structural Damage
- Inland Wind/Pressure Decay Models
- Satellite (polar – 1960, Dvorak technique 1974, INSAT 1982)
- Buoys
- Aircraft Reconnaissance (?)

Intensity estimation:

(a) Satellite:

(1) INSAT/METSAT

(2) Intensity from NOAA SSD:

(b) Radar

(c) Synoptic analysis

(d) Model analysis

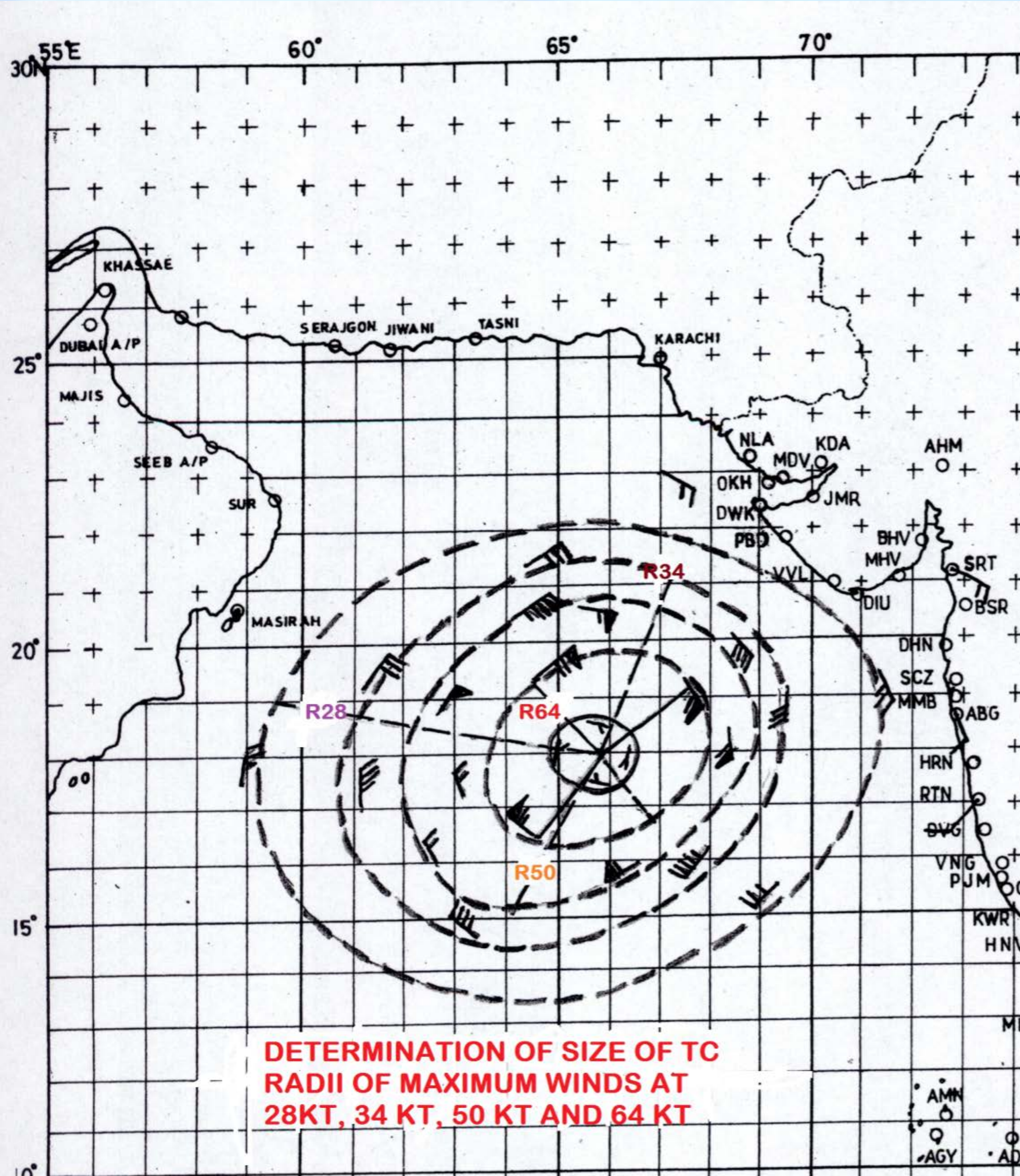
(e) Intensity determined by other warning centres

(e) Finally agreed official intensity

(f) Confidence

In synoptic method, the available surface observations are taken into consideration to find out maximum sustained wind and number of closed isobars at the interval of 2 hPa within a specified region around the system centre (5 deg. Lat/long. Box)

Intensity estimation: Synoptic method



In synoptic method, the available surface observations are taken into consideration to find out maximum sustained wind and

number of closed isobars at the interval of 2 hPa within a specified region around the system centre (5 deg. Lat/long. Box)

Intensity estimation: Dvorak's Technique

C.I. Number	*Max. Wind Speed (knots)*	*Pressure depth (in mb)*
1	25	
1.5	25	
2	30	4.5
2.5	35	6.1
3	45	10.0
3.5	55	15.0
4	65	20.9
4.5	77	29.4
5	90	40.2
5.5	102	51.6
6	115	65.6
6.5	127	80.0
7	140	97.2
7.5	155	119.1
8	170	143.3

The technique relies on four distinct geophysical properties that relate organised cloud patterns to TC intensity.

1. Vorticity, 2.Vertical wind shear,

3. Convection, and 4. Core temperature.

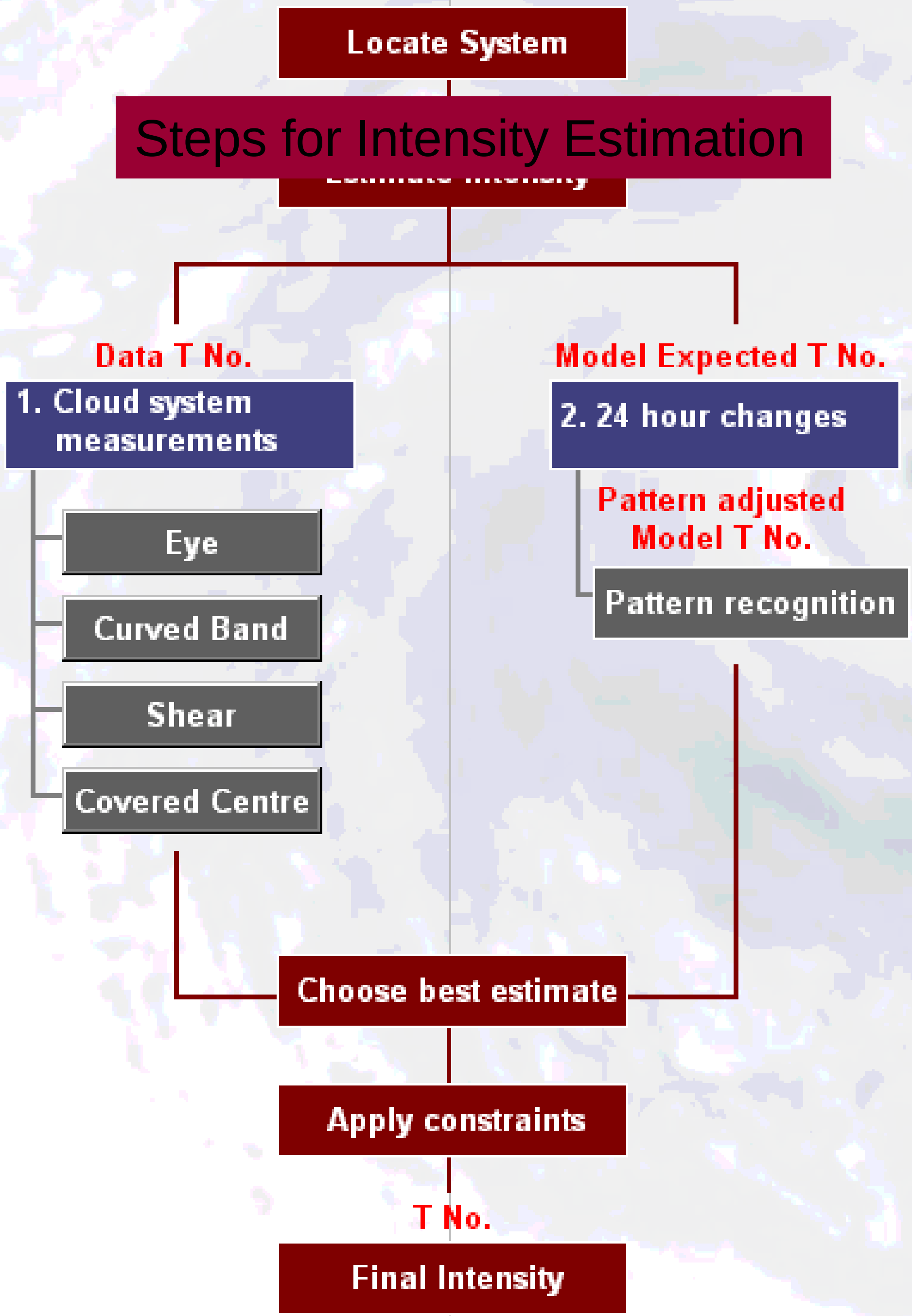
Recent developments

1. ADT
2. AODT
3. Application of DT to microwave imageries
4. Application of DT over land

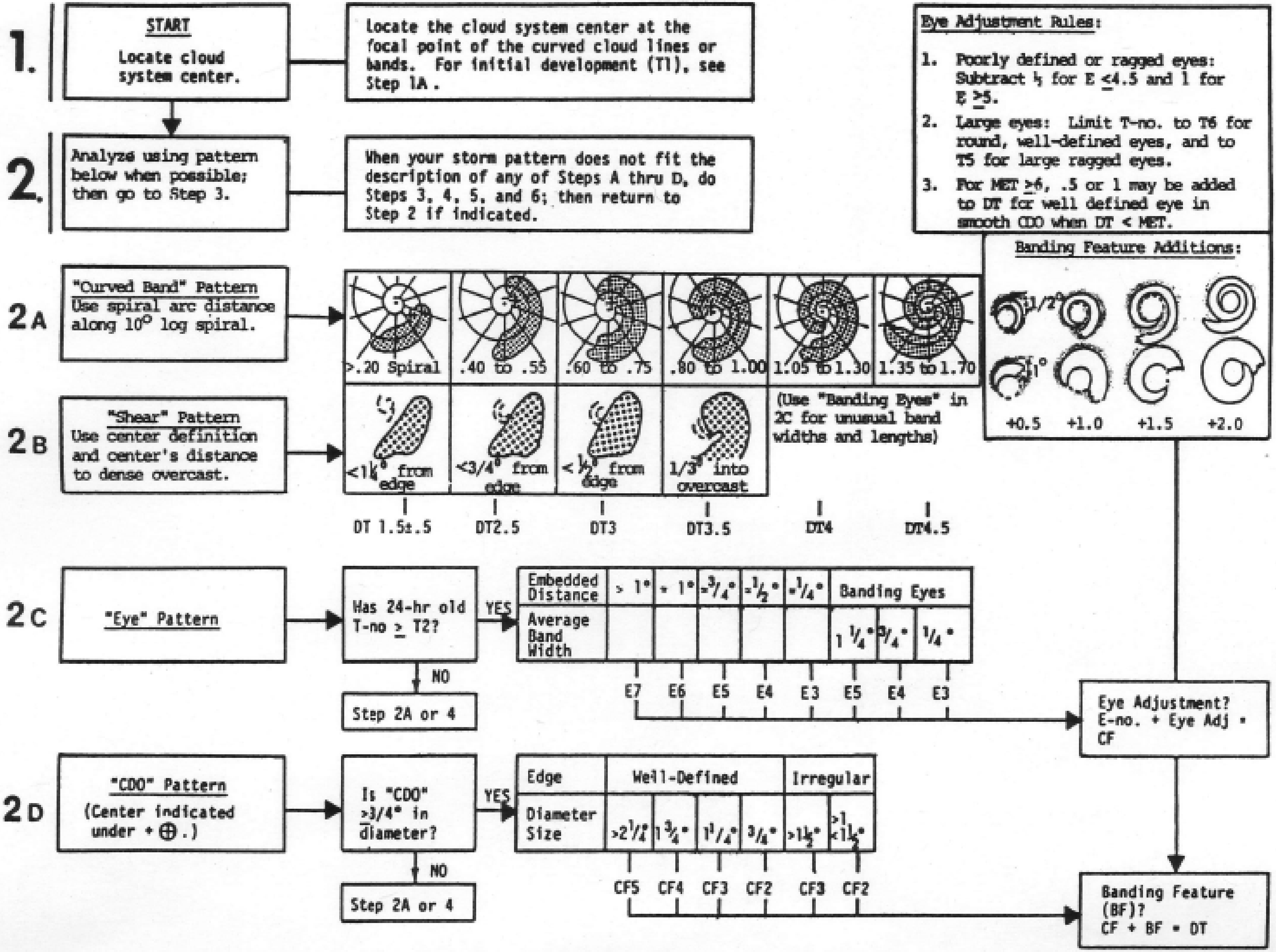
Limitations

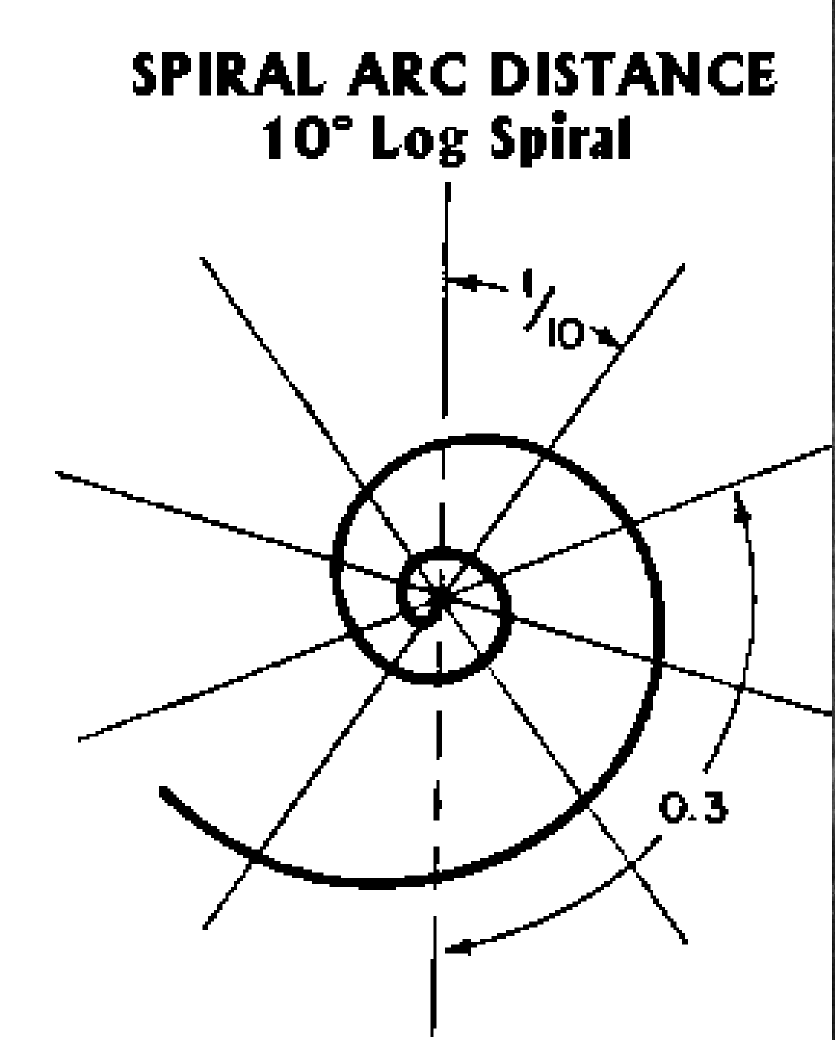
Not verified over NIO, Averaging problem, Pressure wind relationship also not verified

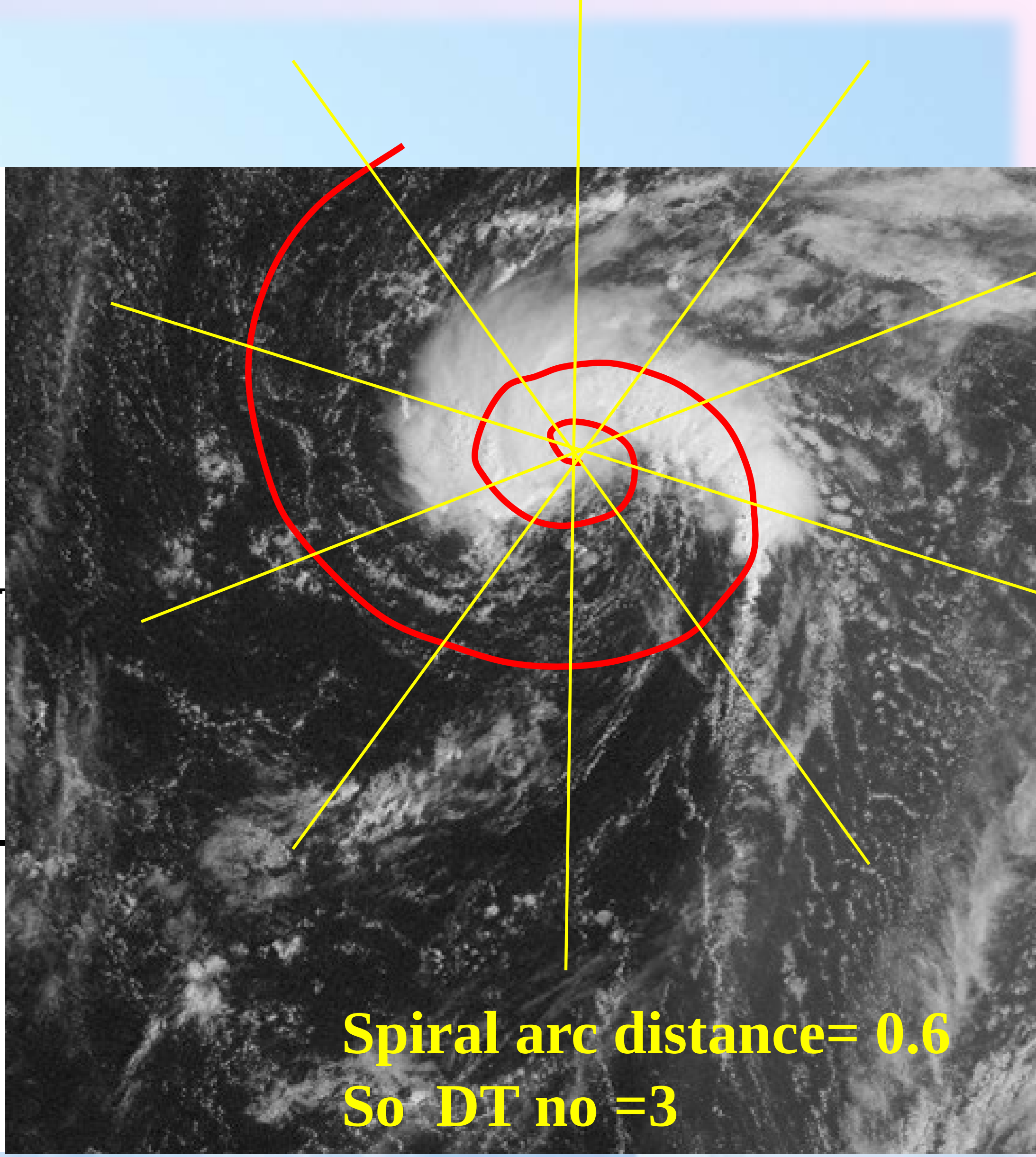
Steps for Intensity Estimation



VIS Analysis Diagram-1







DT number is determined by curvature of band around 10° log spiral

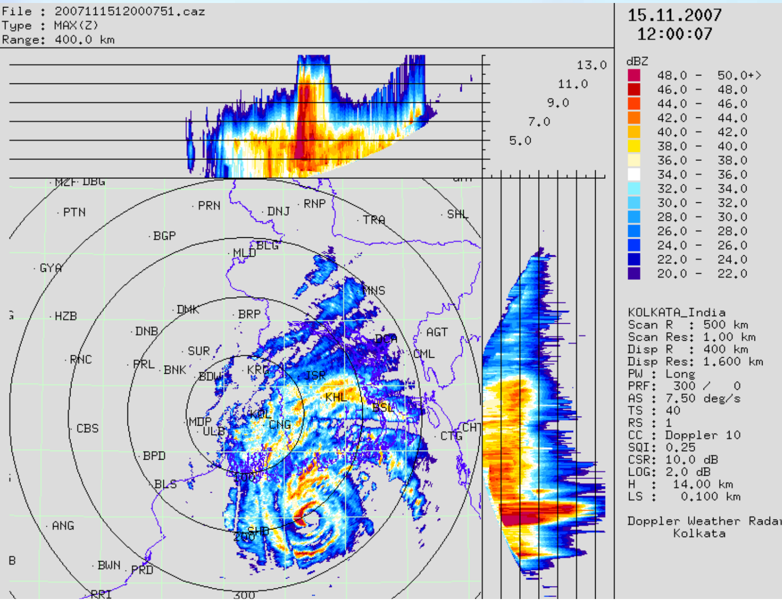
Check list for other satellite derived products

7. Lower level convergence :
   a. Maximum value and region of occurrence) :
   b. Convergence in forward sector
   c. Tendency during past 06/12/24 hrs
8. Upper level divergence :
   a. Maximum value and region of occurrence :
   b. Divergence in forward sector
   c. Tendency during past 06/12/24 hrs
9. Lower level vorticity
   a. Maximum value and region of occurrence) :
   b. Vorticity in forward sector
   c. Tendency during past 06/12/24 hrs
10. Vertical wind shear
    a. Minimum value and region of occurrence) :
    b. Wind shear in forward sector
11. Wind shear tendency
    a. Minimum value and region of occurrence :
    b. Wind shear tendency in forward sector :

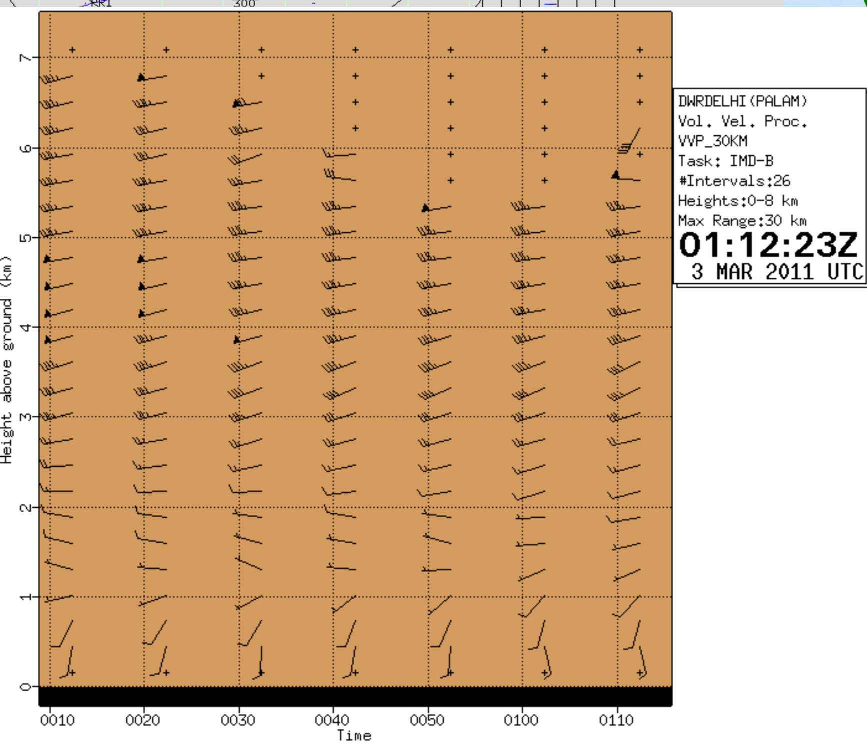
Check list for the north Indian Ocean

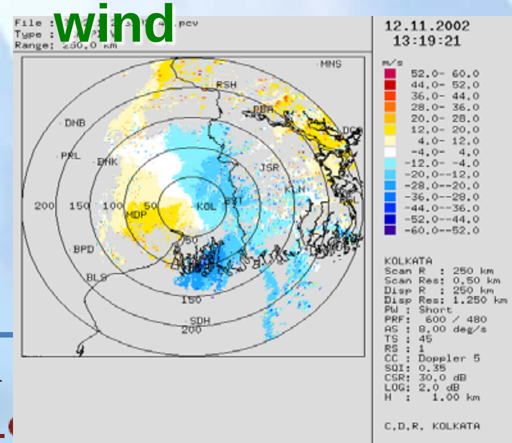
12. QPE
    a. QPE during past 12 hrs (Maximum value and region of occurrence) :
    b. QPE during past 24 hrs (Maximum value and region of occurrence) :
    c. Tendency (Increasing/decreasing) :
13. OLR :
    a. Daily mean (Maximum value and region of occurrence) :
    b. 3 hourly mean (Maximum value and region of occurrence) :
    c. Tendency (Increasing/decreasing) :
14. SST
    a. Maximum SST and region of occurrence
    b. SST in forward sector
    c. Tendency in SST
15. Location and intensity from other sources
    a. NOAA SSD
    b. JTWC satellite estimates

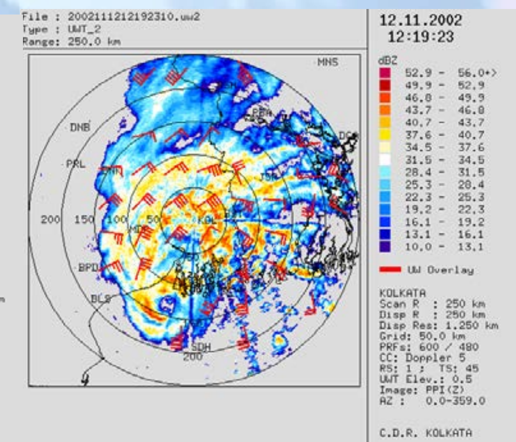
Intensity estimation by Radar



- (a) Radius of maximum reflectivity mostly corresponds to radius of maximum wind
- (b) Radial wind
- (c) Wind distribution by uniform wind technique
- (d) Vertical profile over the station
- (e) Mosaic products
- (f) Use of conversion technique for obtaining 10m wind from radial wind







Radar features for intensity estimation

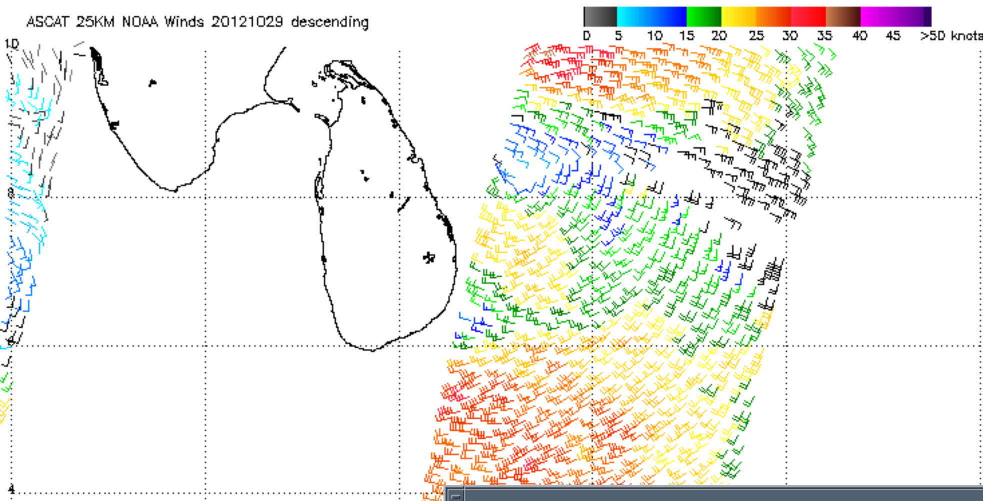
1. Pattern : Line curve/Spiral band/Eye
2. line Curve (Number and tendency, associated maximum reflectivity and its place of occurrence
3. Characteristics of spiral bands (Number and tendency, Maximum reflectivity and its place of occurrence)
4. Eye characteristics :
   - (i) Visible/Invisible, width and Tendency
   - (ii) Open/ closed, If open howmuch and tendency
   - (iii) Circular/elliptical
5. Characteristics of eye wall

