Tropical Cyclone: 
Intensification and movement

M Mohapatra

INDIA METEOROLOGICAL DEPARTMENT
MAUSAM BHAVAN, LODI ROAD, NEW DELHI-110003
mohapatraimd@gmail.com
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

<table>
<thead>
<tr>
<th>Low pressure system</th>
<th>Maximum sustained winds</th>
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<tr>
<td>Low</td>
<td>&lt; 17 knots</td>
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<tr>
<td>Depression</td>
<td>17 – 27 kts 31 – 51 kmph</td>
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<tr>
<td>Deep Depression</td>
<td>28 – 33 kts 52 – 62 kmph</td>
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<tr>
<td>Cyclone</td>
<td>34 – 47 kts 63 – 87 kmph</td>
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<tr>
<td>Severe Cyclone</td>
<td>48 – 63 kts 88 – 117 kmph</td>
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<tr>
<td>Very Severe Cyclone</td>
<td>64 – 89 kts 118 – 166 kmph</td>
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<tr>
<td>Extremely Severe cyclone</td>
<td>90-119 kts 167-221 kmph</td>
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<tr>
<td>Super Cyclone</td>
<td>120 kts &amp; above 222 kmph &amp; above</td>
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<thead>
<tr>
<th>System</th>
<th>Pressure deficit (hPa) at the centre</th>
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<td>Low</td>
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<tr>
<td>Depression</td>
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<td>Very Severe Cyclone</td>
<td>15.5-65.6</td>
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<tr>
<td>Super Cyclone</td>
<td>65.6</td>
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</table>
Determination of Centre

Level 1:
- Database
- VIS/IR imagery
  - Dvorak Technique
  - Comparing of 37GHz and 85GHz
- Center fixes (Valid interval)

Level 2:
- Microwave imagery
- Does the imagery exist on time
- Interpolation
- Center, PI (Level 1)

Level 3:
- Radar imagery
  - VR, CZ
- Center, PI (Level 2)

Level 4:
- Synoptic data
  - Ship, Buoy
    - International synoptic data (through GTS)
    - Domestic synoptic data
- Center, PI (Level 3)

Final best tracks (Metadata)

Decision:
- Optimization
  - Smoothing (within PI)
  - Consistency check
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 observations and AWS.
- In their absence, the radar observations followed by satellite observation is used for this purpose.
Determination of Intensity

Level 1: Satellite based Intensity
- INSAT-3D Dvorak T.No.

Level 2: Comparison with other T Nos
- JTWC (SAT FIX)
- NOAA(SSD)/ ADT (CIRA) etc

Level 3: Other products
- Intensity change from Microwave imageries (85 & 37 GHz)

Level 4: Radar based Intensity
- If system within Radar range
  - Scat. based surface winds/Multi-satellite derived winds, CMV/AMV/IR based wind
  - DWR Radial Velocity reduced to 10m/VVP-2

Level 5: Ground based observations via GTS & other sources
- Synop / AWS (Coastal/Island/ships/buoys/HWSR)

Level 6: Optimisation

Consistency Check

Intensity 11 → Intensity 12 → Intensity 13 → Intensity 14 → Intensity 15 → Intensity Final
Estimated central pressure (ECP)

Level 1
- Examine MSLP based on available data from Buoy, Ship, Coastal 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 $\Delta P$
  - Find ECP

Level 5
- Compare ECP with nearest buoy/ship/island/costal data to optimise ECP
Shape and size (Radius of Outermost closed isobar (ROCI) of Low pressure system

Level 1: Examine MSLP based on available data from Buoy, Ship, Coastal 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 centre of LPA/WML/Depression, find distance of outermost closed isobar in four geographical quadrants (NE, NW, SE, SW) and find average ROCI as average of ROCI-NE, NW, SE, SW

Level 5: Define shape of LPS. If ROCI-NE, NW, SE, SW are equal, it is circular. Otherwise elliptical.
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 inability 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

MSLP : 994 hPa
Pressure Drop : 8 hPa
### Coastal observations for MSLP and wind centre

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

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<tr>
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Utility of Coastal Hourly Observations for landfall point and time

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

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</table>
Current Status of location estimation is mostly satellite driven.
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 cannot measure convection quantitatively
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

[Diagram of a 10° Log Spiral with annotations]
Banding pattern

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

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

28.10.2006
16:48:40

File: 2006102816484046.caz
Type: MAX{2}
Range: 350.0 km

NDX

INDIA METEOROLOGICAL DEPARTMENT
Center fixing in eye pattern
Centre from Radial Velocity Couplet
• 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

MOVEMENT OF THE TROPICAL CYCLONE

A(X1,Y1) at t1

B(x2,y2) at t2

WIND DIRECTION IN 16-POINTS OF COMPASS
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
- 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)
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

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


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

<table>
<thead>
<tr>
<th>C.I. Number</th>
<th>Max. Wind Speed (knots)</th>
<th>Pressure depth (in mb)</th>
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Steps for Intensity Estimation

1. Cloud system measurements
   - Eye
   - Curved Band
   - Shear
   - Covered Centre

2. 24 hour changes
   - Pattern adjusted Model T No.
   - Pattern recognition

Choose best estimate

Apply constraints

T No.