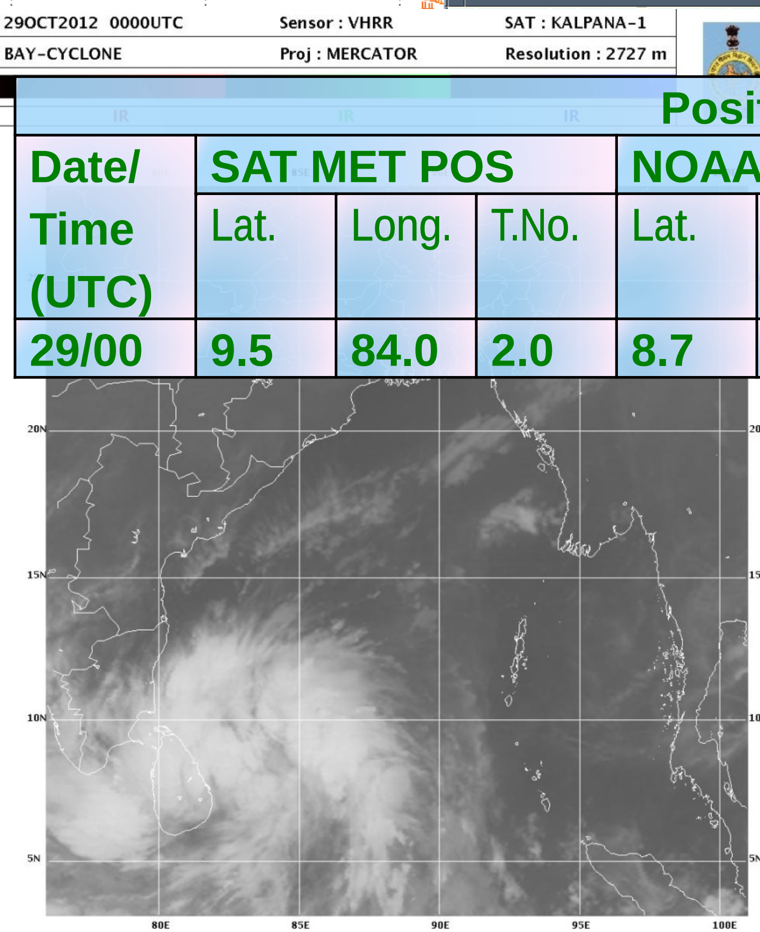
   (i) maximum reflectivity and its place of occurrence and tendency

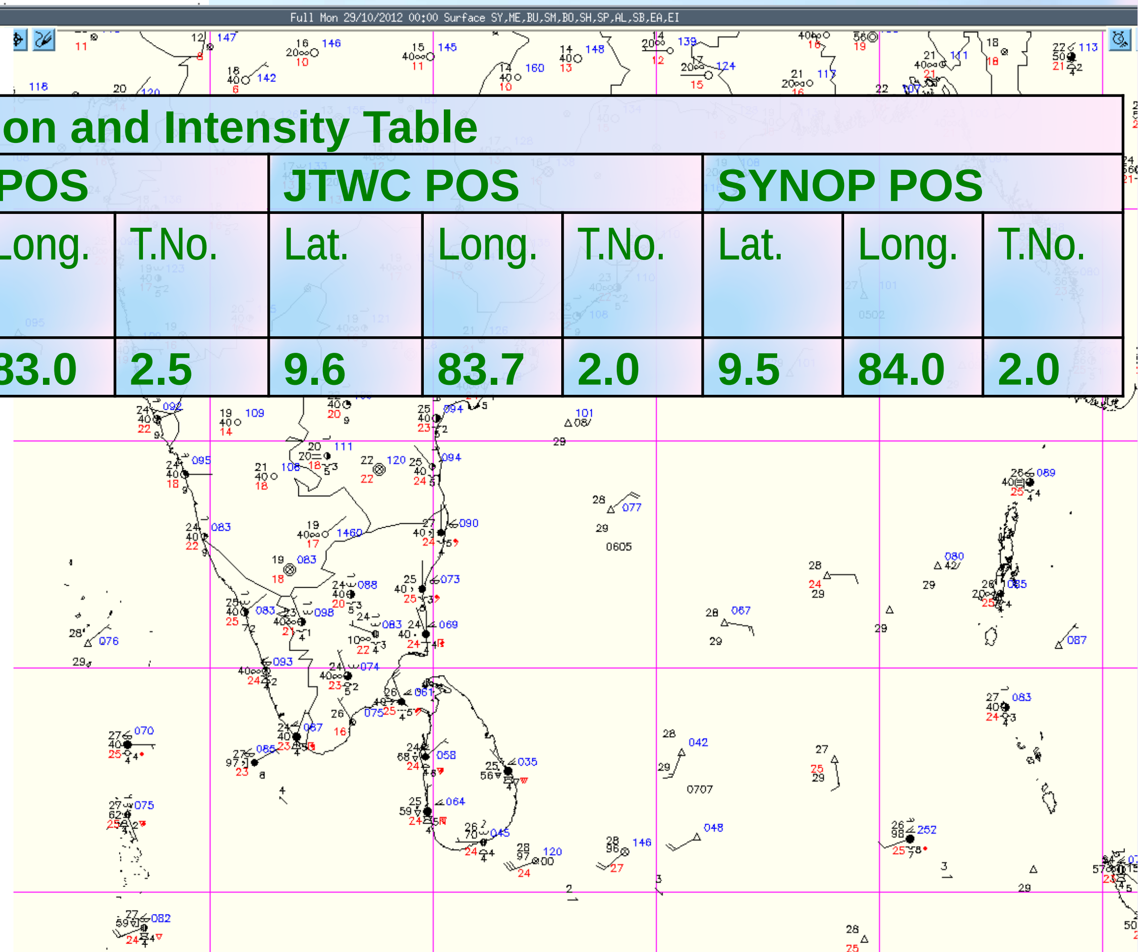
   (ii)Single eye wall/ double eye wall

   (iii)Size of eye and eye wall (Diameter/radius)
6. Maximum wind and reflectivity
7. Radius of maximum reflectivity (in different quadrants)
8. Radius of maximum wind (in different quadrants)
9. Vertical extension of convective clouds

Difficulty in intensity estimation







Position and Intensity Table

Date/ Time (UTC)	SAT MET POS			NOAA POS			JTWC POS			SYNOP POS		
	Lat.	Long.	T.No.	Lat.	Long.	T.No.	Lat.	Long.	T.No.	Lat.	Long.	T.No.
29/00	9.5	84.0	2.0	8.7	83.0	2.5	9.6	83.7	2.0	9.5	84.0	2.0

Intensity estimation error

- Average error in MSW estimation has reduced over the years.
- During the pre-satellite era (till 1960), the average error in intensity estimation may be at least one stage in Beaufort scale (5-15 knots or 3-8 mps upto severe cyclonic storm stage).
- There is no classification of intensity between very severe cyclonic storm and above intensity in Beaufort scale.
- The error could have reduced gradually during polar satellite era.
- It could have been T0.5 (05-20 knots or 3-10 mps) with the introduction of Dvorak's classification of intensity since 1974 (Goyal et al, 2012)

PREDICTION OF MOVEMENT

- CLIMATOLOGY INDICATES PREDOMINANTLY 3 TYPES OF MOVEMENT

_ WESTERLY

_ NORTHWESTERLY

_ RECURVING FROM INITIALLY NORTHERLY TO NORTHEASTERLY DIRECTION

DUE TO NORMAL UPPER AIR FLOW PATTERN OVER SYSYTEM AREA

- THERE IS TENDENCY OF STORM TO MOVE POLE WARD DUE TO DIFFERENCE IN CORIOLIS PARAMETER IN NORTHERN AND SOUTHERN SECTOR OF THE STORM
- GREATER THE DIFFERENCE, FASTER WILL BE THE MOVEMENT
- MANY FORCES ACT ON THE STORM, HENCE TRACK NEVER SMOOTH
- THERE IS ALSO INTERACTION BETWEEN STORM AND EMBEDDED BASIC CURRENT. THIS MANIFESTS AS A TROCHOIDAL MOTION, CLEARLY SEEN IN RADAR FIXES

Cyclone track forecasting methods

i) Statistical Techniques
   i) Analogue
   ii) Persistence
   iii) Climatology
   iv) CLIPER,
   v) Chaos theory and Generic Algorithm method)

ii) Synoptic Techniques – Empirical Techniques

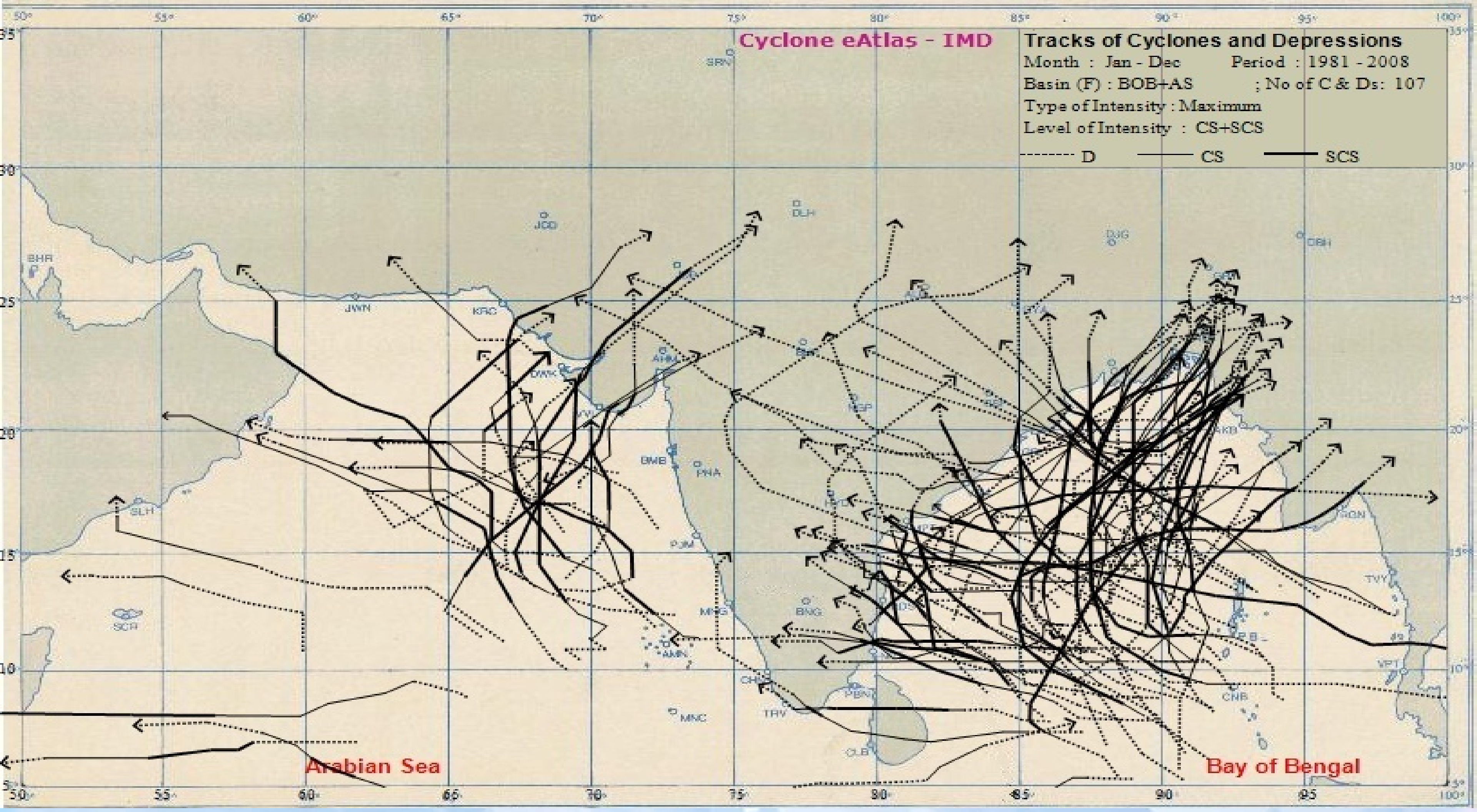
iii) Satellite Techniques Techniques

iv) Radar Techniques

v) NWP Models
   - Individual models (Global and regional)
   - IMDGFS (574), NCMRWF (574), ARP (MeteoFrance, ECMWF, JMA, UKMO, NCEP, WRF (IMD, IITD, IAF), HWRF (IMD), QLM
   - MME (IMD) and MME based on Tropical Cyclone Module (TCM)
   - EPS (Strike probability, Location specific probability

vi) Operational (Consensus) forecast

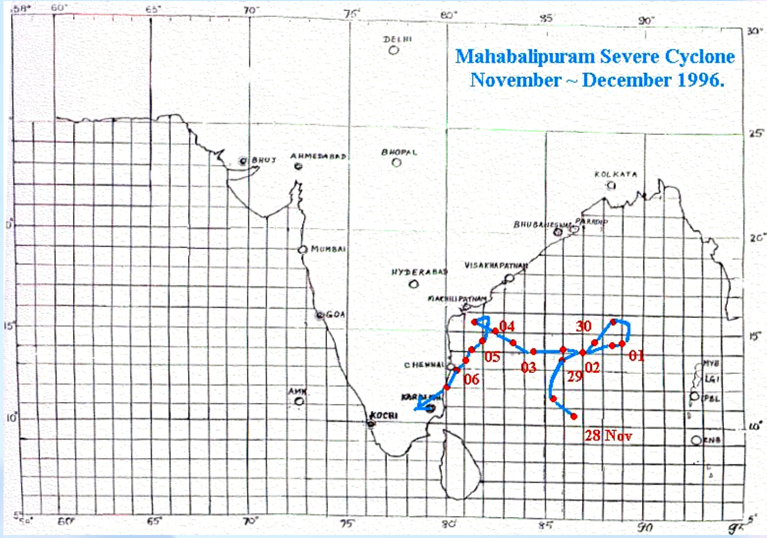
Movement of TCs

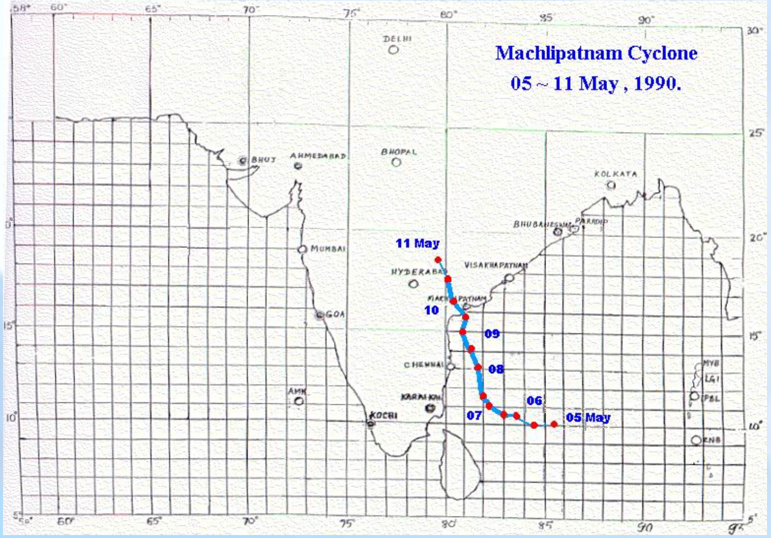


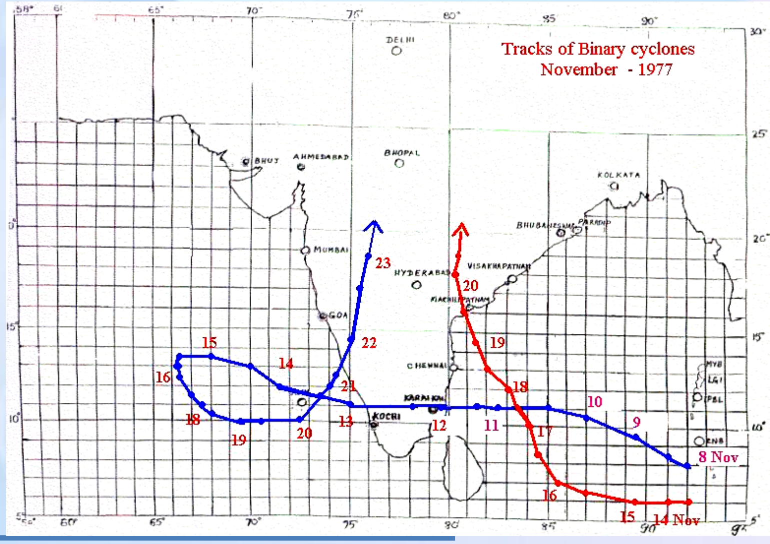
Tracks of cyclones over the north Indian Ocean during 1981-2008

At times cyclones display odd behaviour

- Display changing trends in motion
- Rapid intensification close to a populated coastline.
- Remaining quasi-stationary for long duration
- Displaying erratic tracks such as looping, sudden acceleration or deceleration
- Interaction with other weather systems



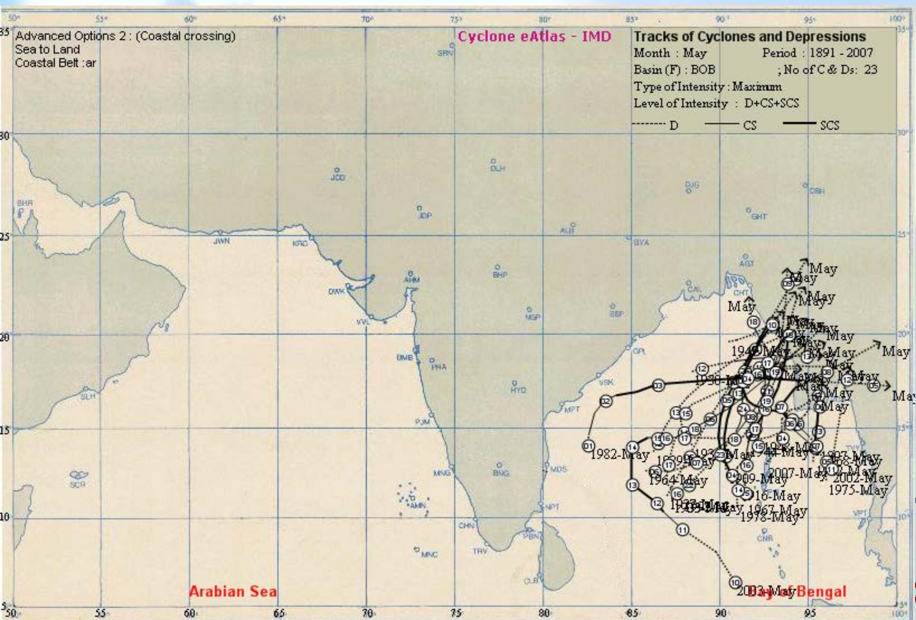




Analog method

1. Six hourly best track data of cyclones over north Indian Ocean since 1990 in digital form
2. 12 hourly data in cyclone Atlas during 1891-2009

   Data from 1877-1890 are also available in hard copies in 1979 edition of cyclone Atlas
3. Adverse weather and damage reports

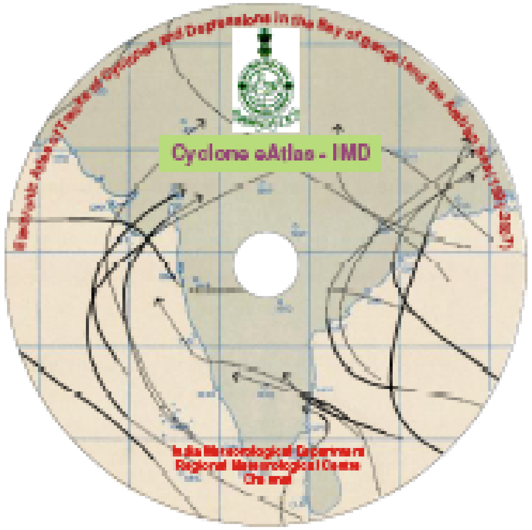


Tracks of Cyclones and Depressions in the Bay of Bengal and the Arabian Sea 1891-2007

Electronic version

June - 2008

Cyclone eAtlas – IMD

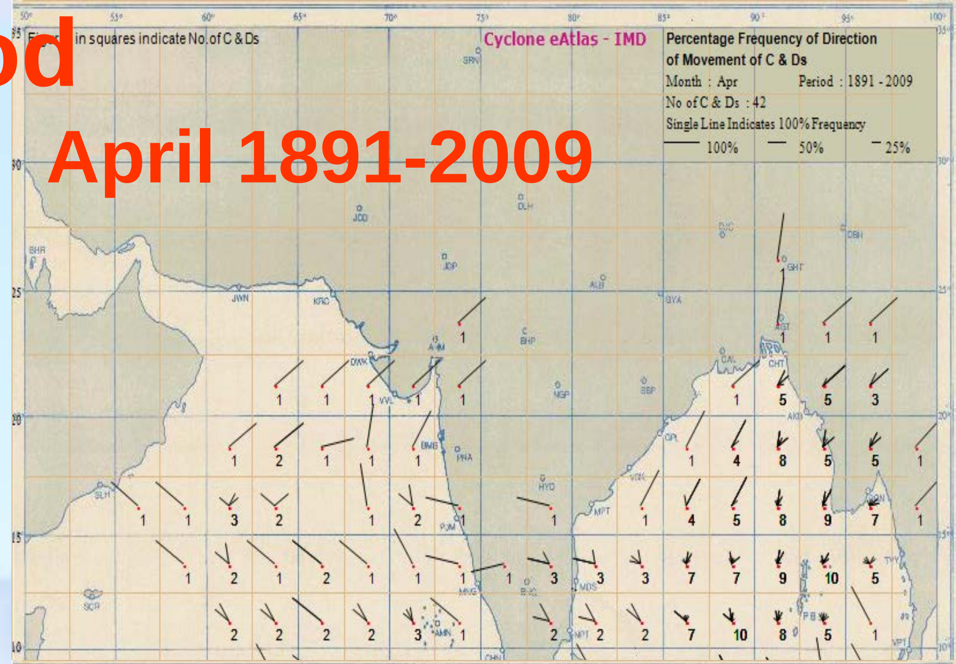


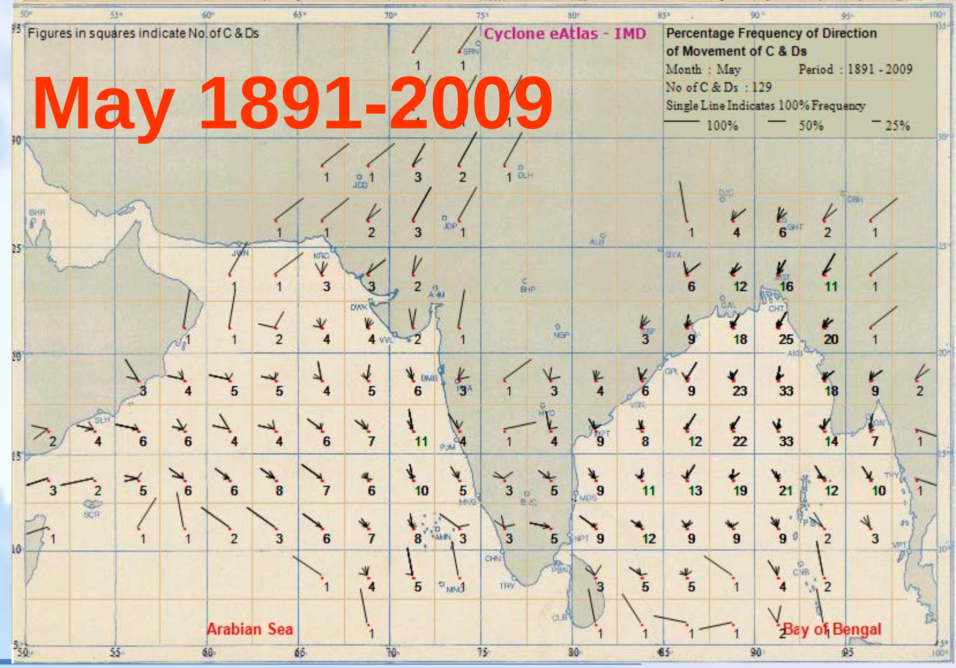
India Meteorological Department
Regional Meteorological Centre
Chennai, India

विज्ञान वि
OGICAL DEPA

Climatological Method

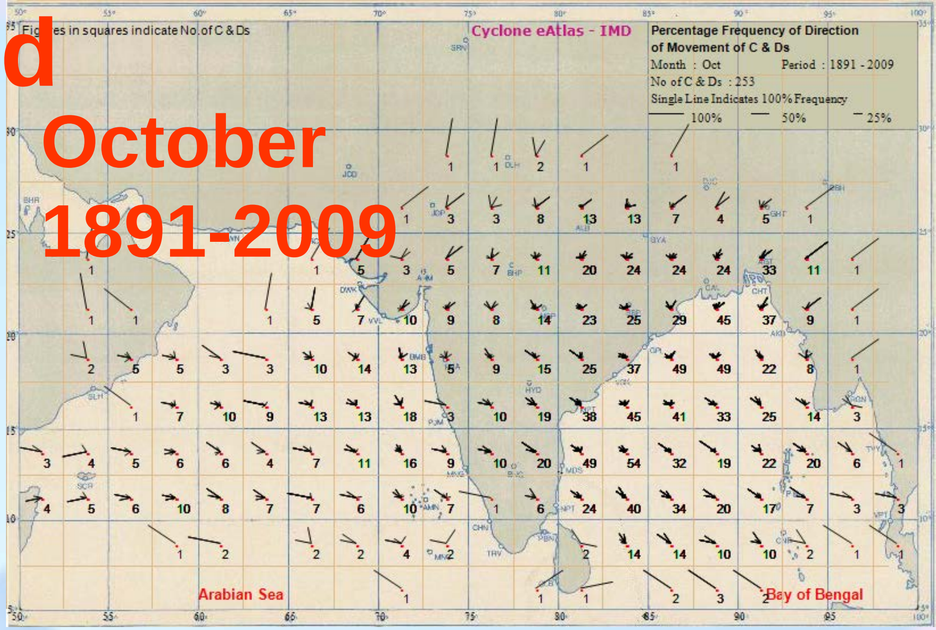
- **Most of the cyclonic disturbances above 15^{o}N move in a north-northeasterly or northeasterly direction**
- **Below 15^{o}N and left of 90^{o} E they generally move in north-northwesterly or northwesterly direction over the Bay of Bengal.**
- **In Arabian Sea below 15^{o}N they move in a north-northwesterly and above it they move northeasterly direction.**

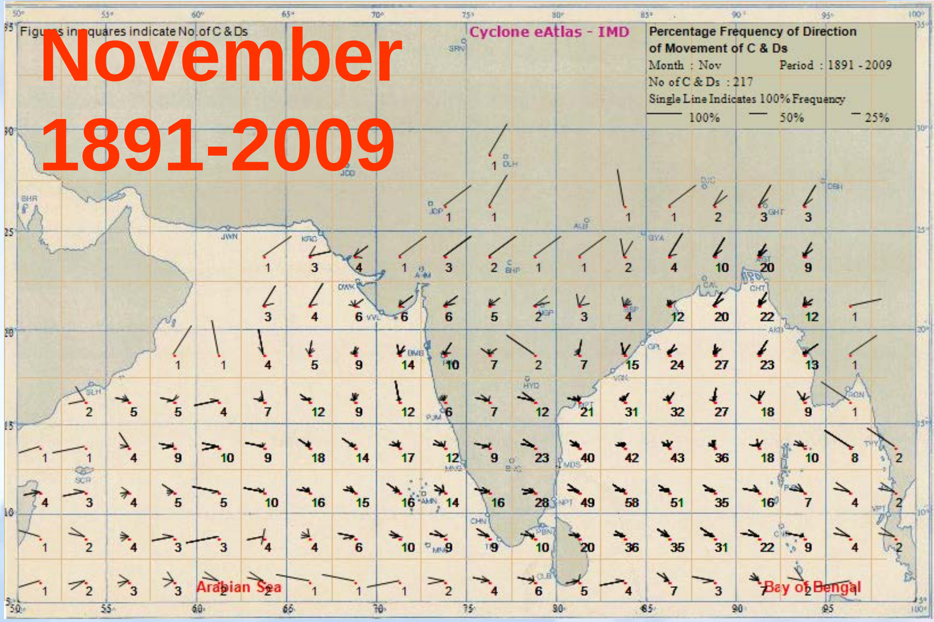




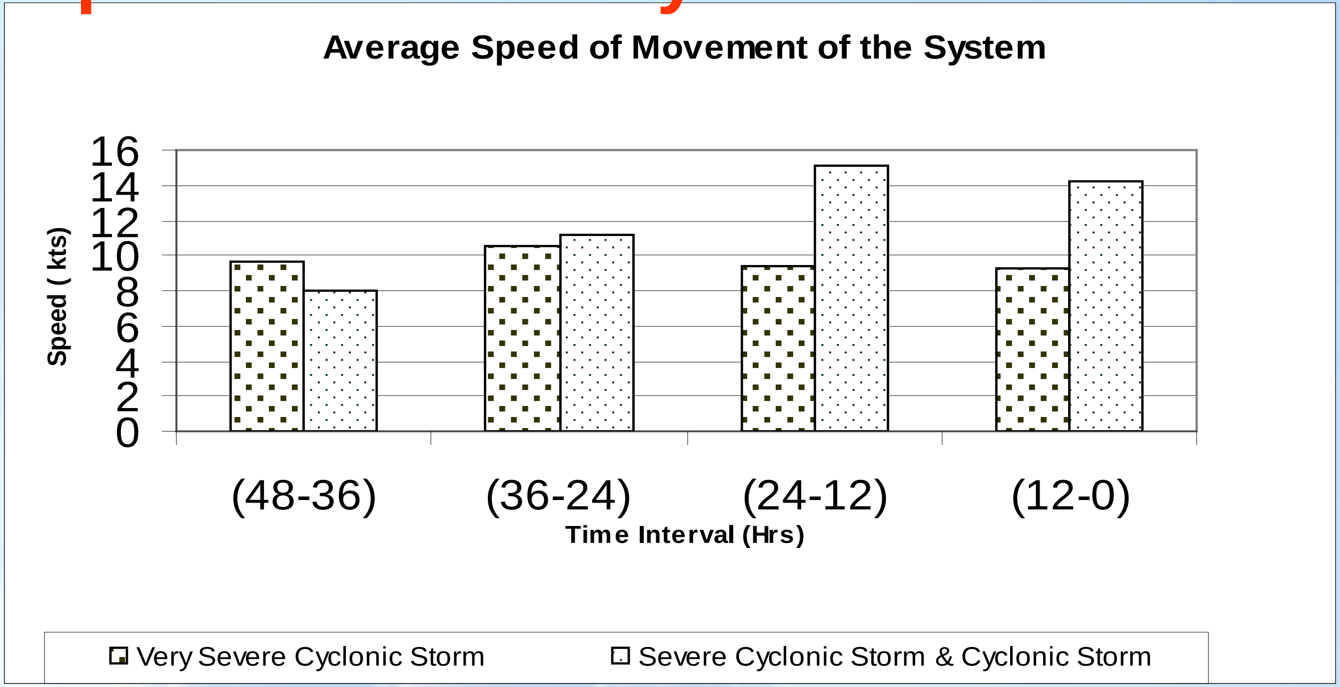
Climatological Method

- During October-November most of the cyclonic disturbances above 20^{o}N move in a north-northeasterly or northeasterly direction whereas below 15^{o}N they generally move in northwesterly direction over the Bay of Bengal.
- In Arabian Sea below 20^{o}N they move in a north-northeasterly and above it they move northeasterly direction.

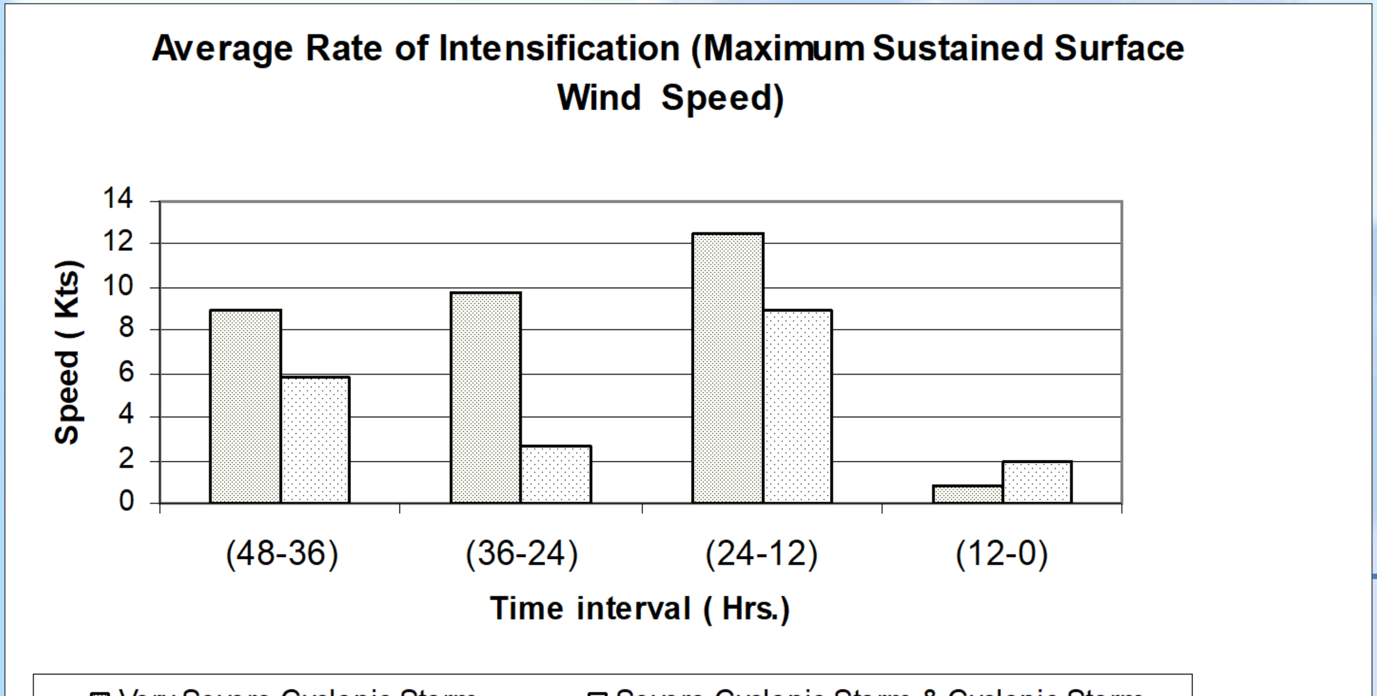




Climatology of Speed VS Intensity



Max. Speed of Movement of SCS (24-12)hrs & in Case VSCS (36-24)Hrs



Max. Rate of Intensification CS & SCS (24-12)hrs and in Case VSCS is also (24-12)Hrs

CLIPER Model

- Its working principle is very simple, it takes monthly climatology of movement and speed of cyclonic disturbances from input files.

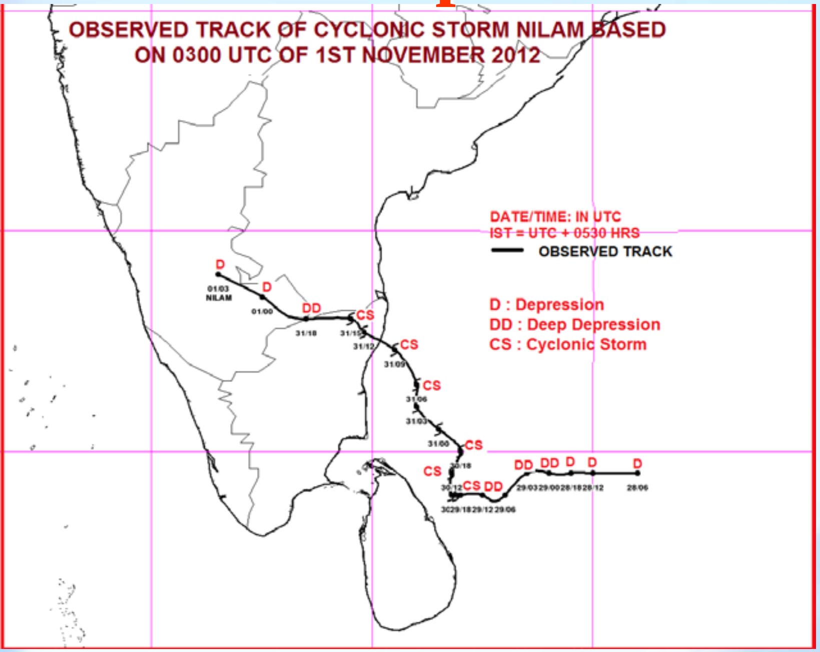
- It calculates the persistency of direction of movement and speed of the cyclonic disturbances for 09,12 and 24 hours as per our choose and forecast for the persistency for next 108 hours.

- It calculates the weighted mean of monthly climatology of direction of movement & direction of speed and persistency of movement & direction of speed which is the resultant direction of motion and speed of the cyclonic disturbance.

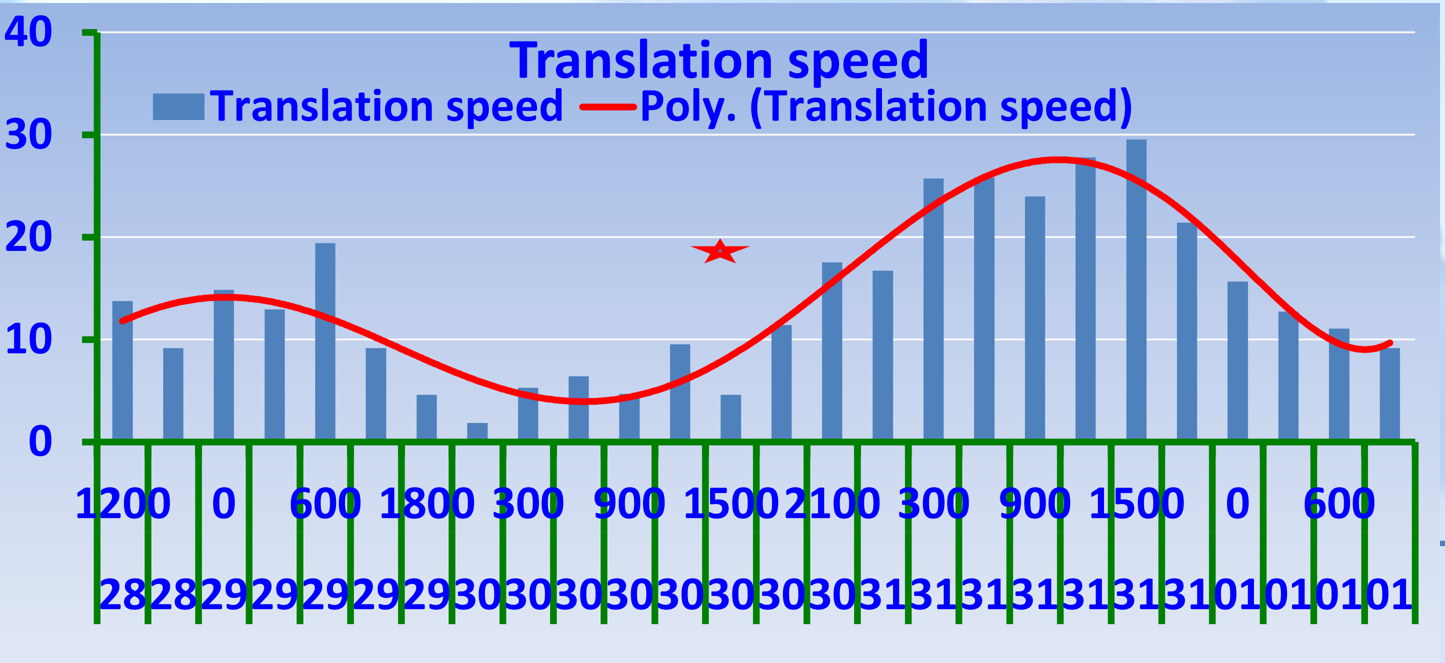
Example

- DATE=28 MONTH=5
- PRESENT LAT/PRESENT LONG= 14.500000 90.5
- PAST LAT/PAST LONG= 13.5 88.0
- ***
- **** CLIMATOLOGY OF STORMS *****
- ***
- FORECAST POSITIONS BASED ON PERSISTENCE:
- 0HOUR 14.5N 90.5E
- 12HOUR 15.5N 93.0E
- 24HOUR 16.5N 95.5E
- 36HOUR 17.5N 98.0E
- 48HOUR 18.5N 100.5E
- 60HOUR 19.5N 103.0E
- 72HOUR 20.5N 105.5E
- 84HOUR 21.5N 108.0E
- 96HOUR 22.5N 110.5E
- 108HOUR 23.5N 113.0E
- ***
- FORECAST BASED ON SEASONAL CLIMATOLOGY
- 0HOUR : 14.5N 90.5E
- 12HOUR : 15.9N 90.3E
- 24HOUR : 17.1N 90.4E
- 36HOUR : 18.3N 90.6E
- 48HOUR : 19.6N 90.8E
- 60HOUR : 21.0N 91.1E
- 72HOUR : 22.1N 91.5E
- 84HOUR : 23.3N 91.9E
- **** CLIMATOLOGY NOT AVAILABLE ***
- AVERAGE OF PERSISTENCE AND CLIMATOLOGY:
- 0HOUR LAT 14.5N 90.5E
- 12HOUR LAT 15.7N 91.7E
- 24HOUR LAT 16.8N 93.0E
- 36HOUR LAT 17.9N 94.3E
- 48HOUR LAT 19.1N 95.7E
- 60HOUR LAT 20.3N 97.1E
- 72HOUR LAT 21.3N 98.5E
- 84HOUR LAT 22.4N 100.0E
- ***

Translation speed and sudden change in direction of TCs



- To summarise, the translation speed gradually decreases for about 24 hrs period pror to change in direction of movement.
- Minimum translation speed becomes about 10 kmph in most of the cases
- This is true for both cases of increase in northerly and southerly components during the change



Track forecasting by synoptic method

TC Motion: The Beta Effect

- The "beta effect" accounts for 10-20% (up to 2 m/s) of TC motion

- Results from quasi-symmetric cyclonic flow superimposed on the north-south gradient of the Coriolis force ($\beta = d\mathbf{f} / dy$)

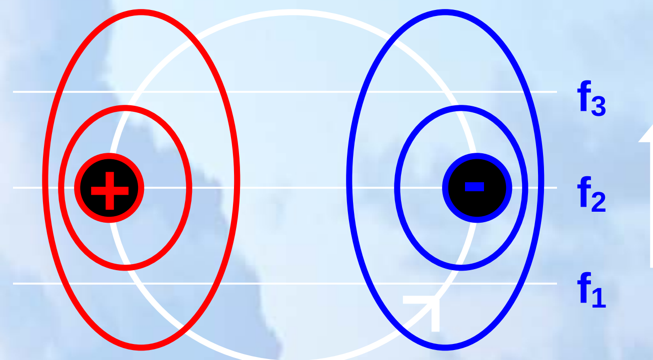
- "Simple" explanation from the Cartesian non-divergent barotropic vorticity equation

$$\frac{\partial \zeta}{\partial t} = -\left(u \frac{\partial \zeta}{\partial x} + v \frac{\partial \zeta}{\partial y} \right) - v\beta$$

Local Vorticity Change | **Advection of Vorticity** | **Beta**

Beta Contribution: An air parcel displaced southward (northward) will acquire positive (negative) relative vorticity

Vorticity Generation via Beta



Initially Symmetric Cyclonic Vortex

- Results in an east-west dipole of maximum negative-positive vorticity generation across the cyclone

TC Motion: The Beta Effect

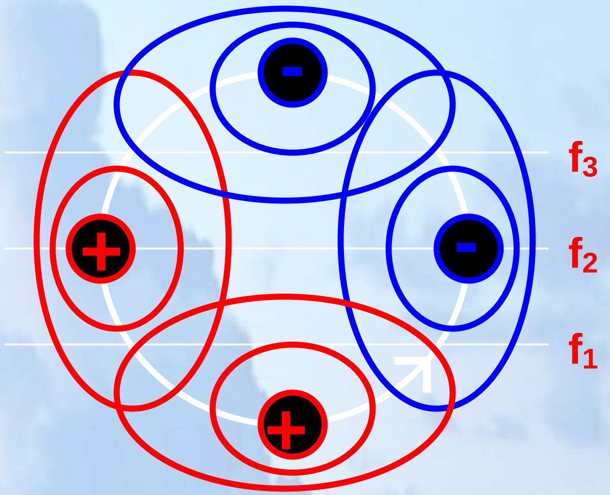
- **Advection Contribution:** The resulting cyclonic advection of the Beta-generated vorticity produces a north-south dipole of local vorticity change

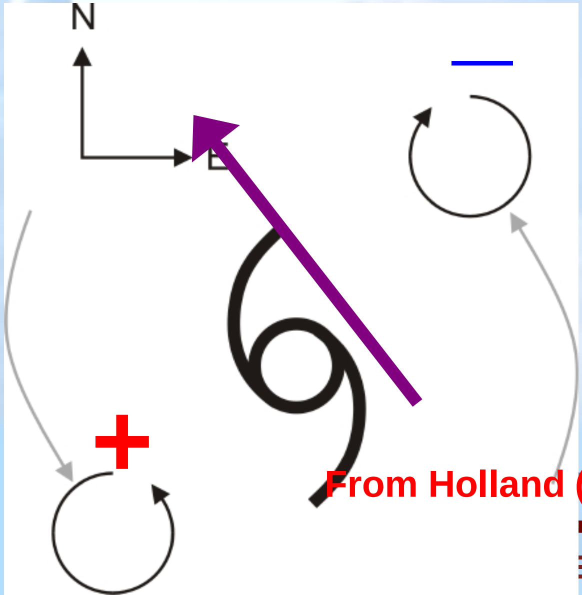
- Their combination **locally** produces two vorticity maxima, called "**beta gyres**", that induce a **northwesterly** component to TC motion (in the northern hemisphere)

$$\frac{\partial \zeta}{\partial t} = -\left(u\frac{\partial \zeta}{\partial x} + v\frac{\partial \zeta}{\partial y}\right) - v\beta$$

Local Vorticity Change | Advection of Vorticity | Beta

Vorticity Generation via Beta and Vorticity Advection



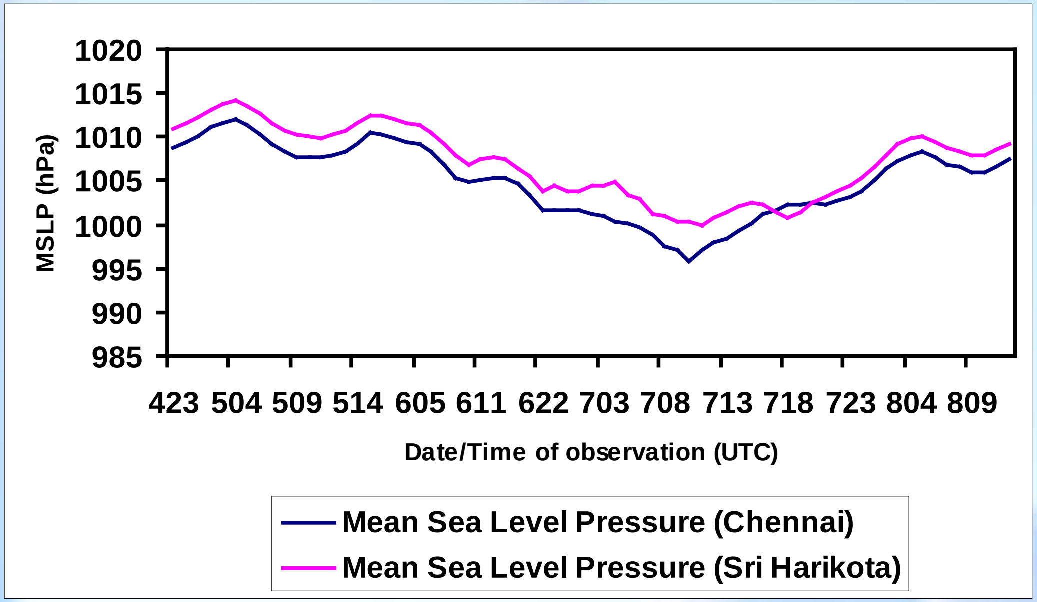


From Holland (1983)

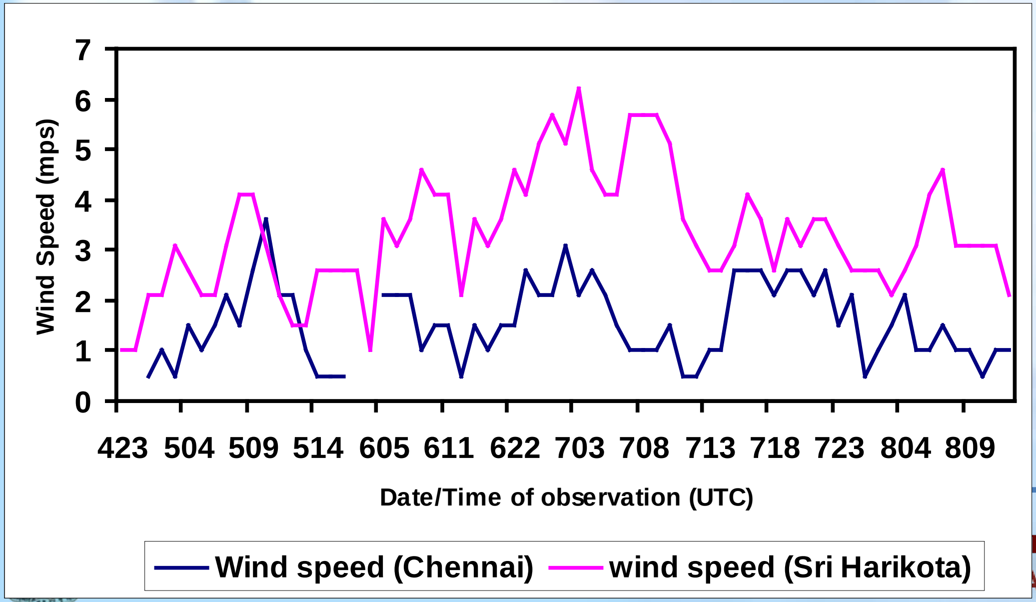
TC Motion (Synoptic) : Importance of P24P24

- The importance of P24P24 observation is amply illustrated in determining the track and land fall point.
- The importance of Isallobars
  - Lines passing through areas of equal pressure changes are known as Isallobars.
  - An Isallobaric low is as good as a pressure low.
  - The area of highest pressure fall (Isallobaric low) indicates the direction in which the system is heading.
  - So Isallobars play a major role in prognosis of cyclonic storms movement.

TC Motion : Utilityof AWS



MSLP and wind speed measured by AWS from 2300 UTC of 04 November to 1200 UTC of 08 November 2010 during severe cyclonic storm, JAL



- **The AWS data including wind and pressure could very well help in monitoring the genesis, intensity, structure and movement of the landfalling cyclonic disturbances.**

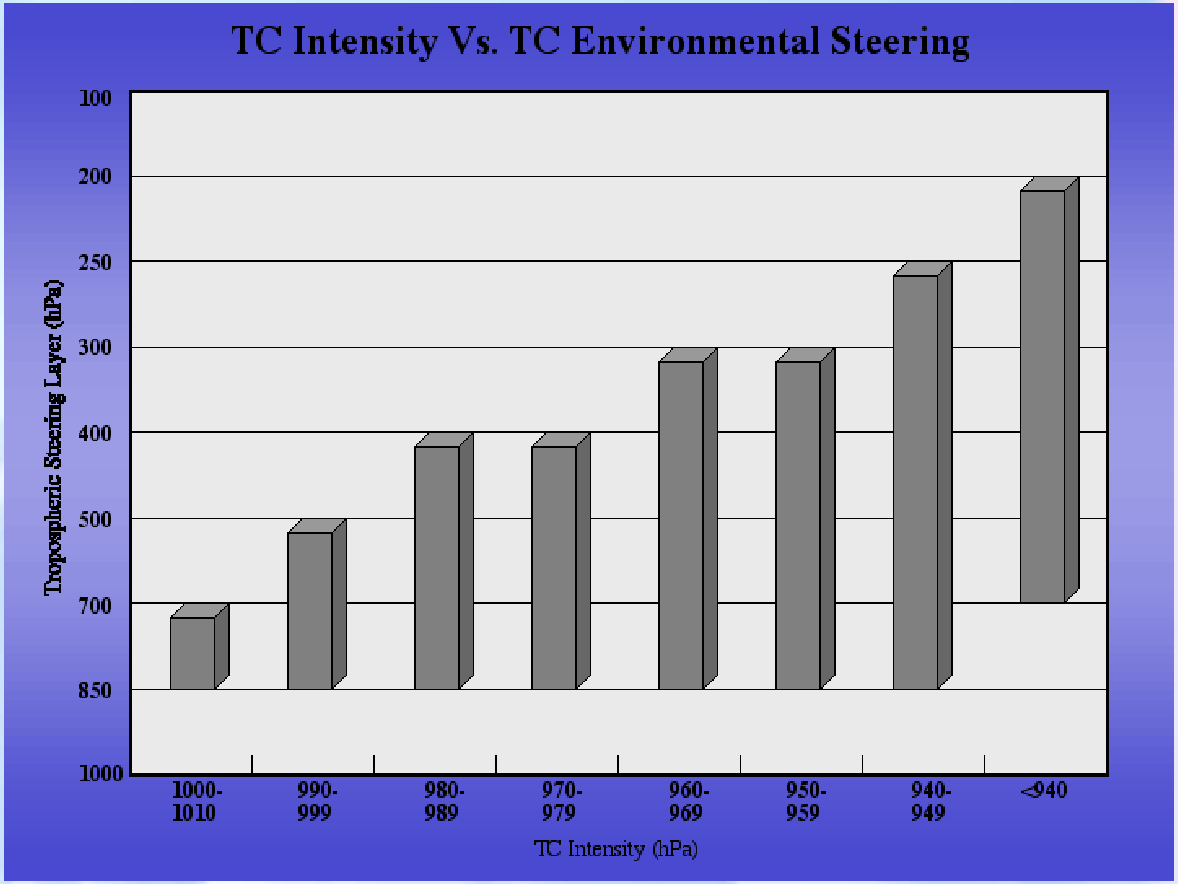
TC Motion (Synoptic): Steering Flow

Motion of Individual TCs:

- The deep layer environmental flow accounts for a large fraction (up to 80%) of TC motion
- Assumes the TC acts as a passive vortex moving with the speed and direction of the mass-weighted deep layer flow
- When a deep layer estimate is unavailable use the following:

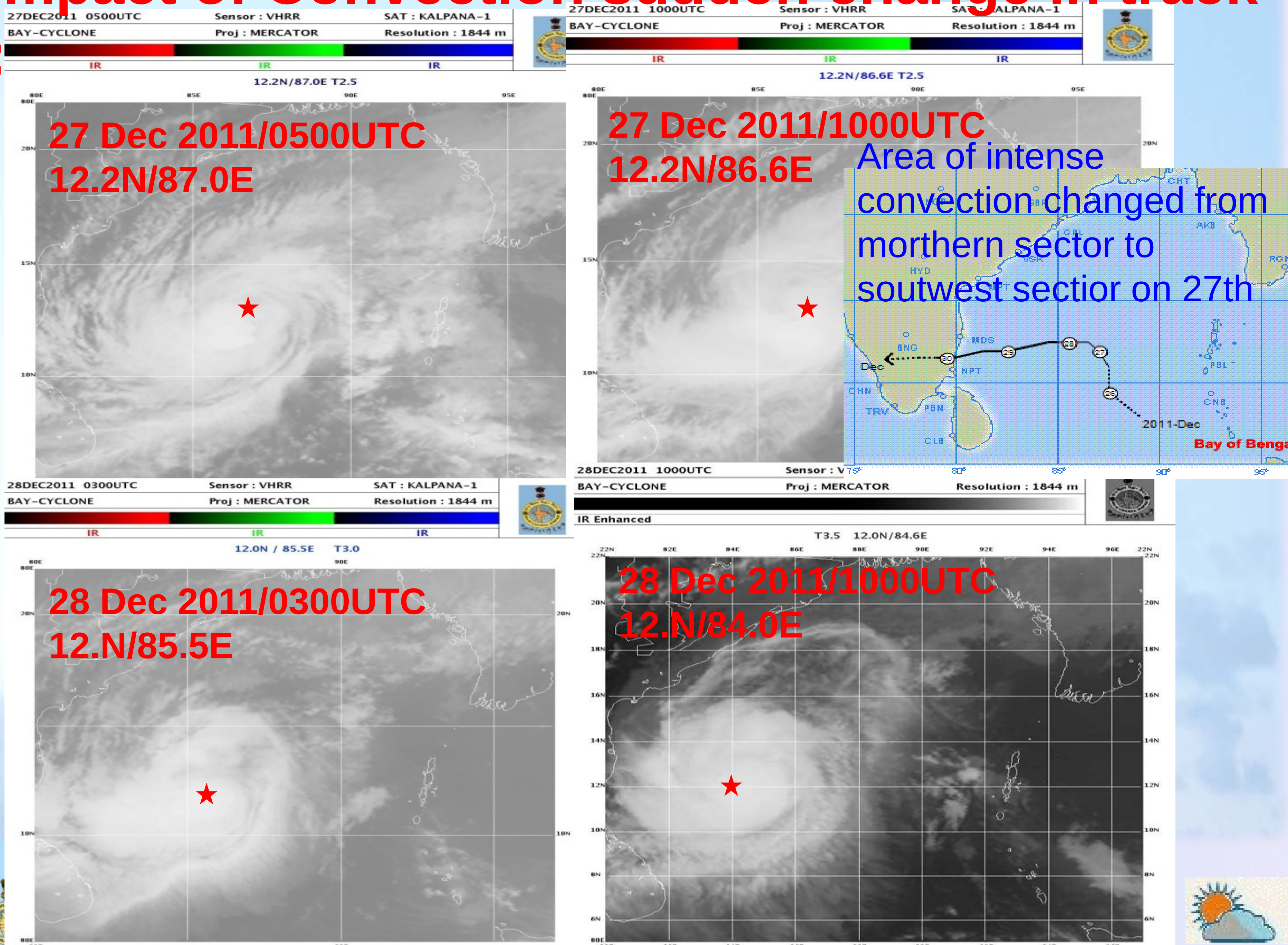
  TD and TS: 700 mb flow

  Hurricane: 500 mb flow



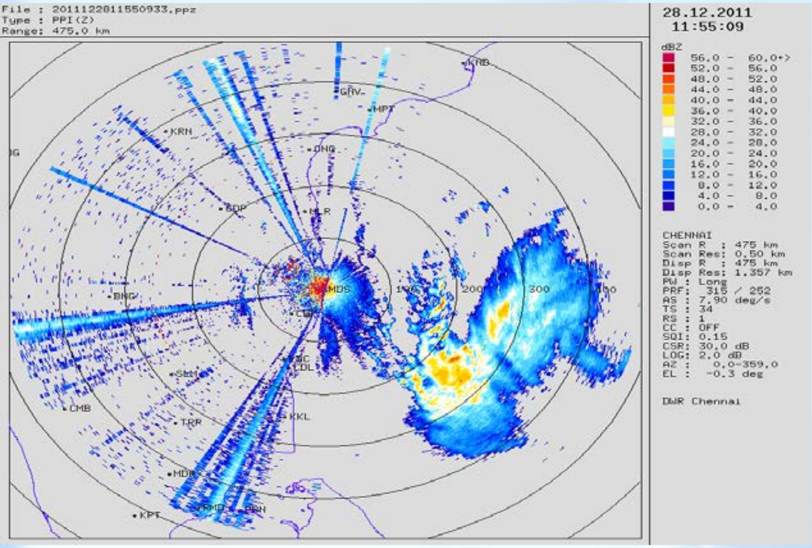
From Velden and Leslie (1991)

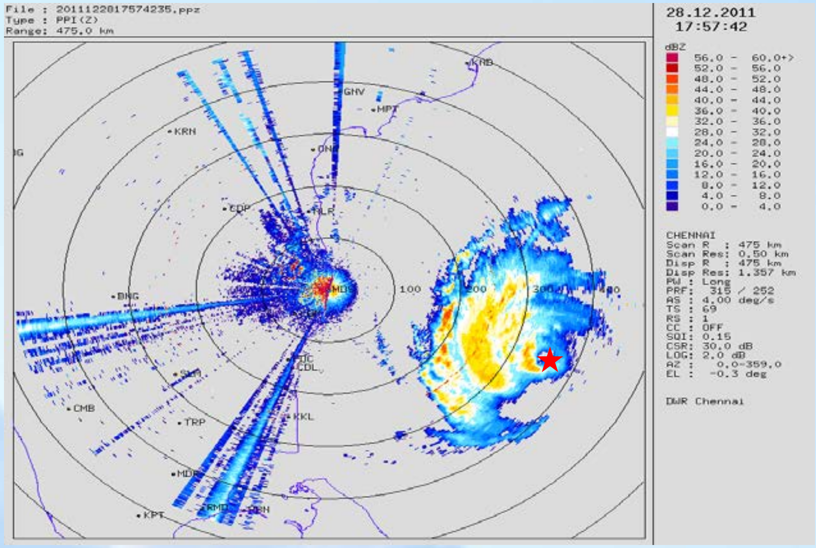
Impact of Convection sudden change in track :

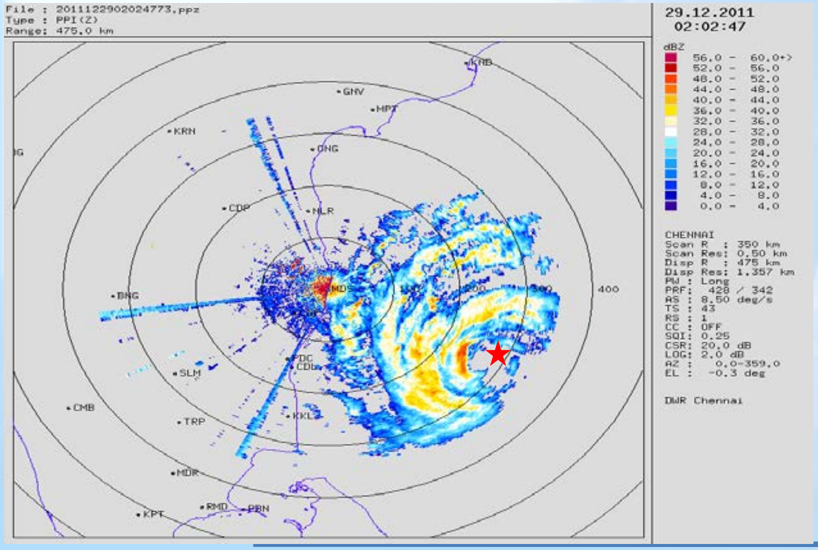


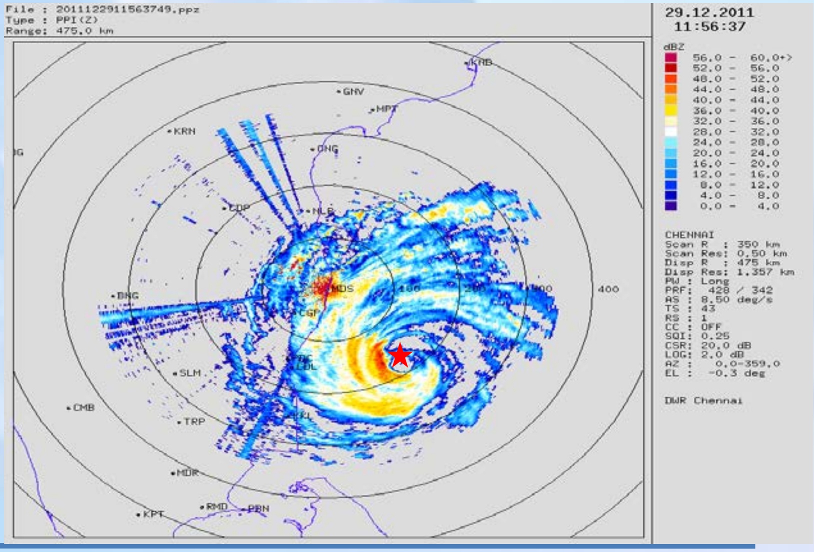
Impact of convection on sudden change in track

Southward shifting of area of intense convection is also seen in DWR imageries

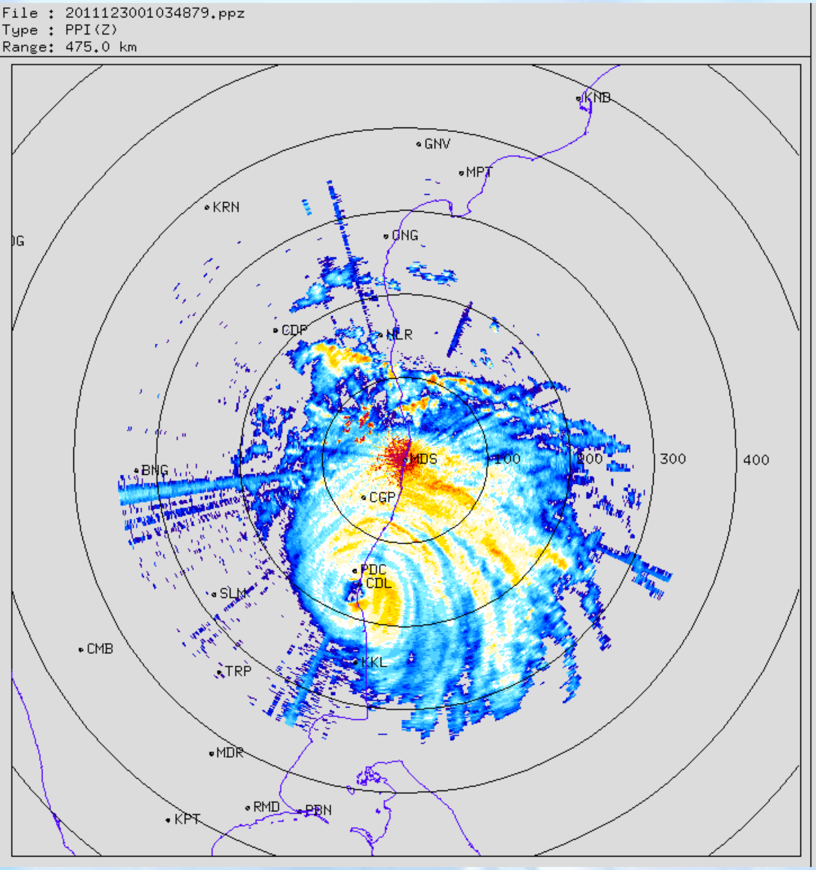


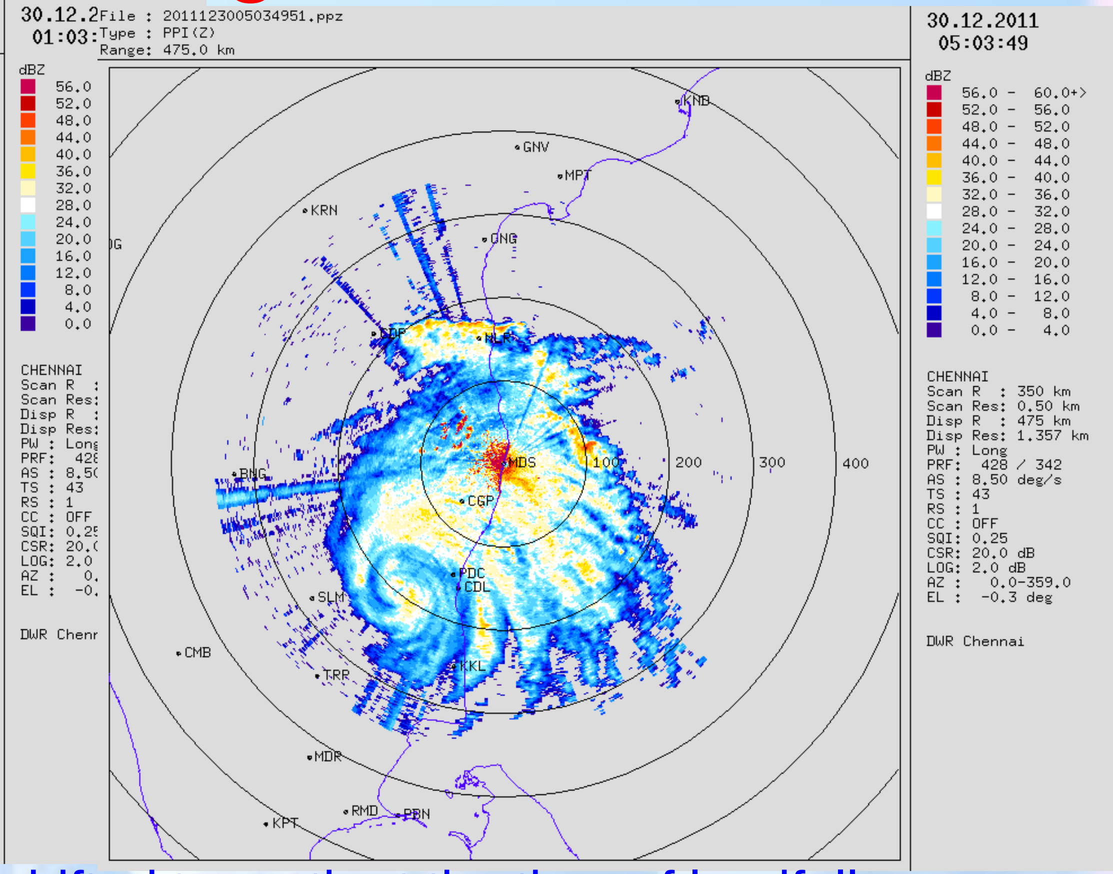






Impact of convection on sudden change in track :





Area of intense convection again shifted to north at the time of landfall

भारत मौसम विज्ञान विभाग
INDIA METEOROLOGICAL DEPARTMENT

TC Motion (Synoptic): Trochoidal Motions

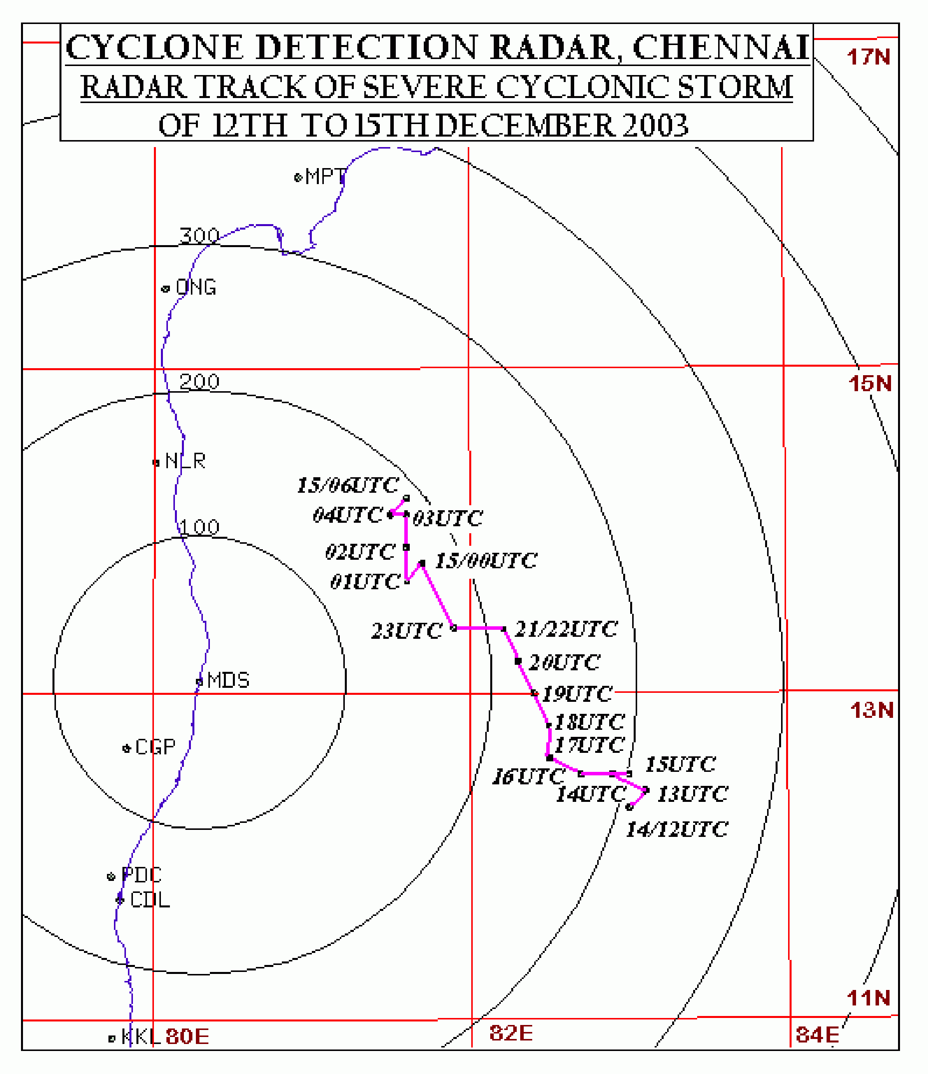
Motion of Individual TCs:

•Many cyclones experience "wobbles", or oscillations, with respect to their time averaged motion vector (usually less than the eye diameter)

• This trochoidal motion is believed to result from the co-rotation of the TC's circulation center with a smaller mesovortex (perhaps generated by a deep convective burst)

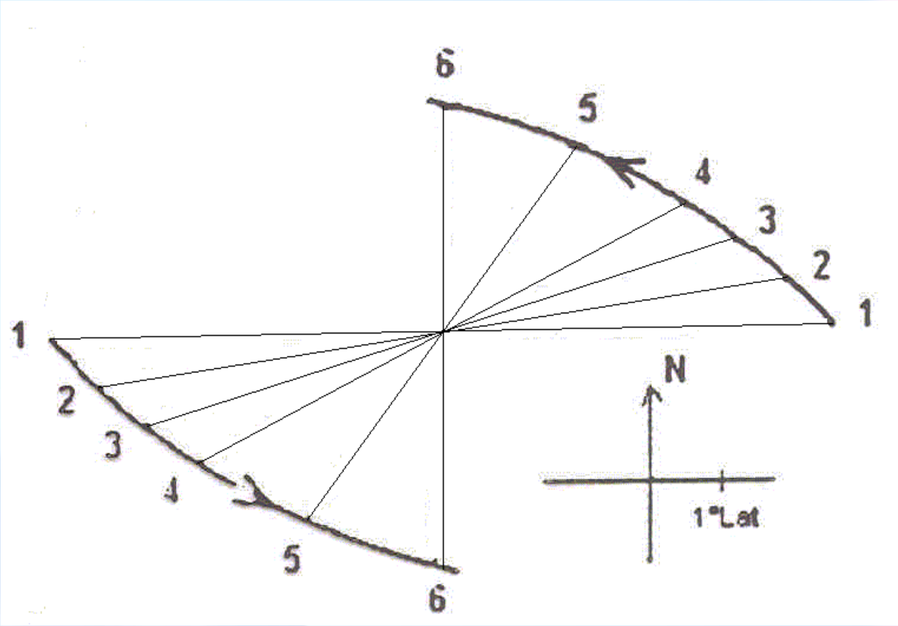
• Trochoidal motions are often removed from the official "best" track

• Trochoidal motions are often misinterpreted as "turns" if TC is tracked from center fix to center fix….forecasters beware



TC Motion (Synoptic) Fujiwhara effect

- Attraction between 2 tropical cyclones close enough each other (named by Dr S. Fujiwhara who first studied the phenomenon)
- The Fujiwhara effect depends on the compared size and intensity of both systems
- It is possible to separate the motion of both vortex as a rotation around their centroid



Empirical rule for the Fujiwhara effect :

Dominates when distance between vortex < 6 degrees of latitude

Becomes progressively less important than the average basic current for a separation distance of 7 to 15 degrees

Is too weak for more than 15 degrees.

Motion of Individual TCs:

- Some storms tend to drift toward their latent heating centroid (which may be offset from the circulation center due to vertical shear)
- Some storms drift toward synoptic- scale troughs (particularly if the trough is deepening)
- Many storms will move toward a weakness in a ridge (a relative low pressure in a high pressure system)
- Common theme: TCs tend to drift toward other areas of low pressure

Track forecasting by radar and satellite

1. Pre-cyclone squall lines (Region of occurrence, time of occurrence
2. Precipitation characteristics (Place and time of occurrence of maximum precipitation)
3. OLR
4. Maximum reflectivity
5. Steering flow

Squall Lines & rain bands:

- Squall lines are a kind of linear organized meso-scale convective systems, cause thunderstorms and torrential rain. Generally it appear ahead of landfalling TCs.
- Squall lines tend to form in the transition area between the TCs and sub-tropical high in a moist environment & with a weaker cold pool than their mid latitude counterparts.
- As per yihong Duan et.al (2011)about 40% of landfalling TCs are associated with Pre-Tc squall lines.
- The squall lines as per Parker and Johns's (2000), the region of ≥ 40 dBz reflectivity extend longer than 100 kms for at least 2-3 hours and convection of this region is organized in linear or quasi linear shape with an apparent common leading edges.

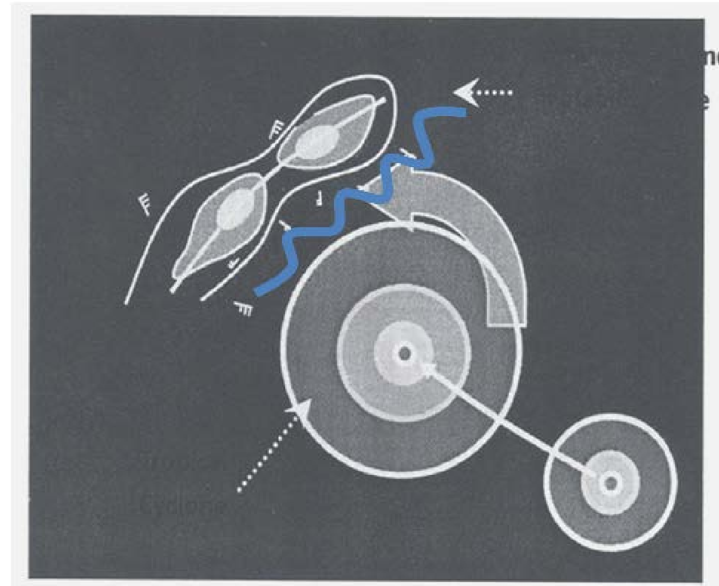


Fig.5 Schematic diagram of the genesis of pre-TC-squall line

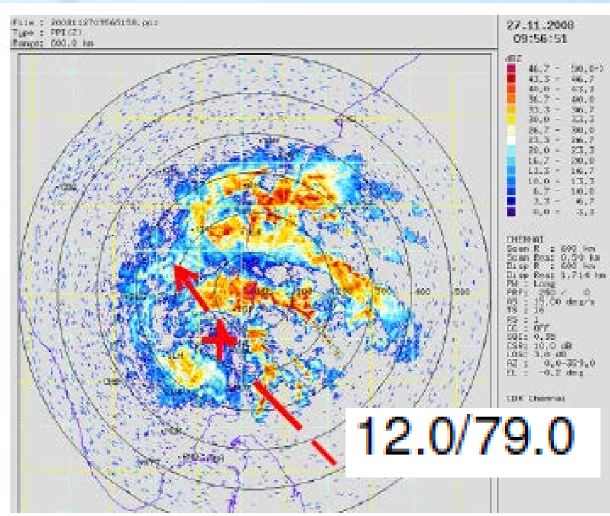


Fig. 3: Doppler weather Radar Chennai imagery in association with cyclonic storm NISHA

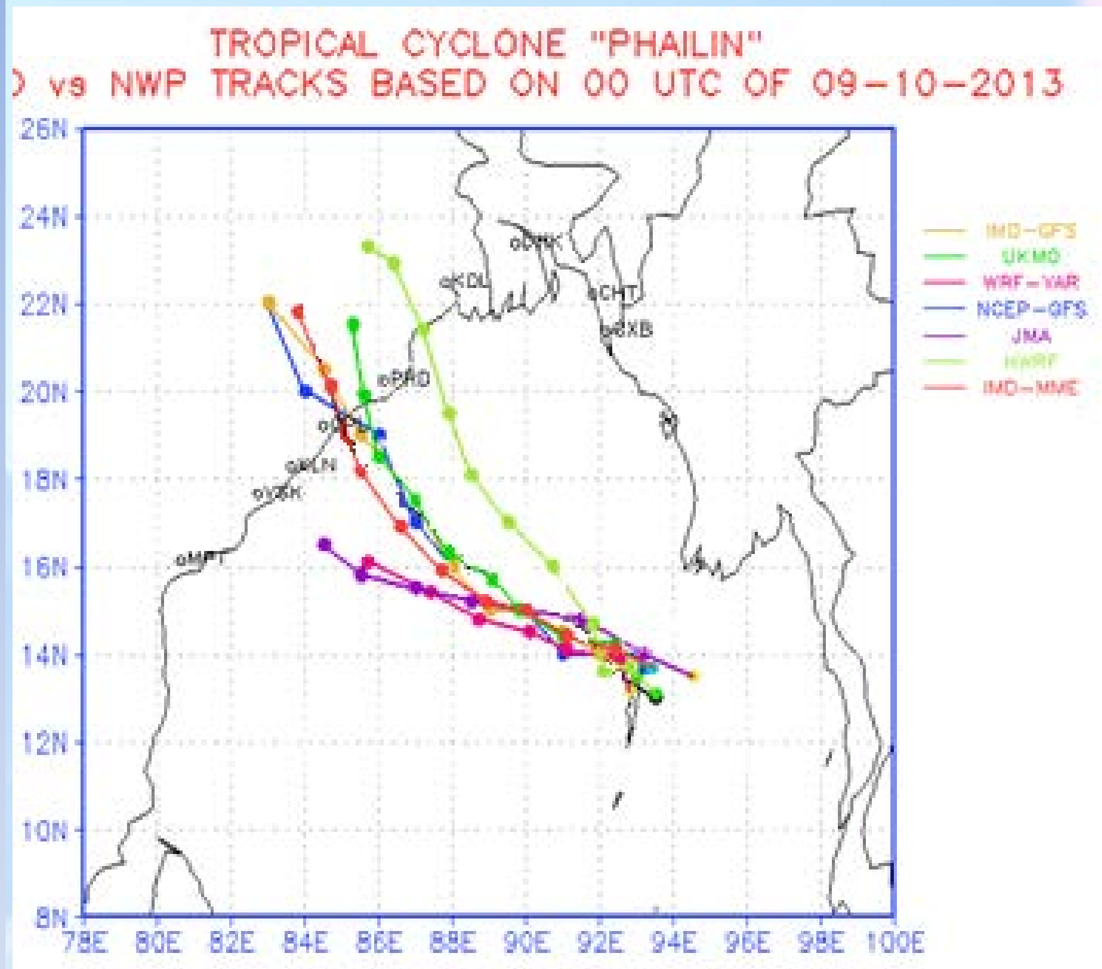
TC Motion : Operational NWP Models

- ❖ **Medium Range Forecast**
  - ***> GFS T-382 /574 L64 with GDAS (00 & 12 UTC)***

  >NWP products available from ECMWF, GFS (NCEP), JMA (Japan Meteorological Agency), UKMO also provided for medium range guidance and genesis prediction.

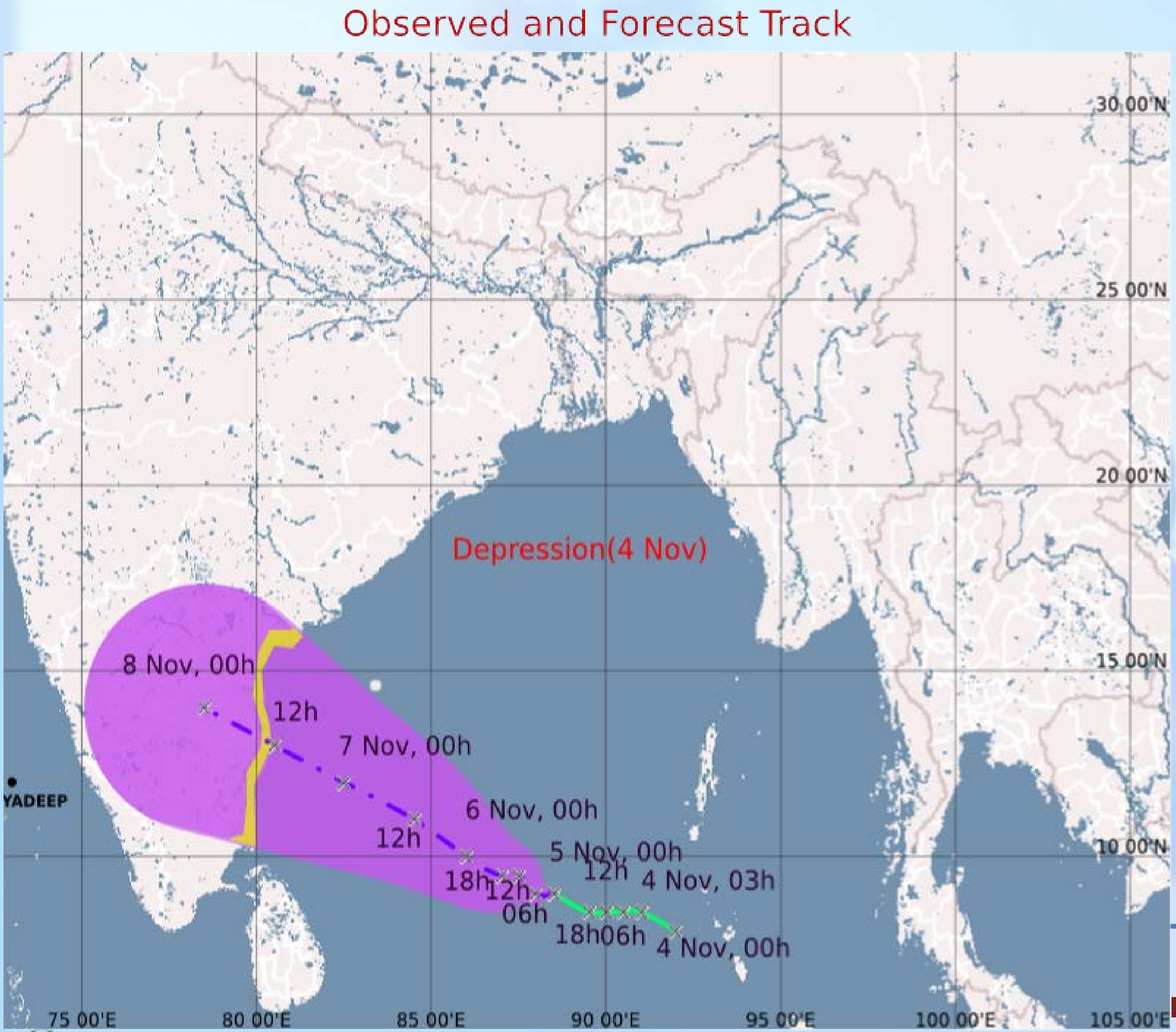
  >NWP division also provided six hourly intensity forecasts and genesis potential inputs during cyclone conditions.

- ❖ **Short Range Forecast**
  - ***WRF (ARW)***
  - ***> WRF (NMM/HWRF)***
  - ***> QLM at 40 km (00 & 12 UTC)***
  - ***> MME Cyclone Forecast and EPS***



Cone of Uncertainty in track forecasting

INDIA METEOROLOGICAL DEPARTMENT



NT

TC intensity forecasting methods

i) Statistical Techniques
   i) Analogue
   ii) Persistence
   iii) Climatology

ii) Synoptic Techniques – Empirical Techniques (as discussed in case of genesis)

iii) Satellite Techniques Techniques

iv) Radar Techniques

v) NWP Models
   - Individual models (Global and regional)
   - IMDGFS (574), NCMRWF (574), ARP (MeteoFrance, ECMWF, JMA, UKMO, NCEP, WRF (IMD, IITD, IAF), HWRF (IMD), QLM
   - Wind probability (To be developed) and risk
   - Threat graphics (To be developed)

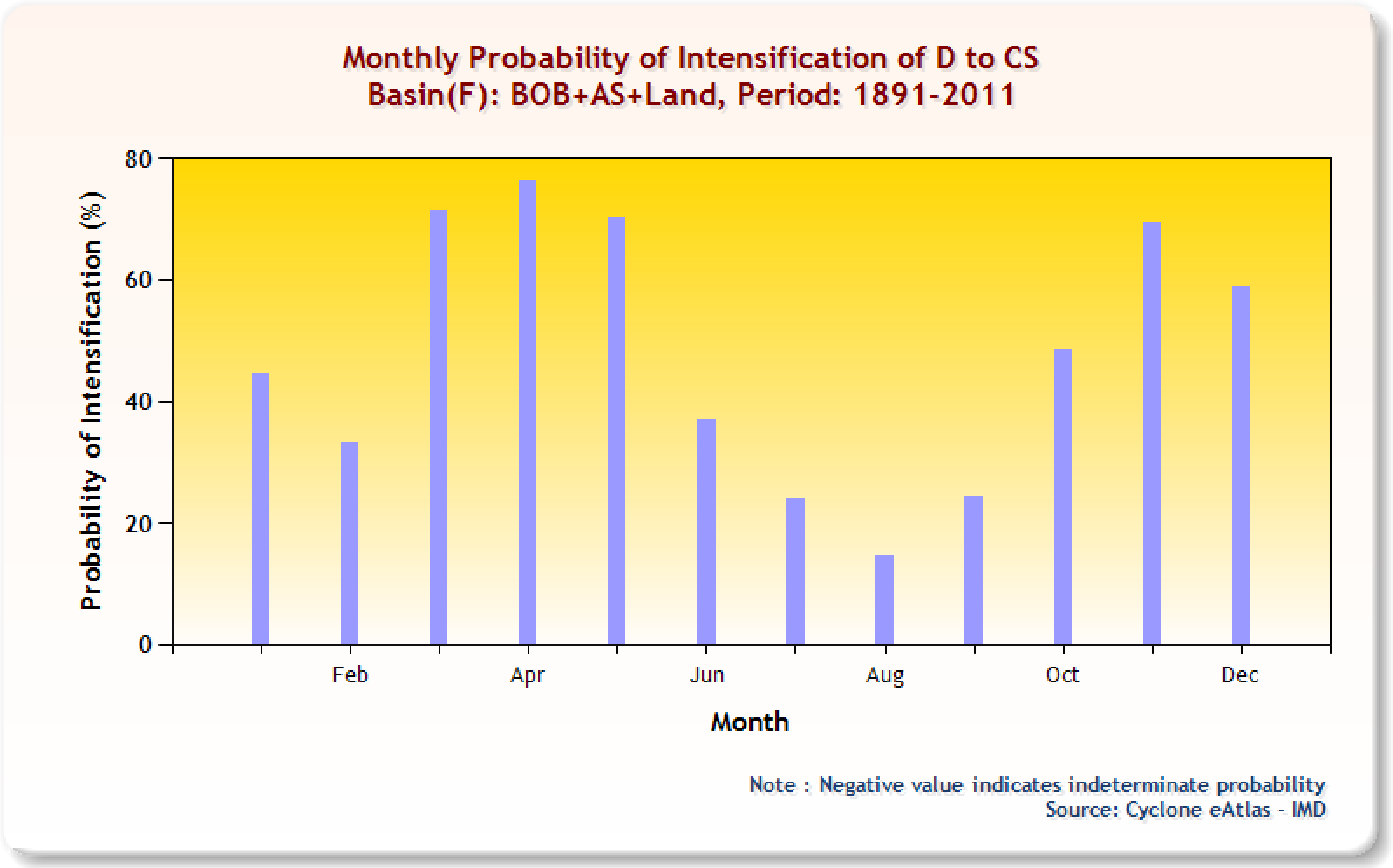
vi) Dynamical Statistical Model (SCIP)

Operational (Consensus) forecast

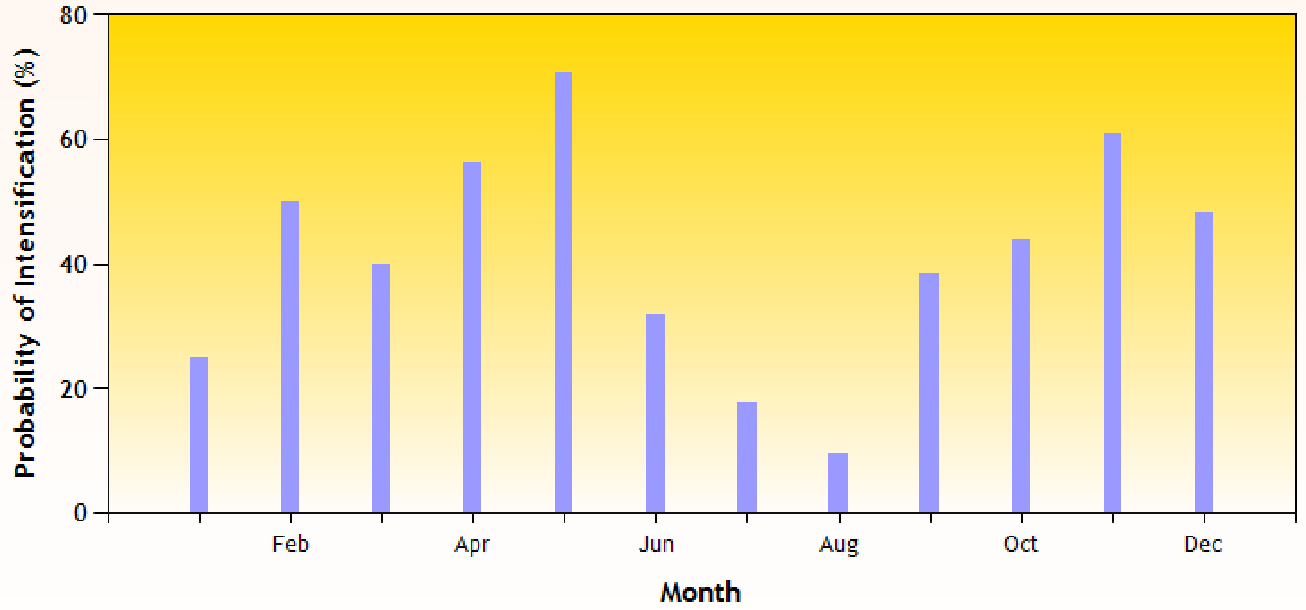
CLIMATOLOGY : DISTRIBUTION OF WIND IN DEPRESSION AND STORM

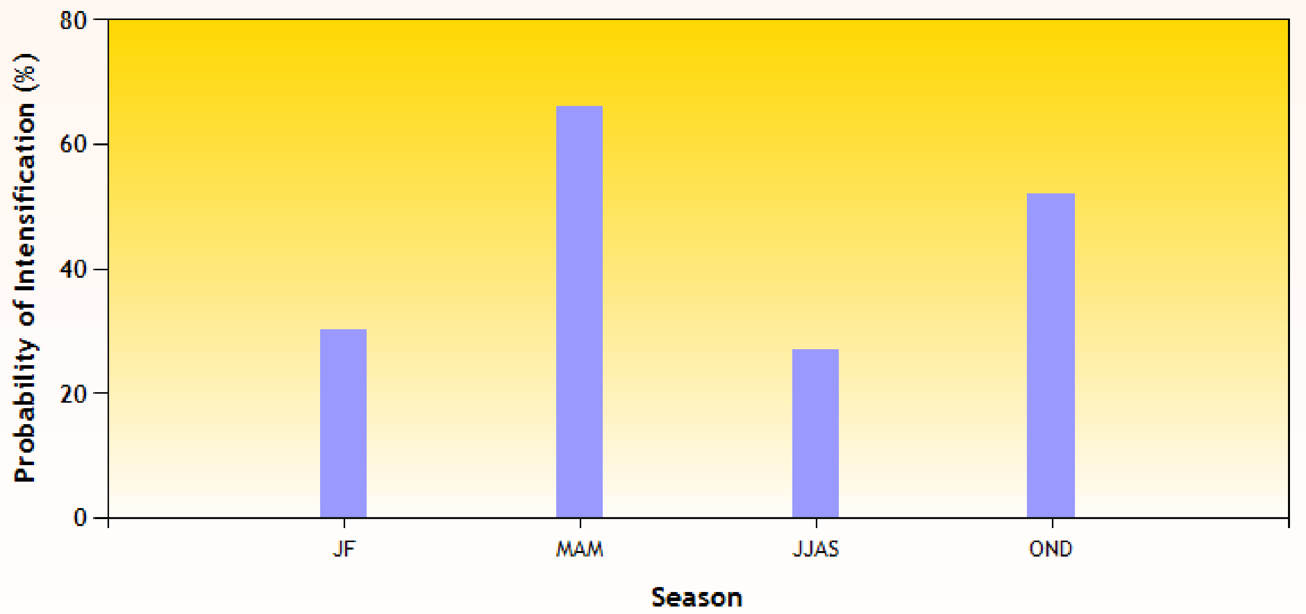
- WINDS CLOSER TO CENTRE ARE WEAK IN A DEPRESSION OR LOW. HIGHER WIND OCCURS ABOUT 2-3 DEG AWAY FROM CENTRE
- WIND SPEED IS HIGHER NEAR THE CENTRE IN A CYCLONIC STORM
- ASYMMETRY IN WIND FIELD IS MORE IN DEPRESSION THAN IN CYCLONE
- HENCE THERE MAY BE DIFFICULT SITUATION IF ONLY WIND SPEED IS CONSIDERED. OTHER INPUTS LIKE SATELITTE AND RADAR INPUTS SHOUD BE TAKEN INTO CONSIDERATION.
- SIGNIFICANT DEPARTURE FROM NORMAL WIND IN TERMS OF DIRECTION OR SPEED OR UNUSUAL DIURNAL VARIATION SHOULD BE NOTED AS POTENTIAL INDICATOR.

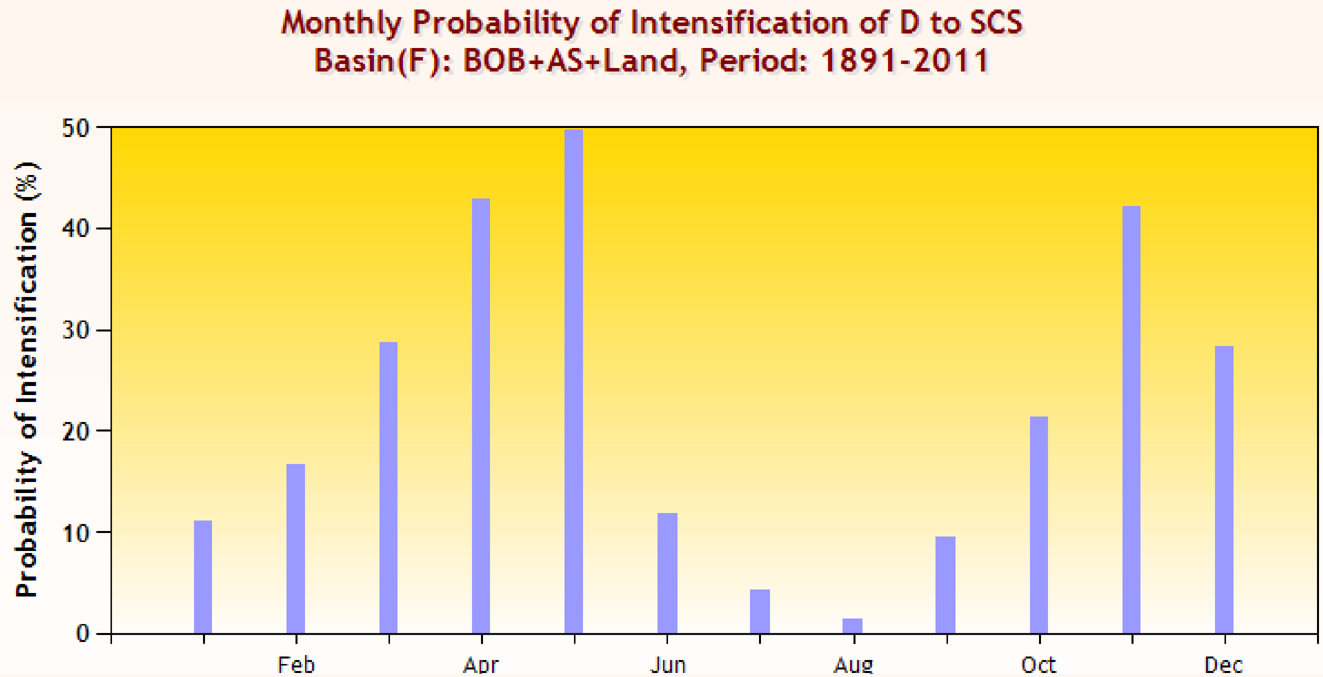
Probability of intensification

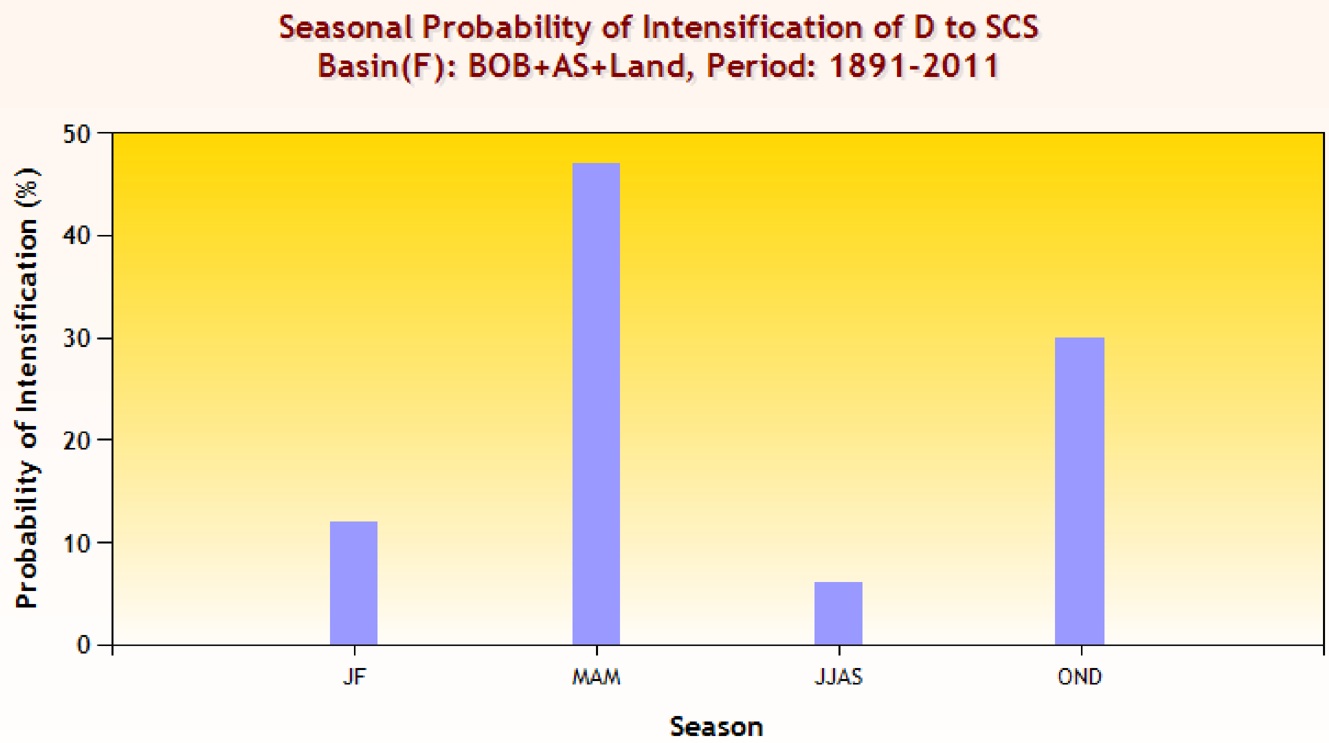


Monthly Probability of Intensification of CS to SCS
Basin(F): BOB+AS+Land, Period: 1891-2011






Monthly Probability of Intensification of D to SCS
Basin(F): BOB+AS+Land, Period: 1891-2011
Probability of Intensification (%)
0
10
20
30
40
50
Feb
Apr
Jun
Aug
Oct
Dec


Seasonal Probability of Intensification of D to SCS
Basin(F): BOB+AS+Land, Period: 1891-2011
Probability of Intensification (%)
0
10
20
30
40
50
JF
MAM
JJAS
OND
Season

Intensity forecasting by satellite method

- Continuous observation of cloud features in visible and IR imageries
- Use of microwave imageries
- Derived products
- (wind shear, vorticity, convergence/divergence
- Monitoring of brightness temperature/ cloud top temperature
- OLR
- QPE

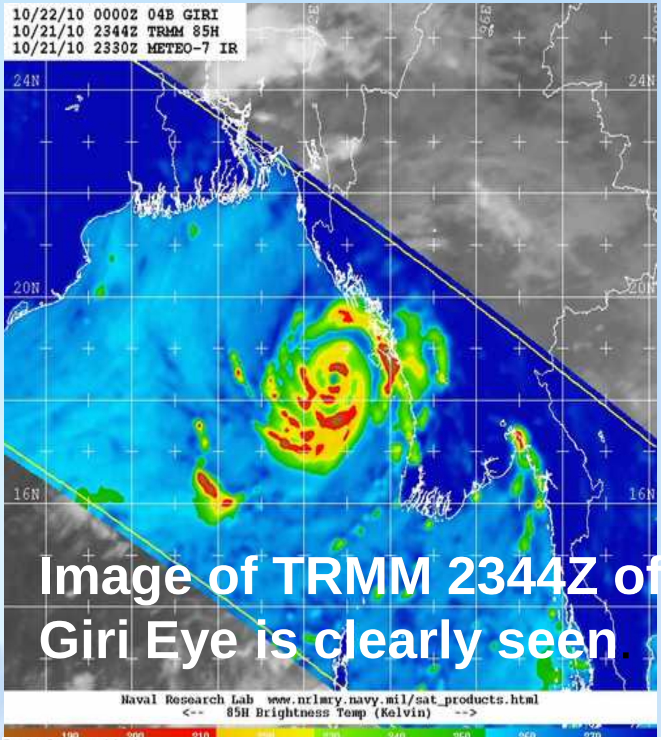
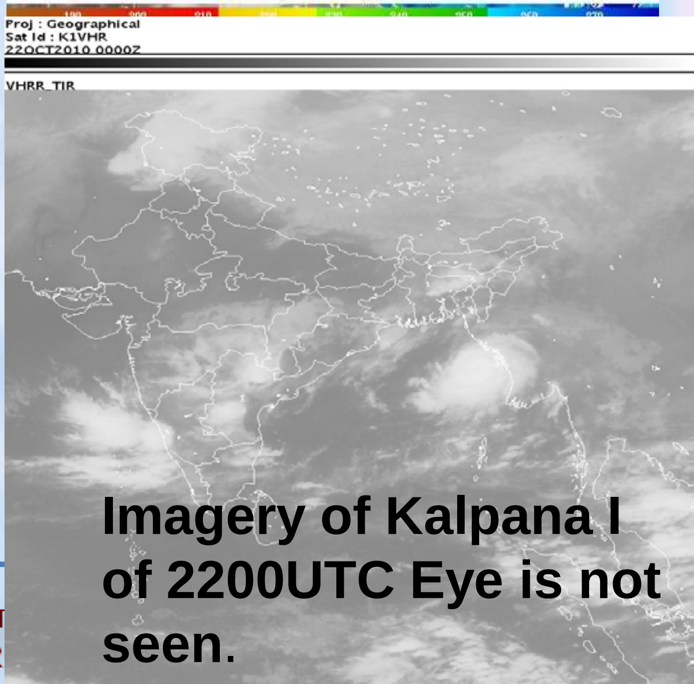


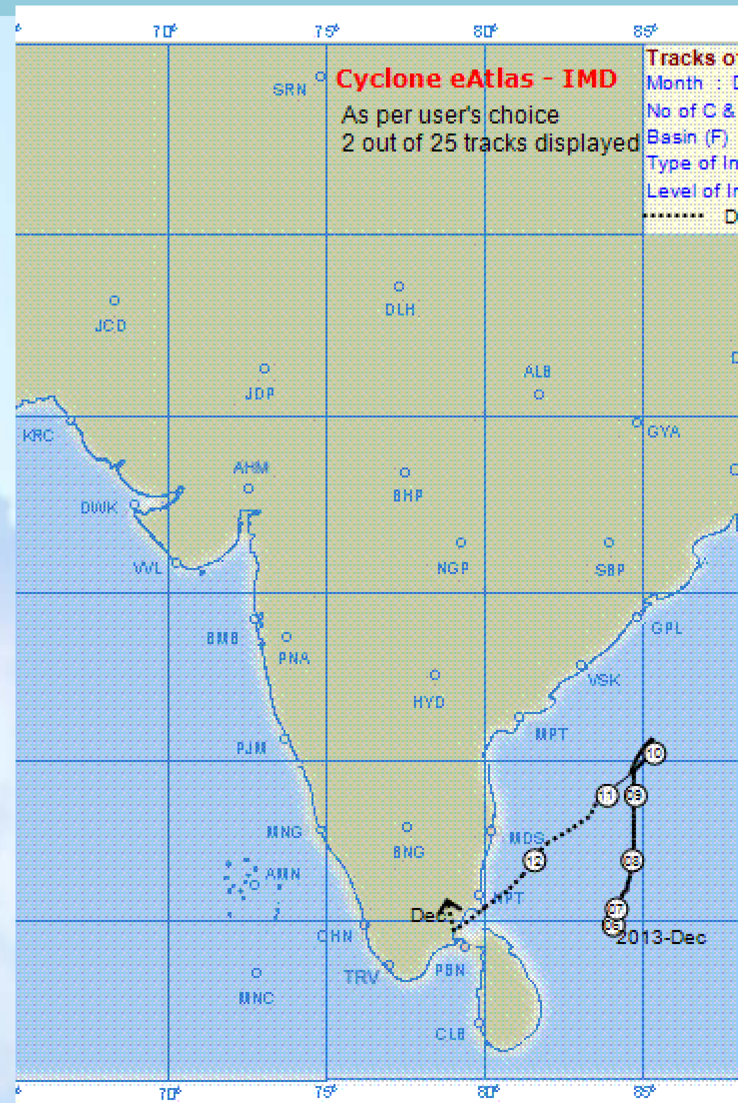
Image of TRMM 2344Z of Giri Eye is clearly seen.



Imagery of Kalpana I of 2200UTC Eye is not seen.

VSCS MADI (8-13 DEC. 2013)

Track of VSCS Madi was most unique. Hence a study was undertaken to analyse the diagnostic features leading to this unique track, intensification and weakening of the system. The following were the salient features of the VSCS Madi:



(i) It had a unique track with near northerly movement till 15.7°N and then recurving southwestwards to Tamil Nadu coast.

(ii) It moved very slowly during its northward journey and speed peaked up gradually after the re-curvature to southwest.

INTENSIFICATION PARAMETERS

Same as genesis parameters

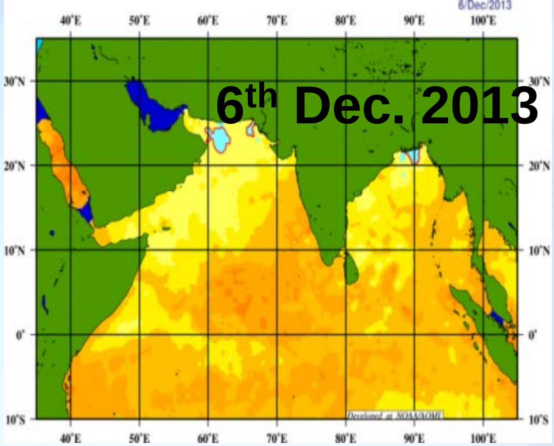
Dynamic Parameters

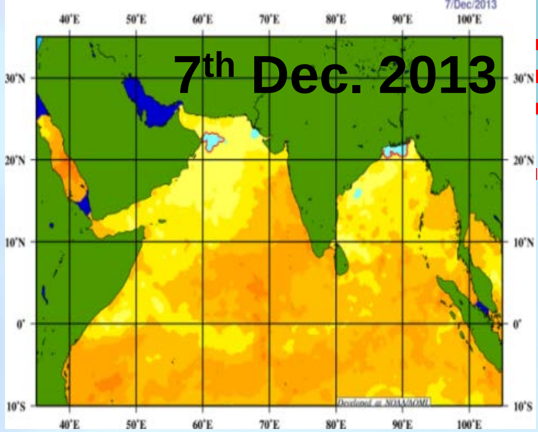
1. **Low level relative vorticity**
2. **Coriolis parameter**
3. **Inverse of the vertical wind shear of the horizontal wind between lower and upper troposphere (950 and 200 hPa levels)**

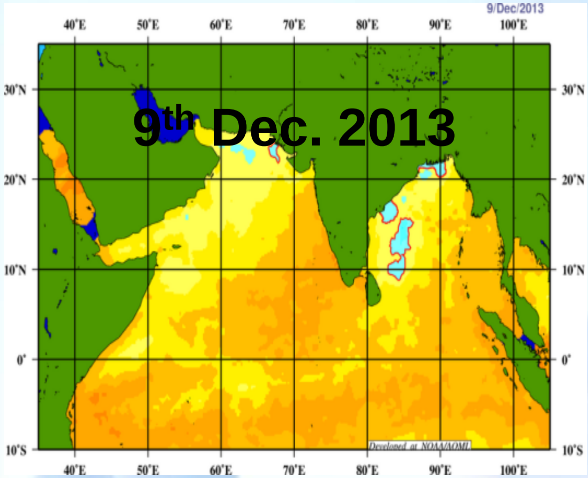
Thermodynamic Parameters

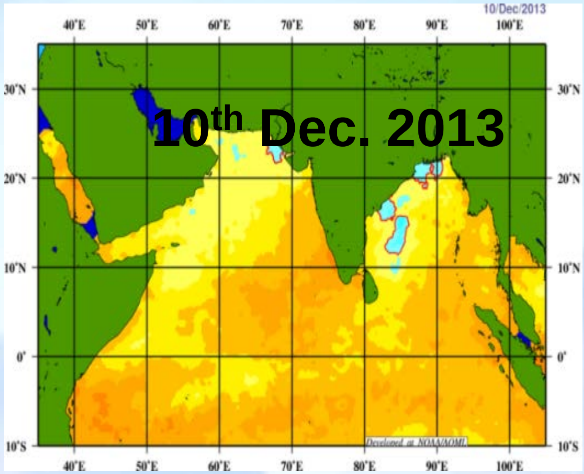
1. **Ocean Thermal energy to a depth of 60 m.**
2. **Degree of Conditional Instability as given by $\partial\theta e/\partial p$ (between surface and 500 hPa**
3. **Mid tropospheric Relative Humidity (between 700 and 500 hPa level)**

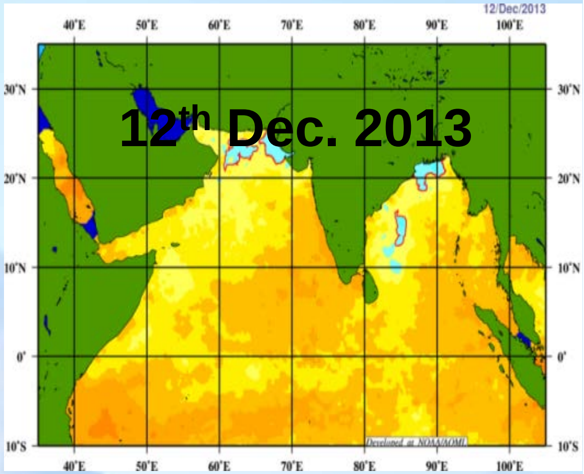
SEA SURFACE TEMPERATURE

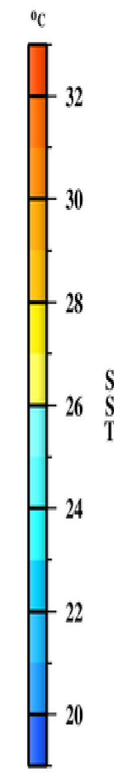






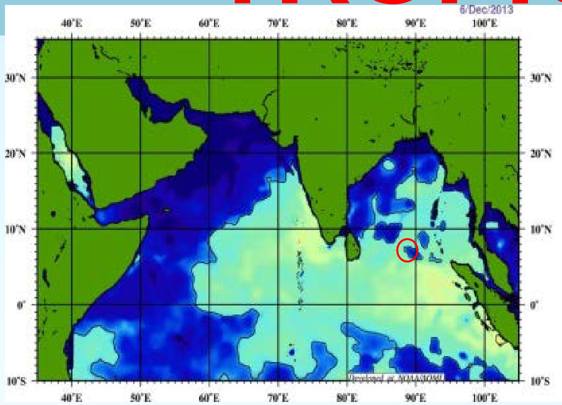




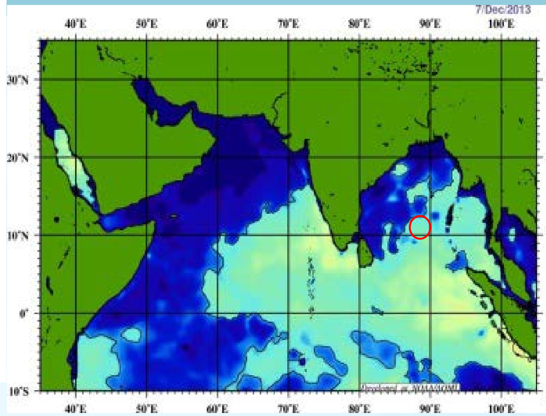


- The sea surface temperature during genesis was about 26-28°C but on 9th and 10th it had moved to the sea area where SST was less than 26 °C and hence weakened.
- It then again moved to warmer SST over southwest BoB and therefore the system could retain its intensity of Depression on 11 and 12th till it crossed coast.

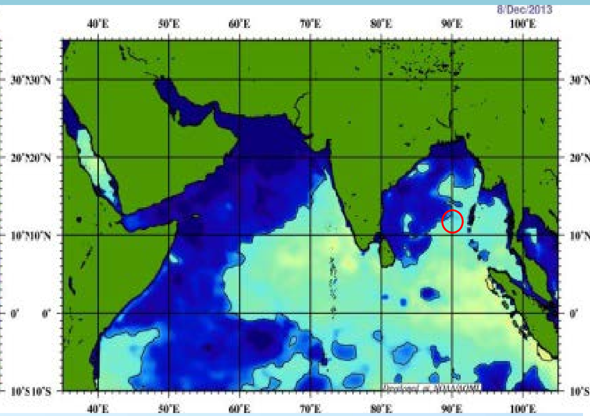
TROPICAL CYCLONE HEAT



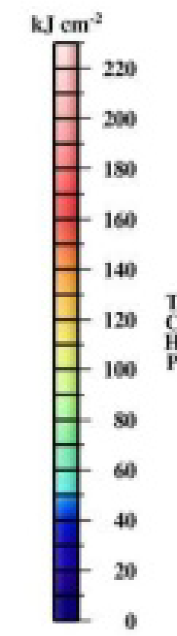
6th Dec. 2013

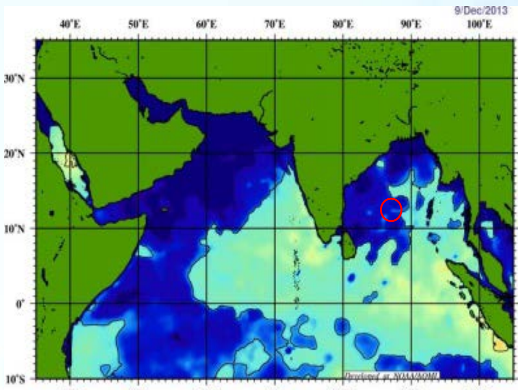


7th Dec. 2013

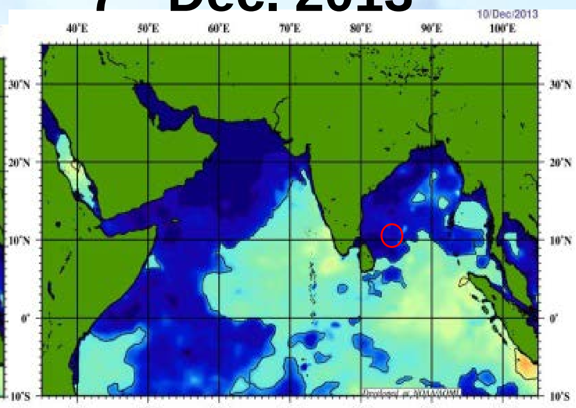


8th Dec. 2013





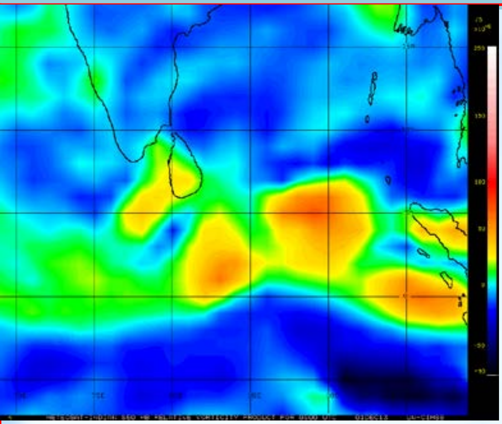
9th Dec. 2013



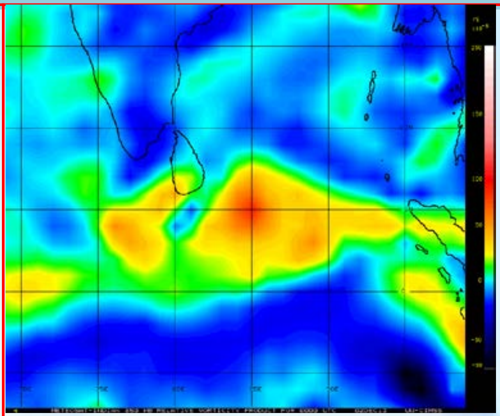
10th Dec. 2013

- Ocean thermal energy was more than 50 kJ cm-2 during 6-8 Dec. 2013, the system intensified from Depression to VSCS and
- less than 50 kJ cm-2 from 9-11 when the system weakened from VSCS to Depression.

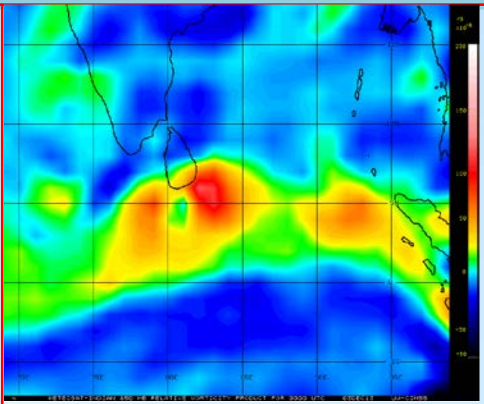
Low Level Relative Vorticity – 850 hPa



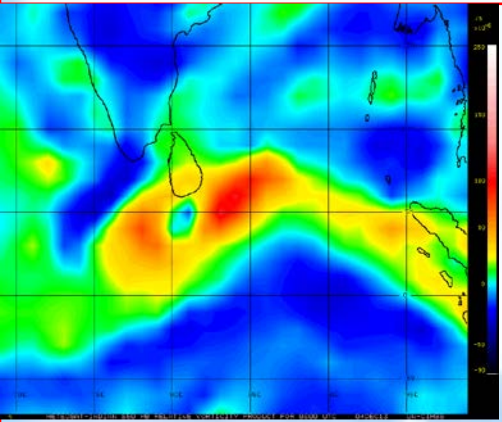
1st Dec. 2013



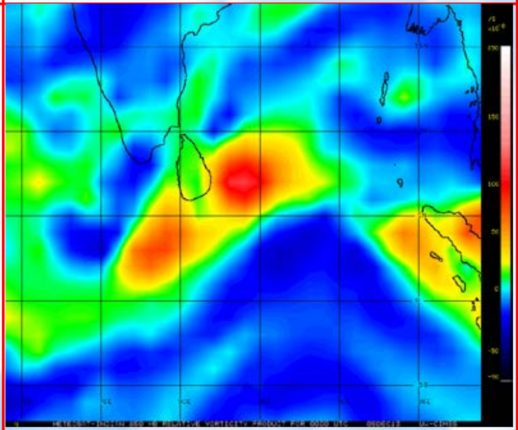
2nd Dec. 2013



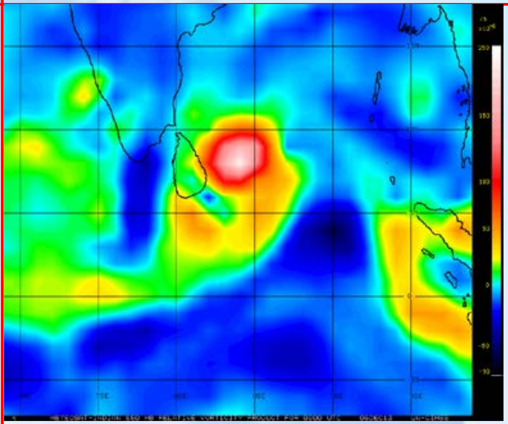
3rd Dec. 2013



4th Dec. 2013



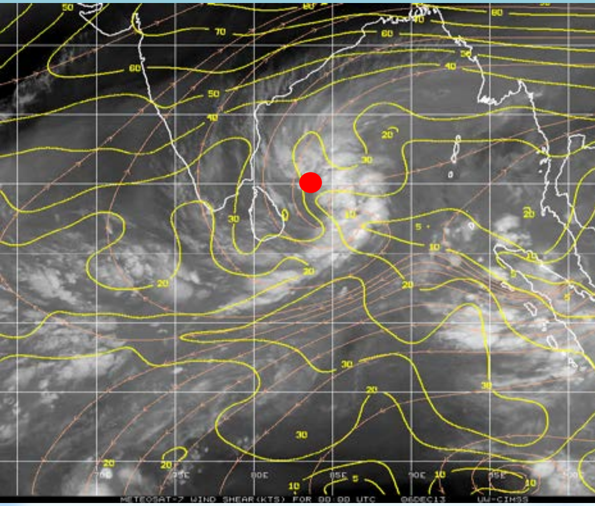
5th Dec. 2013



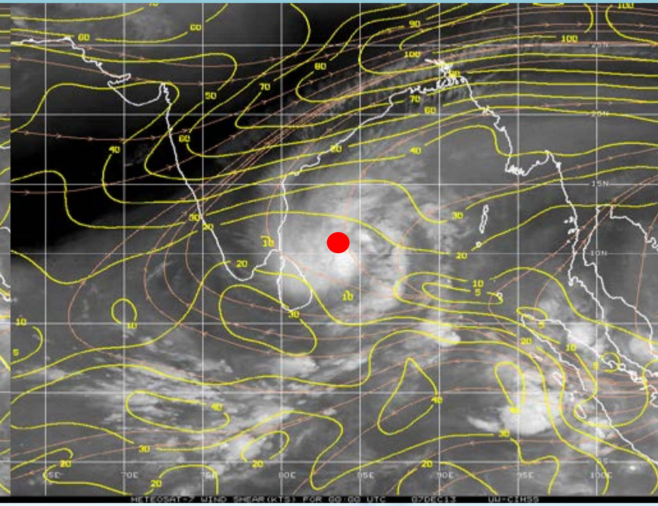
6th Dec. 2013

A pre-existing low pressure area from south China Sea which moved westwards and became well marked on 4th. The lower level convergence and relative vorticity increased from 5th to 6th December, 2013.

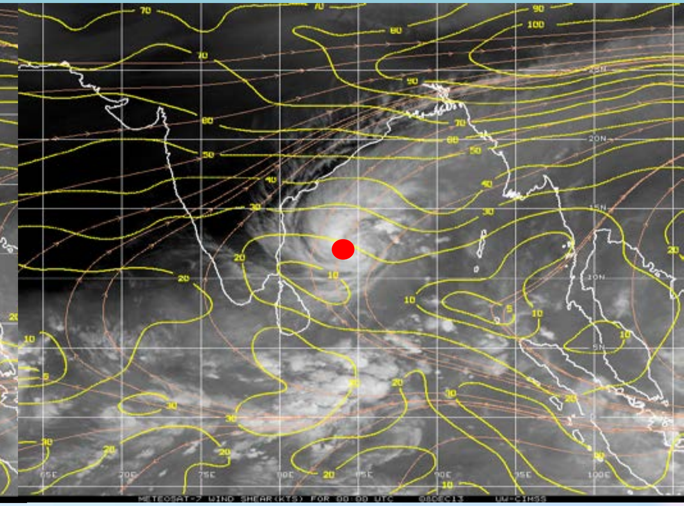
LOW LEVEL WIND SHEAR



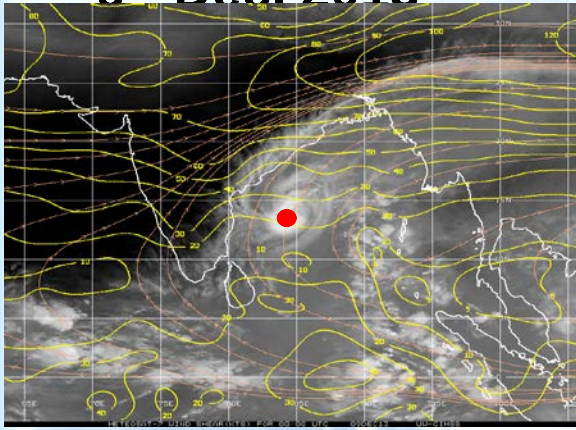
6th Dec. 2013



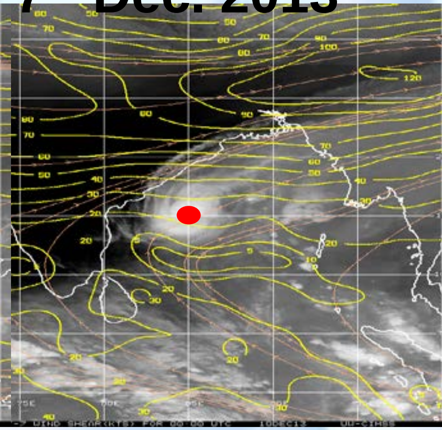
7th Dec. 2013



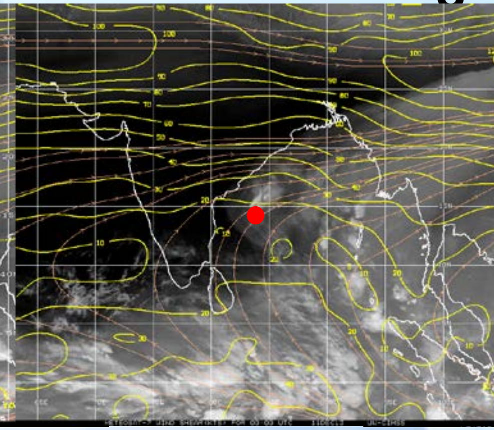
8th Dec. 2013



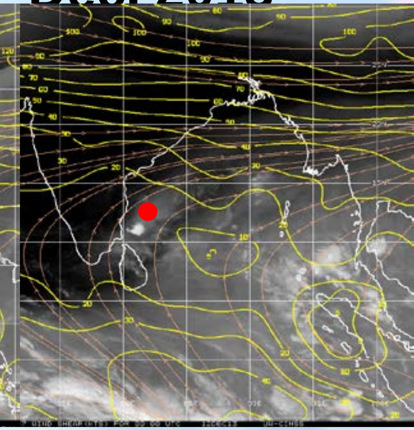
9th Dec. 2013



10th Dec. 2013



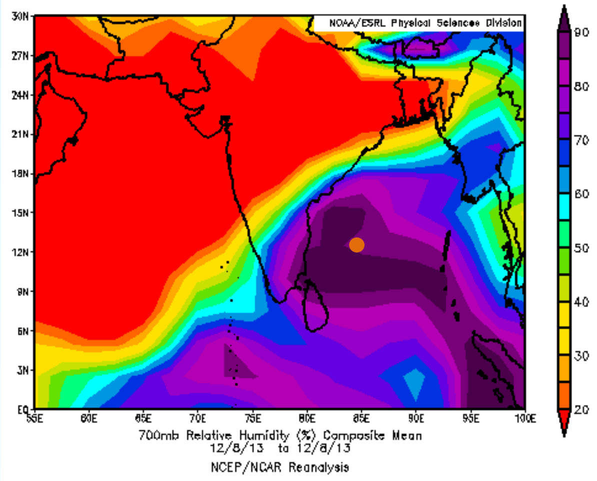
11th Dec. 2013

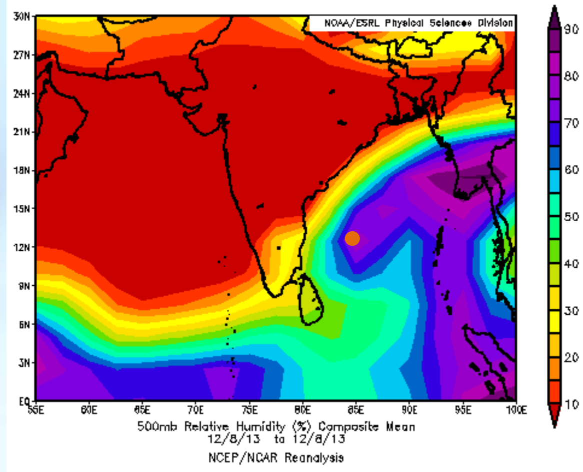


12th Dec. 2013

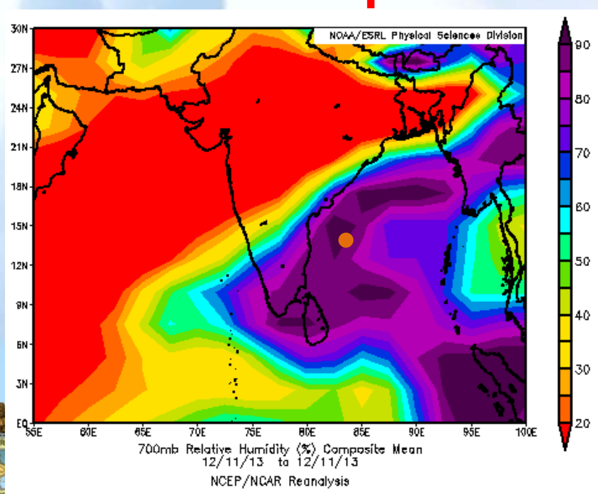
The vertical wind shear of horizontal wind had been low to moderate (10-20 kts) during its life course but increased and became high (20-30 knots) only for a brief period from 0900 UTC of 9th and on 10th when the system weakened from VSCS to CS.

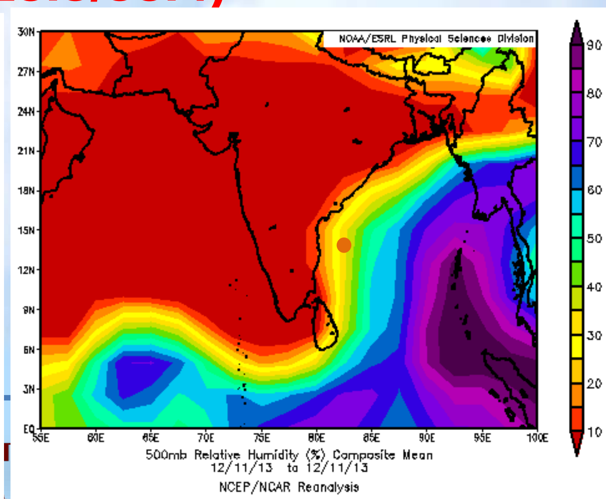
Mean humidity distribution at 700 hPa level and 500 hPa level on 8th (Intensification, mean position of the storm 12.5/84.7)





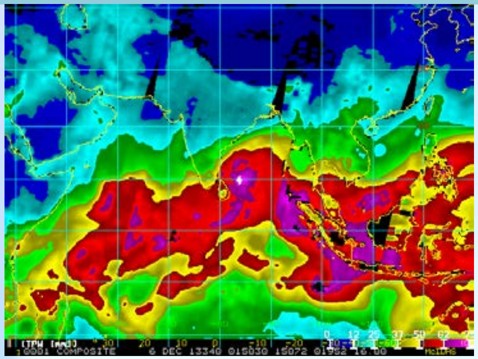
Mean humidity distribution at 700 hPa level and 500 hPa level on 11 (Weakening mean position 13.8/83.4)



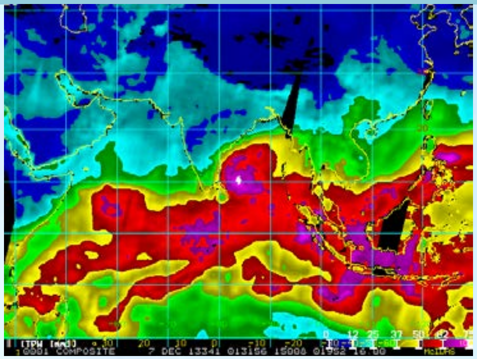


- **According to Gray, a minimum threshold of 40% Mid Tropospheric RH is necessary for tropical cyclogenesis.**
- **Low Mid Tropospheric humidity would lead to the entrainment of relatively dry environment air into the parcel and a reduction in up-draft parcel buoyancy.**
- **the relative humidity at 500 hPa on 11th near the storm centre. was less than 40%.**

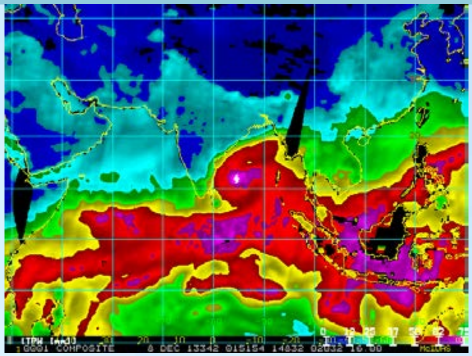
TOTAL PRECIPITABLE WATER



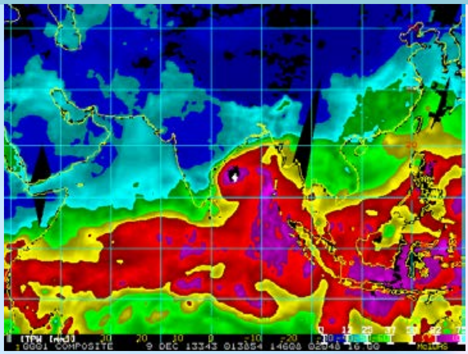
6th Dec. 2013



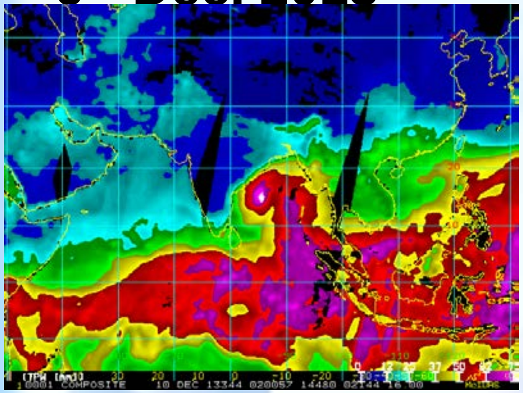
7th Dec. 2013



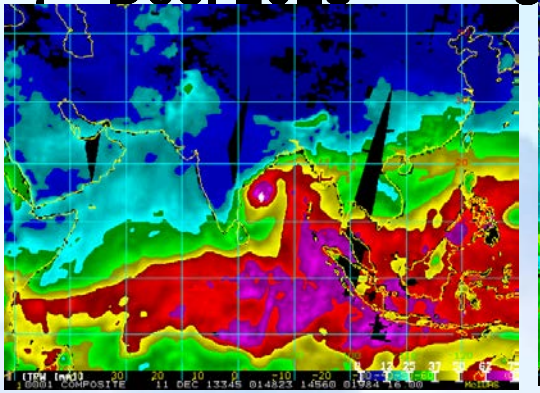
8th Dec. 2013



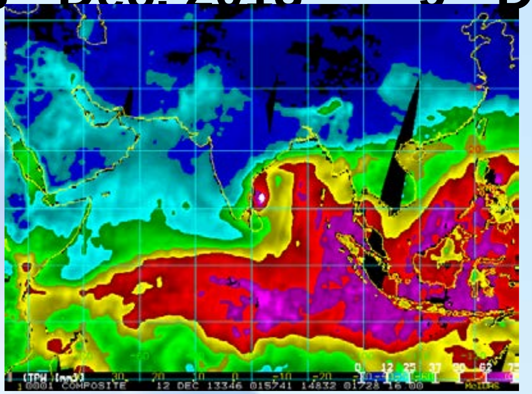
9th Dec. 2013



10th Dec. 2013



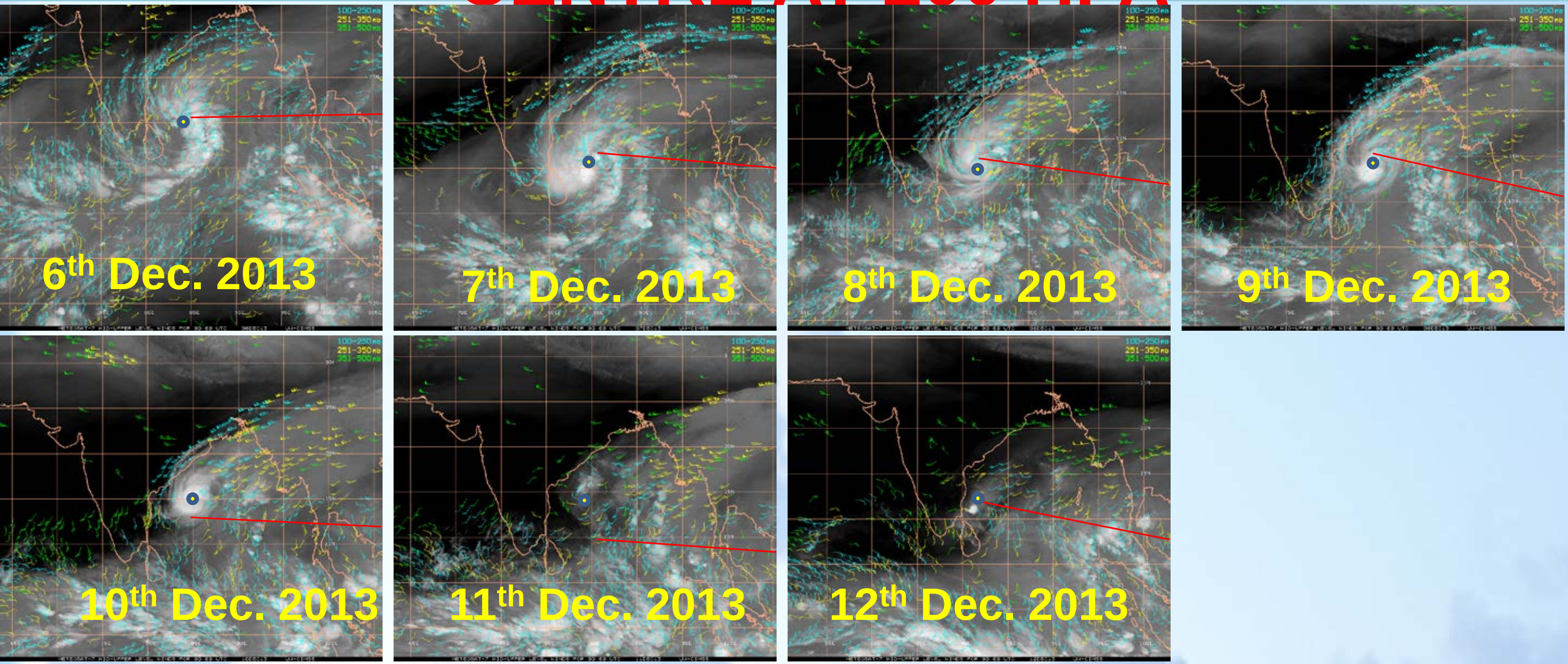
11th Dec. 2013



12th Dec. 2013

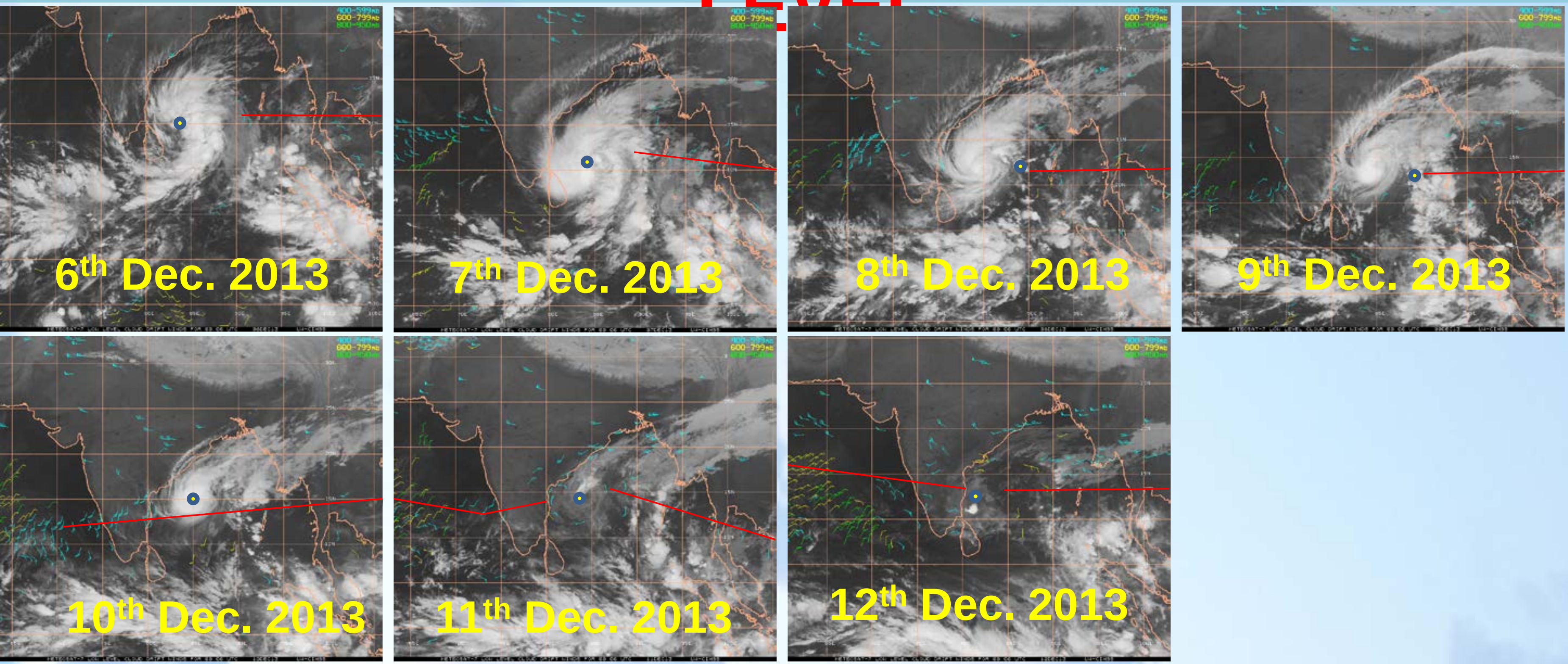
- The Total Precipitated Water (TPW) imageries during 6-12 Dec. indicates that the dry and cold air penetrated into the southwestern periphery of the cyclone from 10th Dec.
- It gradually penetrated further towards the centre of the cyclone from the southern side.
- As a result, it isolated the core of the cyclone from the warm and moist air from the southeast sector at 0500 UTC of 11 December

POSITION OF RIDGE AND THE STORM CENTRE AT 200 HPA



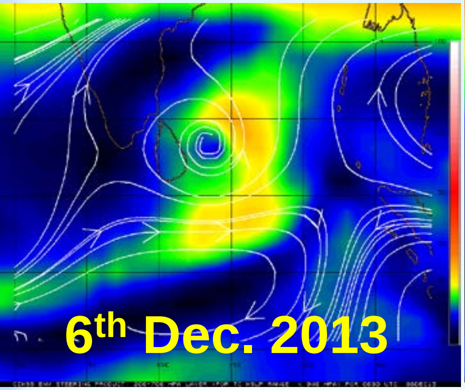
- **Ridge at 200 hPa ran about 10° N during the cyclone's life period. When the system was close to the ridge, it moved slowly.**
- **As it lay north of the ridge on 10th , it moved north-northeastwards under influence of upper tropospheric steering ridge which moved northward alongwith northward movement of TC.**

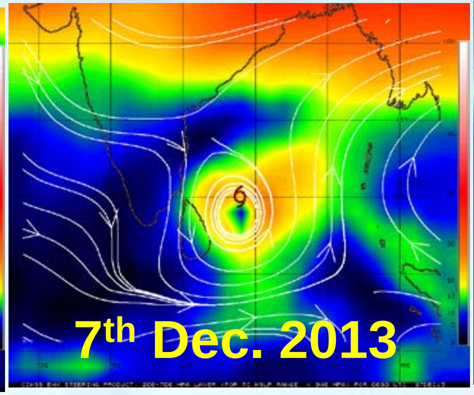
CIRCULATION AT MID TROPOSPHERIC LEVEL

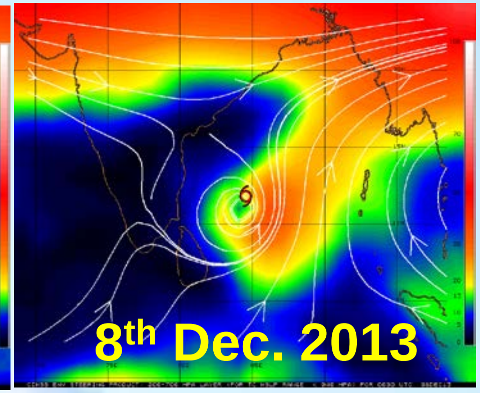


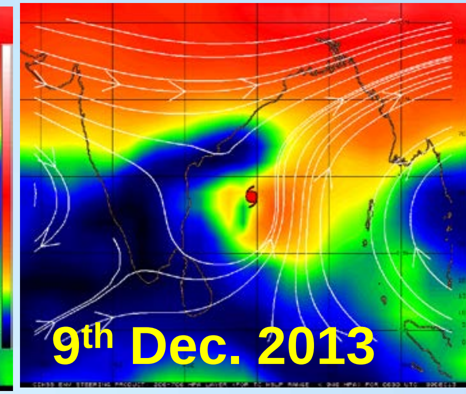
- **Due to gradual weakening of system, the steering level changed from upper troposphere to lower and middle troposphere.**
- **The influence of the upper tropospheric anticyclonic circulation to the east of system centre decreased and that of lower and middle level anticyclonic circulation lying to the west of the system centre increased.**
- **As a result, the severe cyclonic storm re-curved westwards initially and then southwestwards commencing after 0900 UTC of 10th December.**

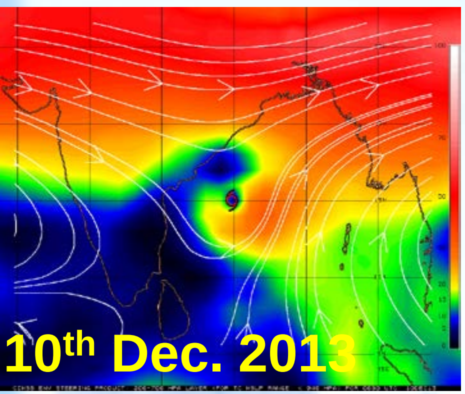
STEERING BY THE MID AND UPPER TROPOSPHERIC LEVEL CIRCULATION

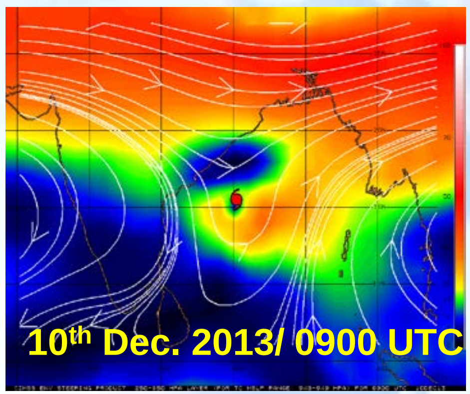


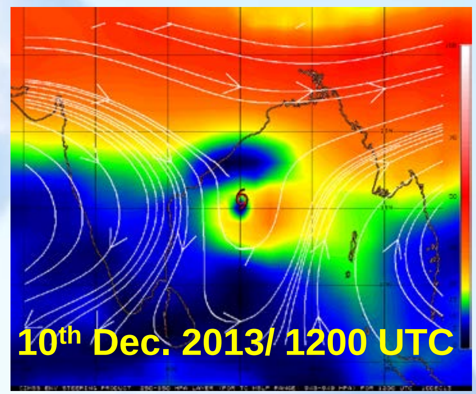


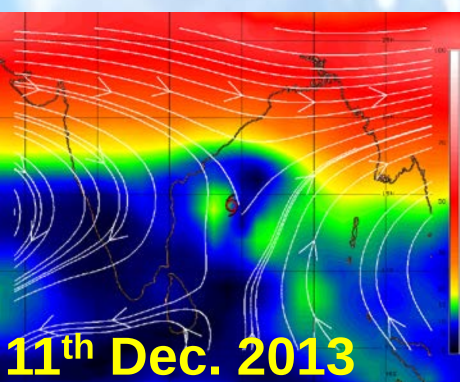


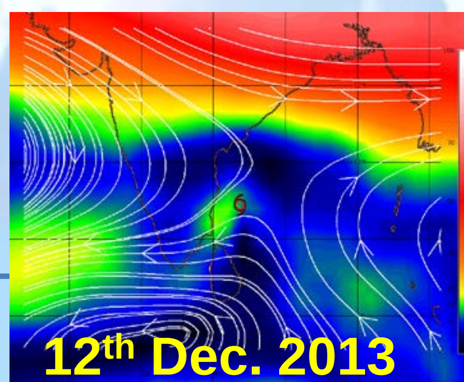




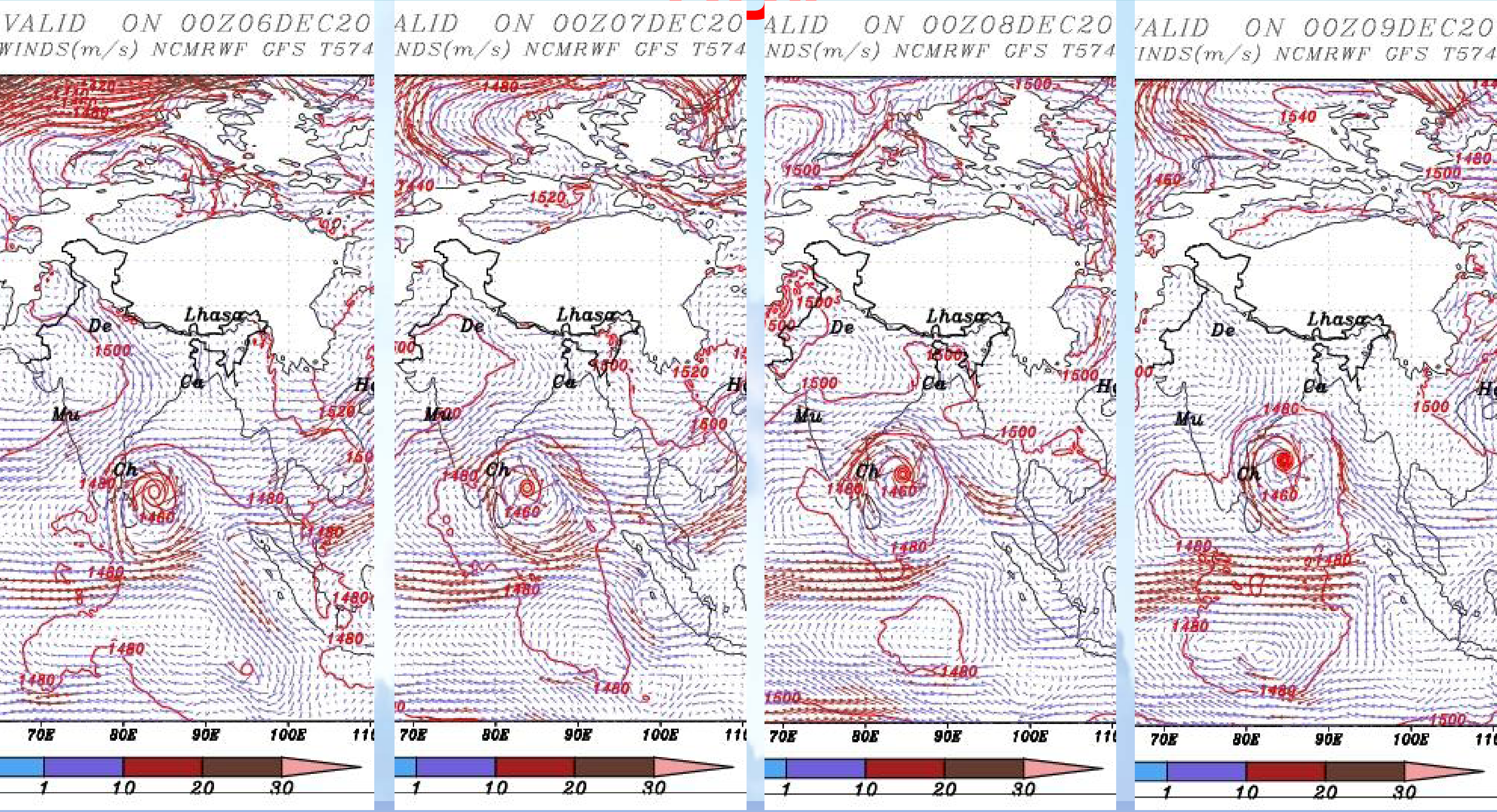






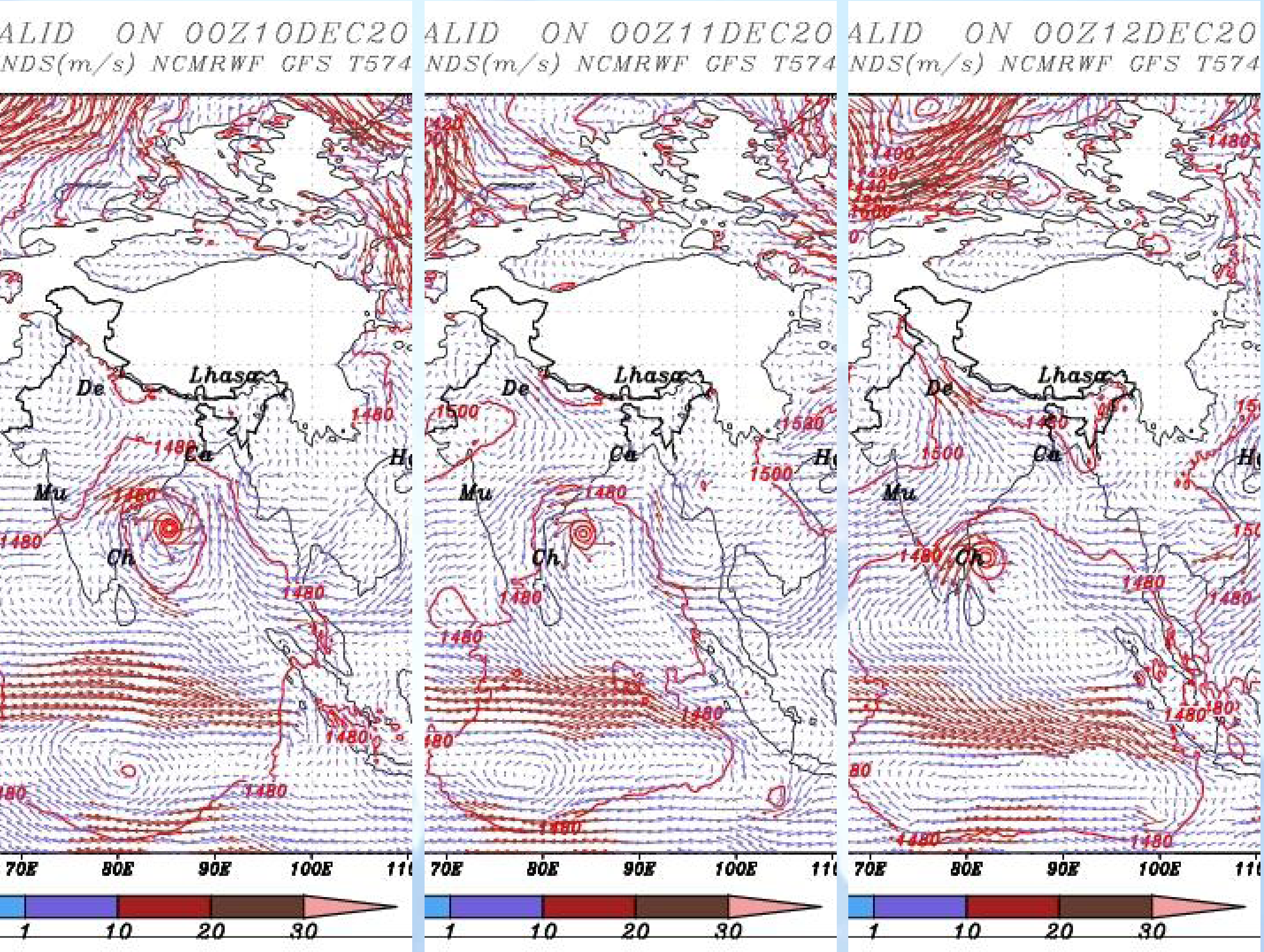


NE MONSOON CIRCULATION AT 850 HPA



- Low level northeast Monsoon strengthened with formation of Madi
- Helped in southwestward movement when the TC weakened over west central Bay of Bengal

NE MONSOON CIRCULATION AT 850 HPA



WEAKENING

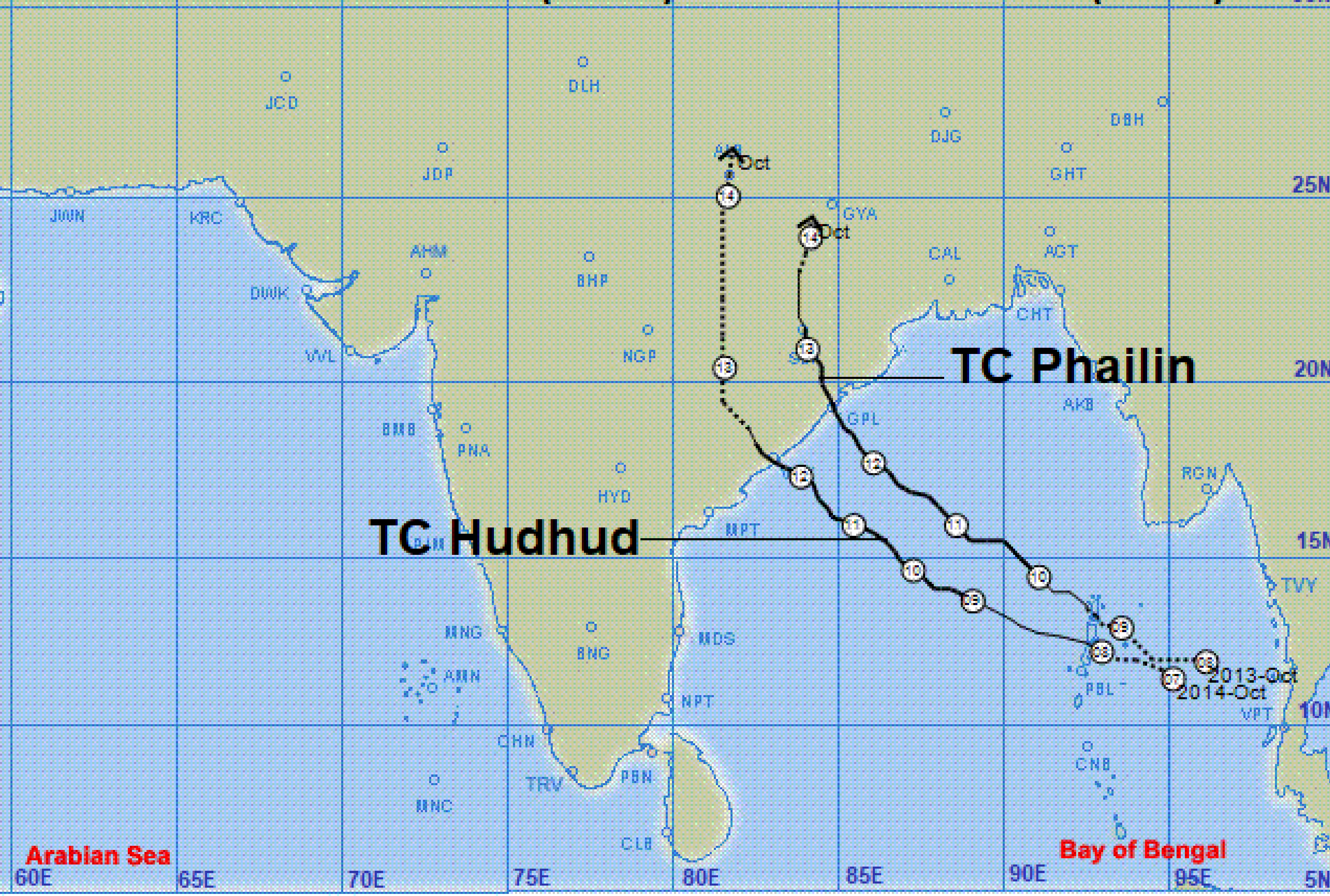
Following reasons were responsible for the weakening:

1. As the system moved north of 15° N, it encountered cooler sea surface temperature.
2. The RH at the mid tropospheric level was less than 40 % from 10th Dec.
3. Entraintment of cold and dry air from 11th Dec. isolated the core of the system.

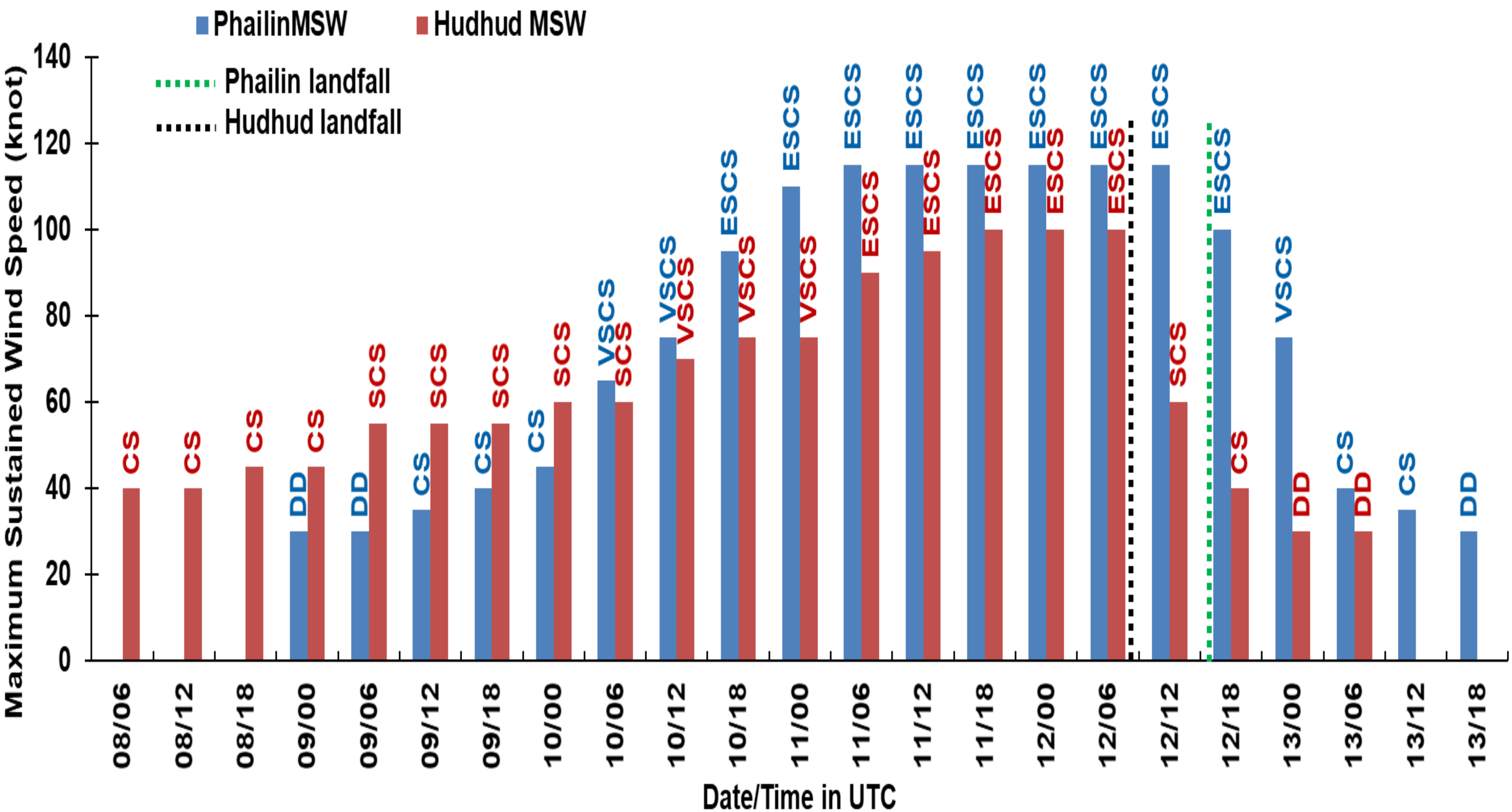
Rapid Intensification

- According to National Hurricane Centre (NHC), USA:
- Rapid deepening : If the ECP of a TC falls at the rate of 1.75 hPa/hour or 42 hPa in 24 hours
- Explosive deepening: If it is 2.5 hPa/hour for 12 hours or 5 hPa/hour for at least six hours.
- Rapid intensification/weakening: If Vmax changes by 30 knots during past 24 hrs(Kaplan and DeMaria, 2003)

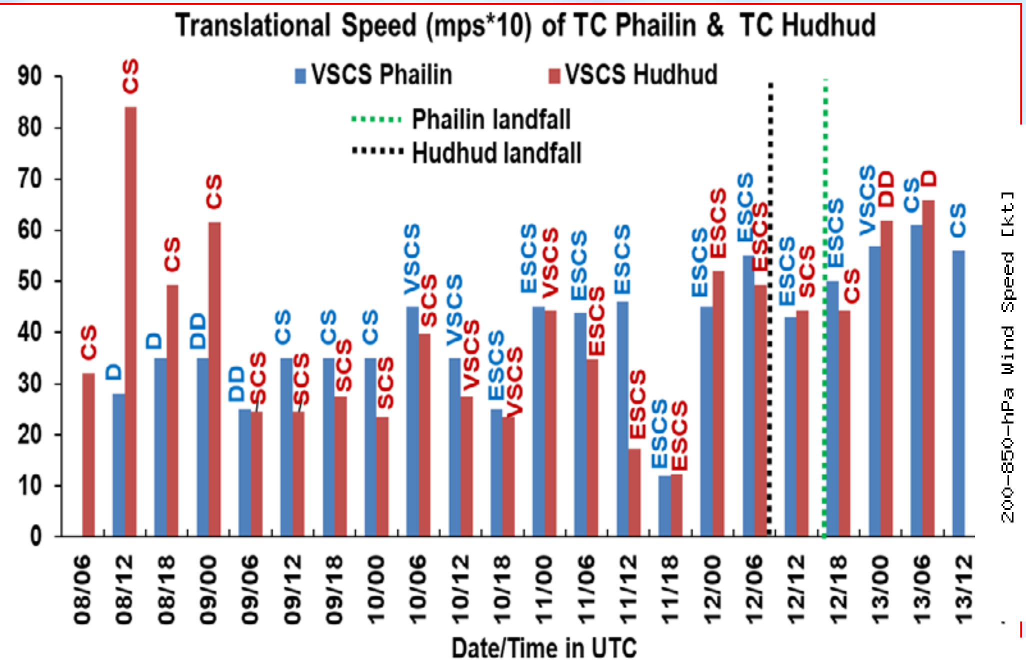
Tracks of TC Phailin (2013) and TC Hudhud (2014)

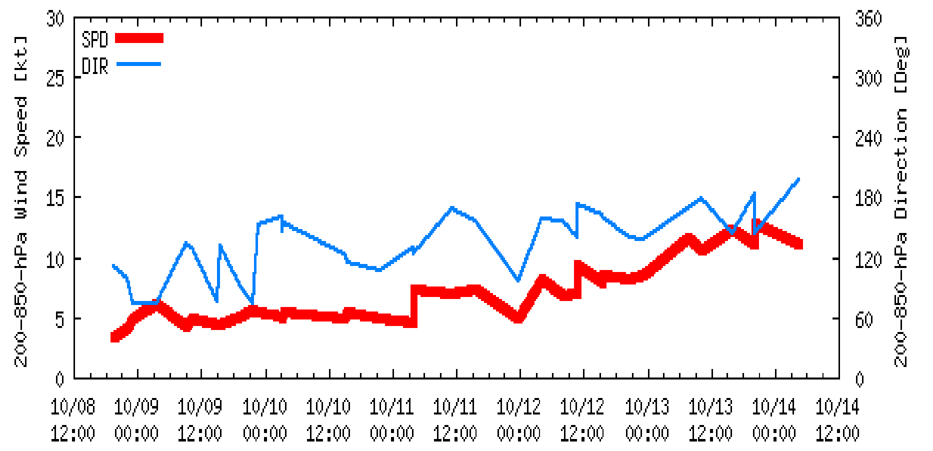


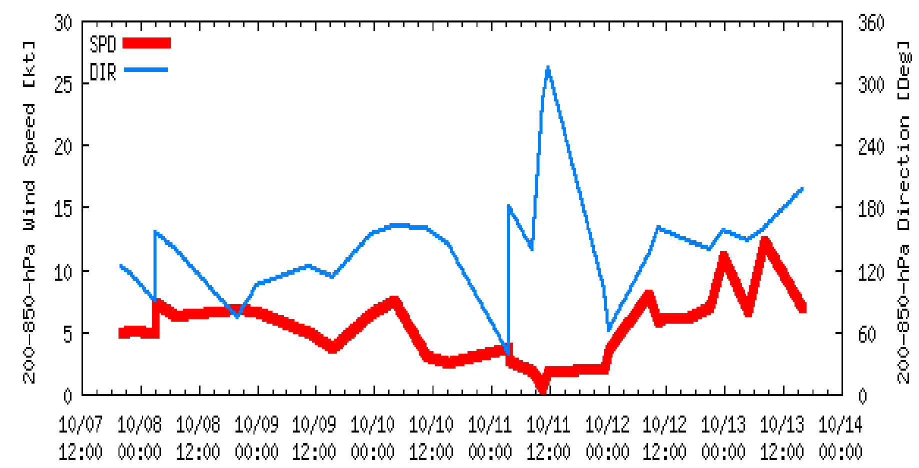
Maximum Sustained Wind (MSW) Speed of TC Phailin & TC Hudhud



Translational Speed and Intensity

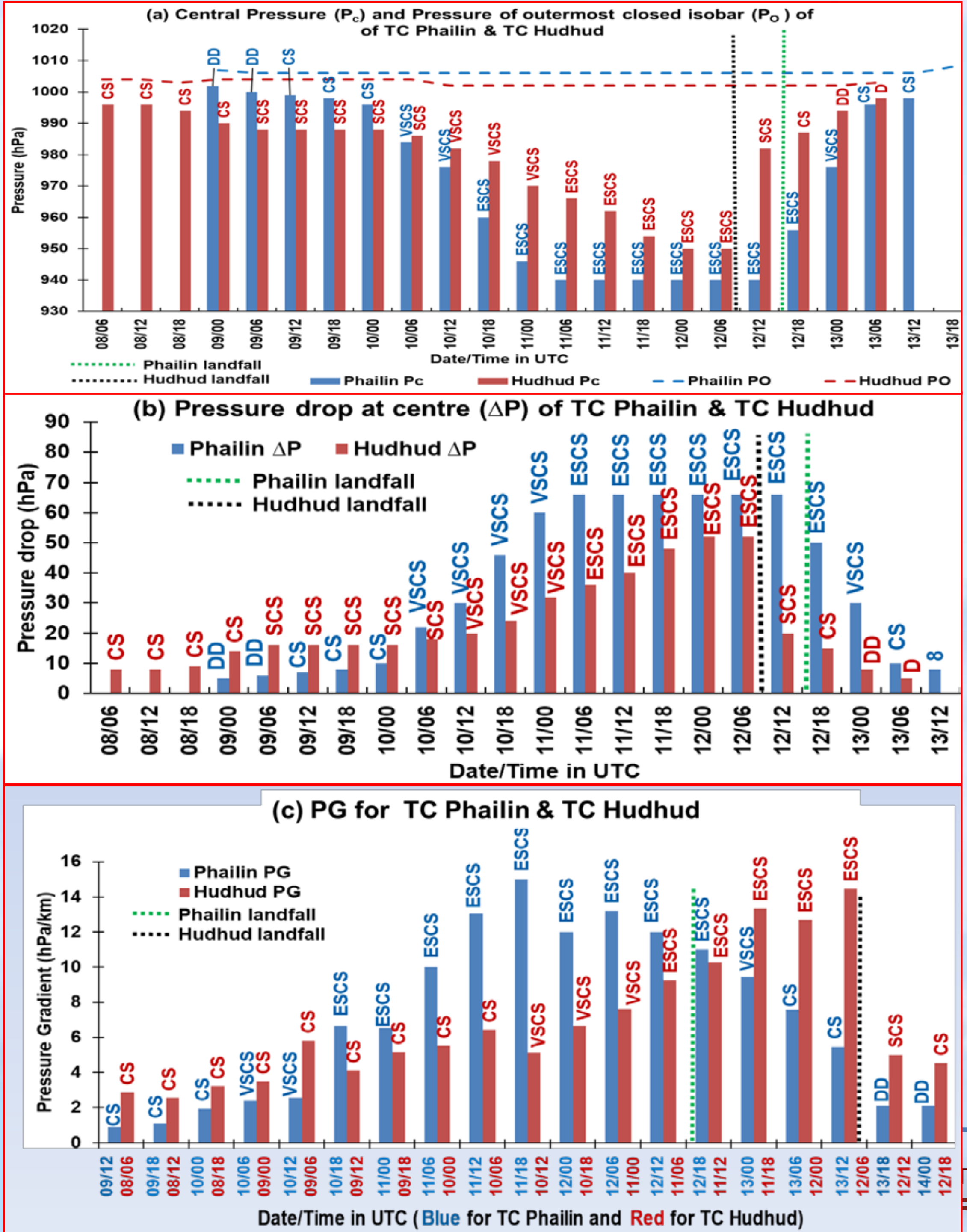






Month/Date Time (UTC)

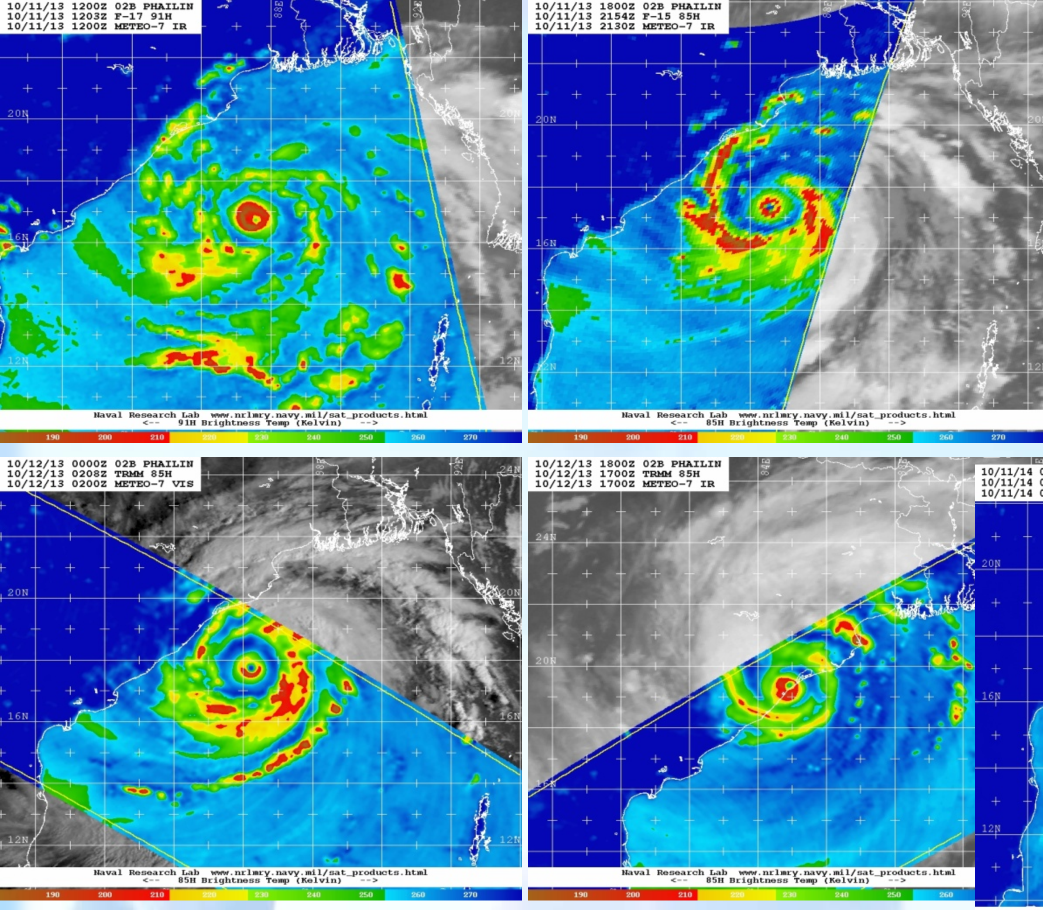
Pressure Drop and intensity



RTMENT

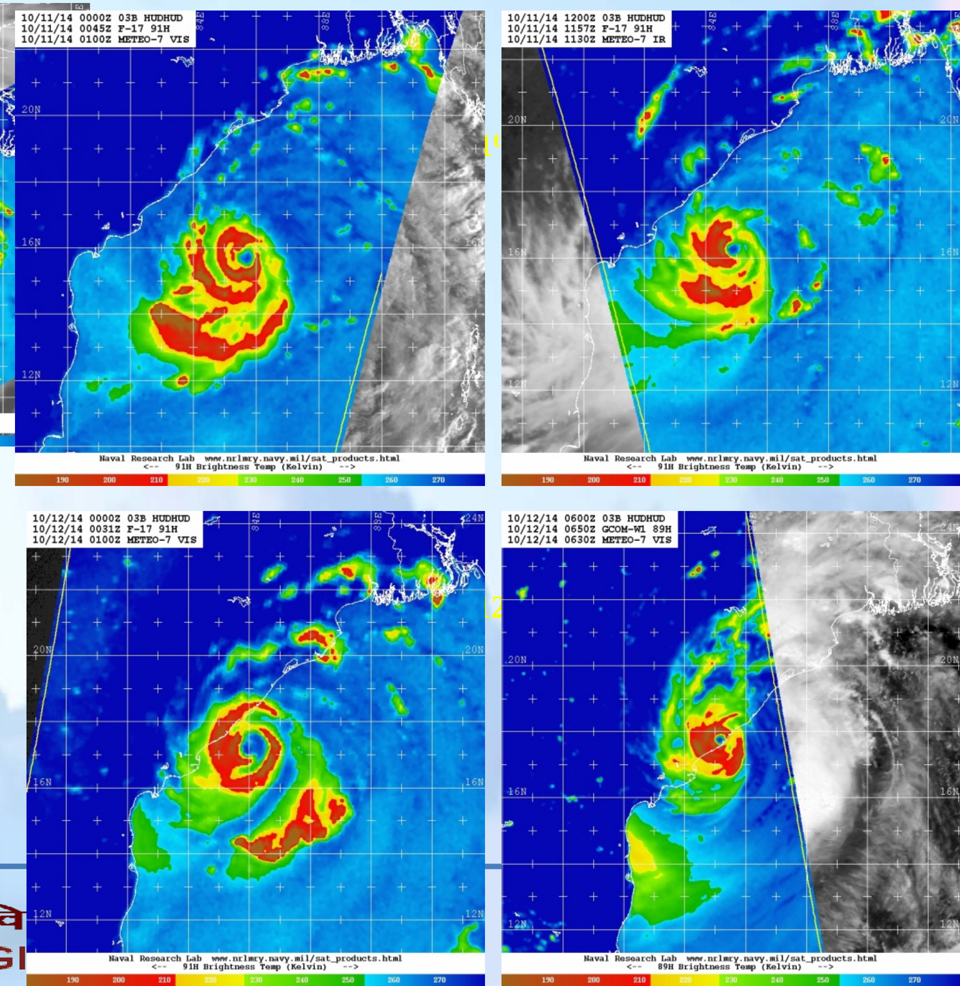
Eye characteristics

- TCs tend to form an eye detectable by aircraft (and presumably by microwave imagery) at a central pressure of 991±9 hPa, at an analysed best track intensity of 30±8 ms^{-1} (58±16 knots) (statistics are median value at eye formation along with interquartile range). Vigh and Rozoff (2012).
- Eye is first seen at lower levels (at about 5 km): Vigh and Rozoff (2012).
- Once genesis occurs, TCs tend to form eye within 48 hrs of reaching tropical storm strength with MSW of 34 knots and more (Vigh and Rozoff, 2012).
- 51% of TC over north Atlantic with banding pattern later developed an eye
- Average satellite observed diameter of the TC eye is about 55-85 km. Eyes with diameter less than 55 km are considered as small and those less than 85 km are considered to be large.
- According to Vigh *et al.* (2012), 75% of the eyes emerge with diameters below 25nm (46 km).
- Storms rapidly intensify at the time of eye formation.



Phailin

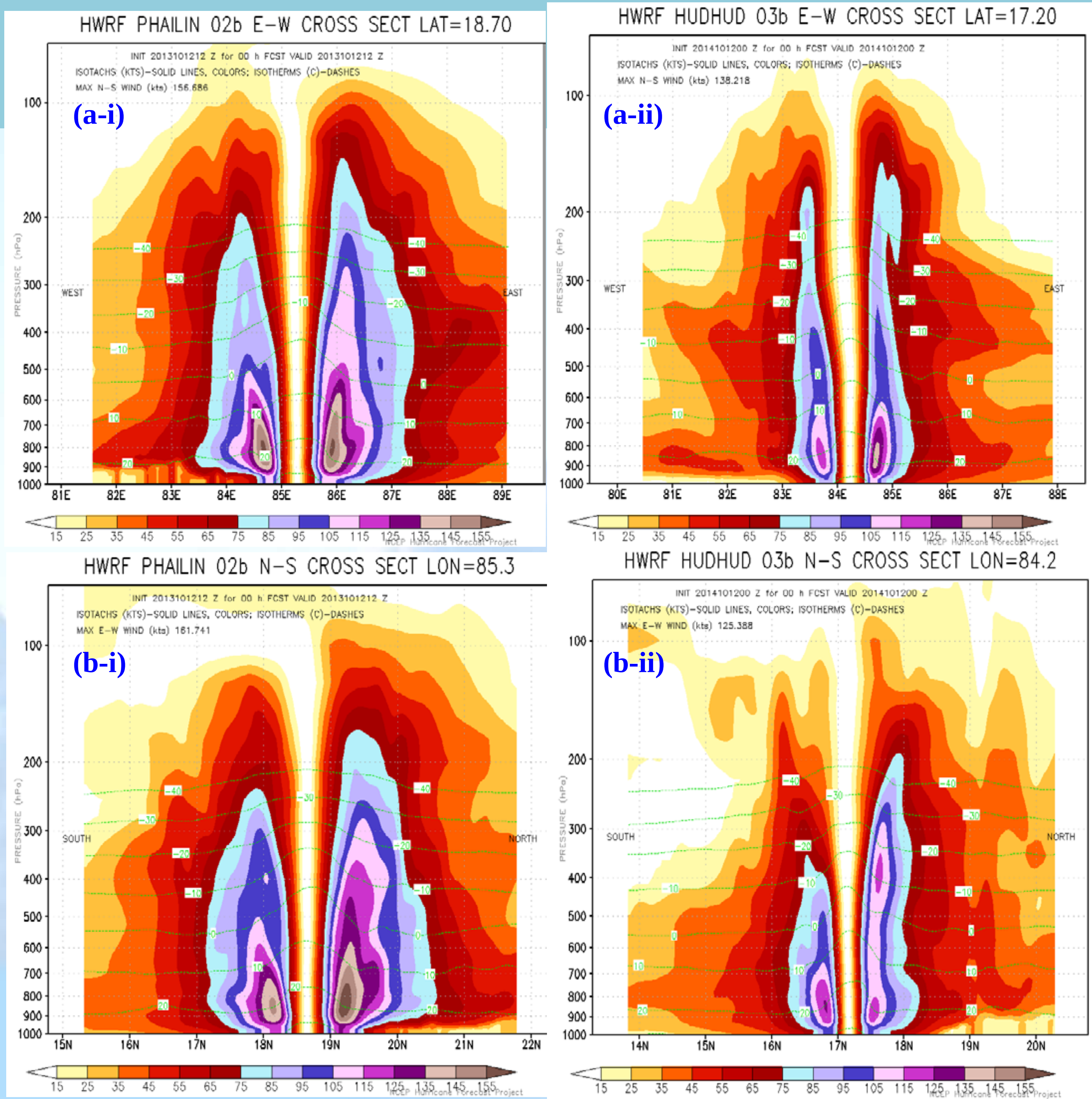
Hudhud



Eye characteristics

- Durden (2013) finds that the pressure altitude of the maximum temperature anomaly varies between 760 and 250 hPa
- There is a positive correlation between the maximum anomaly level and storm intensity, size, upper-level divergence, and environmental instability.
- The temperature anomaly is defined as the difference between the observed temperature in the TC eye and a reference temperature representative of the conditions either outside or in the absence of the TC.
- According to Durden (2013), an average anomaly of at least 4 K is needed for even the weakest storms.
- Using the proportionality of pressure drop to average anomaly (roughly a factor of 5), an average temperature anomaly of 13K would correspond to a 65-hPa pressure drop.
- Willoughby (1979) and Shapiro & Willoughby (1982): Temperature (height) of the clouds in the central region of the TC shows the strength of the updraft, which is part of secondary circulation. Colder (taller) clouds are associated with a more intense secondary pattern.

Phailin



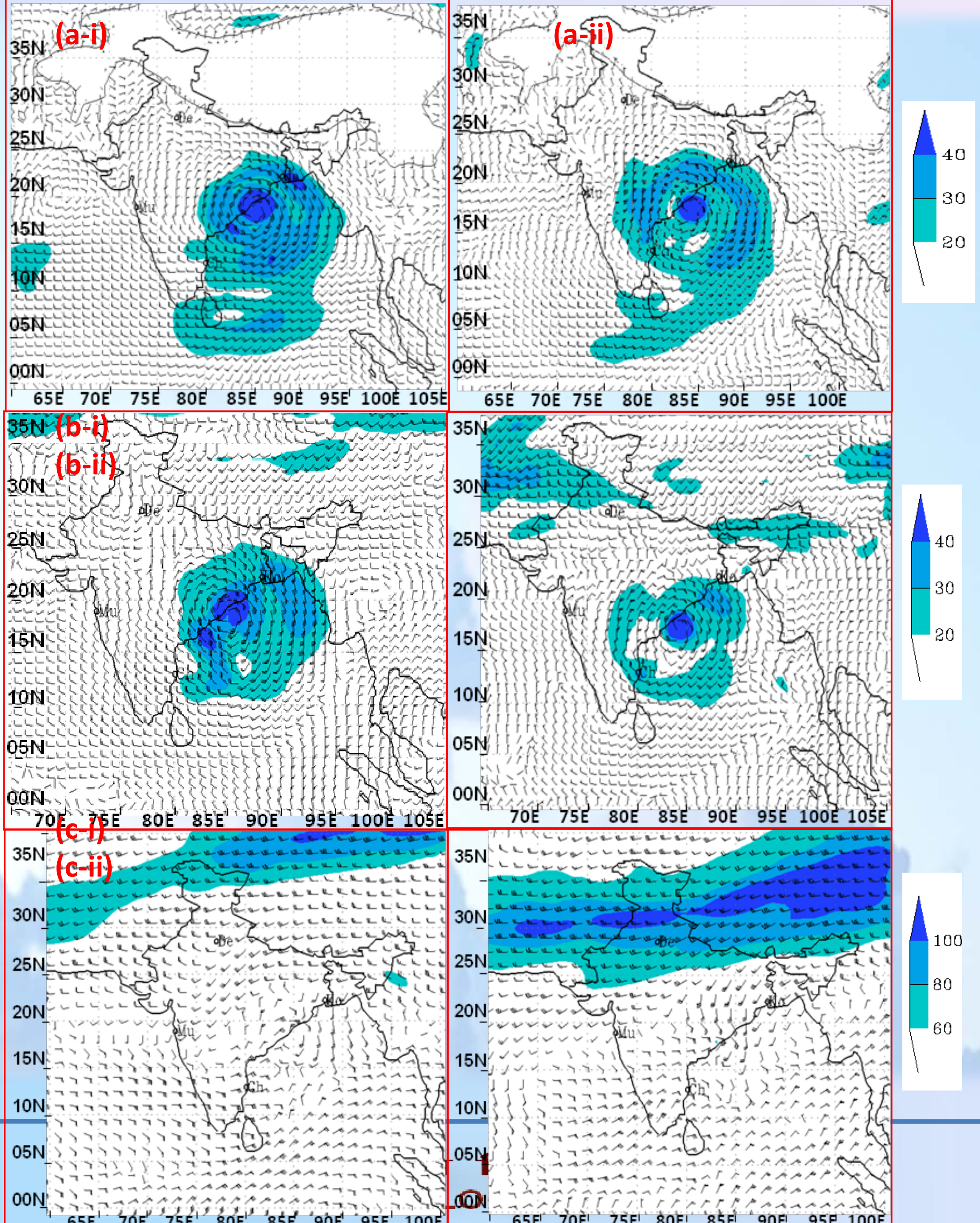
Hudhud

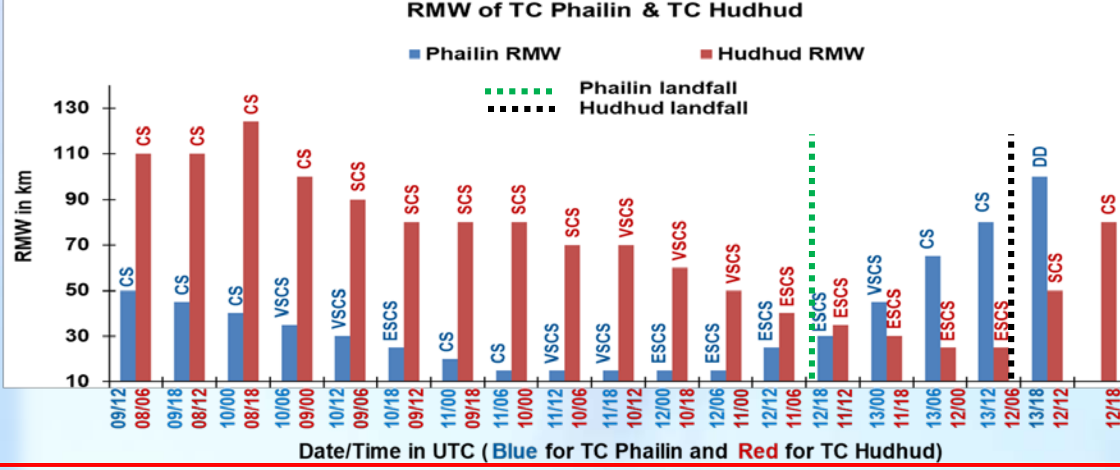
Structure/Size

- Vigh and Rozoff (2012): RMW contracts from a median RMW of 80 km at 35 knots to approximately 45 km at 55 knots. For intensities of 65 kt and above, the rate of RMW contraction slows considerably.
- Carrasco et al (2014): TCs experiencing RI start with a significantly smaller size than those not undergoing RI.
- Cyclones not experiencing RI are approximately 10 n mi larger than cyclones undergoing RI when using RMW and mean R34 as the initial size parameters.
- In contrast, when using ROCI as the size parameter, there is only a negligible difference in size between the non-RI and RI cases.
- Emanuel (1989: Initial size of the vortex, as measured by RMW, played a substantial role in its subsequent intensification rate.
- If the initial vortex is too large, then no subsequent intensification occurs.
- Carrasco et al (2014): it is difficult for RI to occur after about 90 km for RMW.
- Stern et al., 2015: As a TC intensifies, strengthened eyewall convection induces counter downdrafts and thus increase the warming in the eye which in turn contributes to decrease in central pressure (Willoughby, 1998). Contracting pressure gradient around the maximum wind allows the wind to rise and move inward from the RMW, leading to contraction of eye and eyewall.

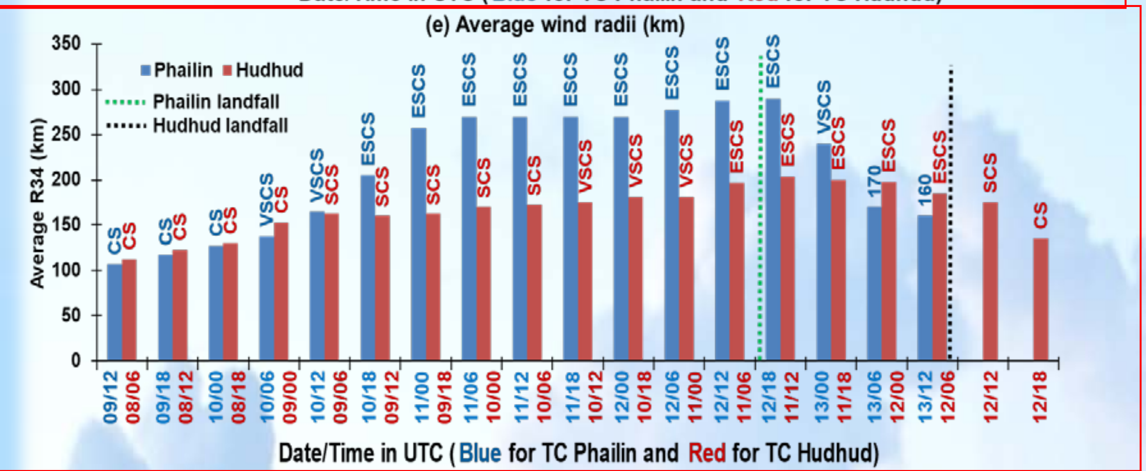
Phailin

Hudhud

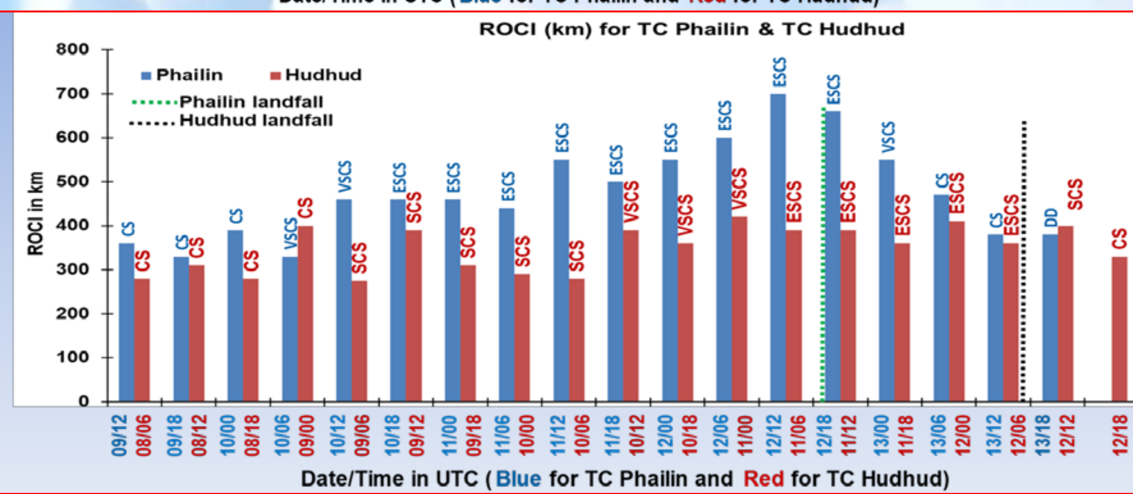




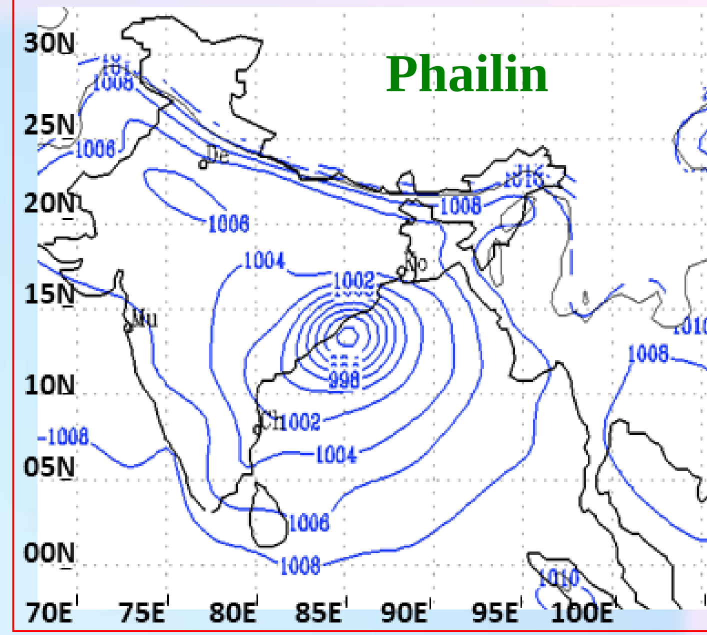
RMW of TC Phailin & TC Hudhud
Phailin RMW
Hudhud RMW
Phailin landfall
Hudhud landfall
RMW in km
Date/Time in UTC (Blue for TC Phailin and Red for TC Hudhud)



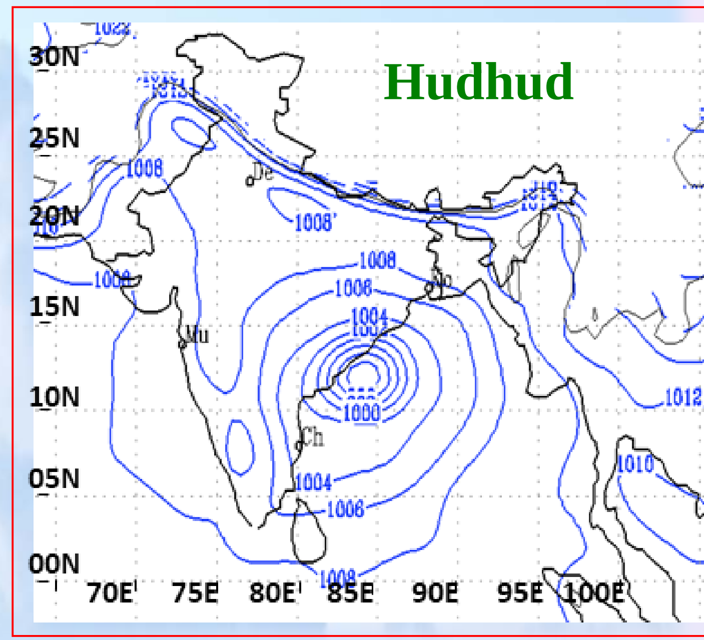
(e) Average wind radii (km)
Phailin
Hudhud
Phailin landfall
Hudhud landfall
Average R34 (km)
Date/Time in UTC (Blue for TC Phailin and Red for TC Hudhud)



ROCI (km) for TC Phailin & TC Hudhud
Phailin
Hudhud
Phailin landfall
Hudhud landfall
ROCI in km
Date/Time in UTC (Blue for TC Phailin and Red for TC Hudhud)



Phailin



Hudhud

Structure/Size

- size of a TC wind field can vary with Ocean basin, time of the year, latitude, P_c, stage of development and environmental pressure (Atkinson, 1971, Frank and Gray, 1980, Cocks and Gray, 2002, Kimball and Muelakar, 2004, Mohapatra and Sharma, 2015).
- Knaff *et al.* (2014): Propensity of large TCs increases when TCs form during seasons that are characterised by enhanced low level vorticity and when TCs move towards the environment characterised by increasingly baroclinic, especially after peak in intensity and prior to recurvature.
- TC tends to grow more as they intensify.
- Kimball and Muelakar (2004): R34, R50 and R64 tend to be smaller in size for intensifying TCs.
- Carrasco et al (2014): it is difficult for RI to occur after about 260 km for mean R34. For both RMW and R34 size parameters, these thresholds lie near the boundary separating the medium and large cyclones, suggesting that once the TC has a large RMW and/or mean R34, it is rare for it to undergo RI.

Thank you