Final Intensity
VIS Analysis Diagram - 1

1. START
   Locate cloud system center at the focal point of the curved cloud lines or bands. For initial development (T1), see Step 1A.

2. Analyze using pattern below when possible; then go to Step 3.

   2A. "Curved Band" Pattern
       Use spiral arc distance along 10° log spiral.

   2B. "Shear" Pattern
       Use center definition and center's distance to dense overcast.

2C. "Eye" Pattern
   Has 24-hr old T-no ≥ T2?
   YES
   No
   Step 2A or 4

2D. "CDO" Pattern
   (Center indicated under + ⊙)
   Is "CDO" > 3/4" in diameter?
   YES
   NO
   Step 2A or 4

Eye Adjustment Rules:
1. Poorly defined or ragged eyes:
   Subtract 1/2 for E ≤ 4.5 and 1 for E ≥ 5.
2. Large eyes:
   Limit T-no. to T6 for round, well-defined eyes, and to T5 for large ragged eyes.
3. For MET ≥ 6, .5 or 1 may be added to DT for well-defined eye in smooth CDO when DT < MET.

Banding Feature Additions:
(Use "Banding Eyes" in 2C for unusual band widths and lengths)

Eye Adjustment?
E-no. + Eye Adj = CF

Banding Feature (BF)?
CF + BF = DT

Embedded Distance
Average Band Width
Banding Eyes

Edge
Well-Defined
Irregular

Diameter Size
> 2 1/2" 1 1/2" 1 1/4" 3/4" 1/4" < 1/4"

CF5 CF4 CF3 CF2 CF3 CF2
DT number is determined by curvature of band around 10° log spiral.

Spiral arc distance = 0.6
So DT no = 3
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 how much 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
### Position and Intensity Table

<table>
<thead>
<tr>
<th>Date/Time (UTC)</th>
<th>SAT MET POS</th>
<th>NOAA POS</th>
<th>JTWC POS</th>
<th>SYNOP POS</th>
</tr>
</thead>
<tbody>
<tr>
<td>29/00</td>
<td>9.5 84.0 2.0</td>
<td>8.7 83.0 2.5</td>
<td>9.6 83.7 2.0</td>
<td>9.5 84.0 2.0</td>
</tr>
</tbody>
</table>

**Difficulty in intensity estimation**
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 system 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

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
Most of the cyclonic disturbances above 15°N move in a north-northeasterly or northeasterly direction.

Below 15°N and left of 90° E they generally move in north-northwesterly or northwesterly direction over the Bay of Bengal.

In Arabian Sea below 15°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°N move in a north-northeasterly or northeasterly direction whereas below 15°N they generally move in northwesterly direction over the Bay of Bengal.

- In Arabian Sea below 20°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.
DATE=28       MONTH=5
PRESENT LAT/PRESENT LONG=   14.50000   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
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 ($\beta = df / dy$).

“Simple” explanation from the Cartesian non-divergent barotropic vorticity equation.

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

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

Source: Dr. Matthew D. Eastin
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).

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

From Holland (1983)
TC Motion (Synoptic) : Importance of P24P24

- The importance of P24P24 observation is amply illustrated in determining the track and landfall 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: Utility of 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

Area of intense convection changed from northern sector to southwest sector on 27th.
Impact of convection on sudden change in track

Southward shifting of area of intense convection is also seen in DWR imageries.
Area of intense convection again shifted to north at the time of landfall
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.
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

Observed and Forecast Track

Depression (4 Nov)

8 Nov, 00h
7 Nov, 00h
6 Nov, 00h
5 Nov, 00h
4 Nov, 03h
18h06h
18h12h
12h
6 Nov, 00h
5 Nov, 00h
4 Nov, 03h
18h06h
18h12h
12h
7 Nov, 00h
8 Nov, 00h

75.00'E
80.00'E
85.00'E
90.00'E
95.00'E
100.00'E
105.00'E

10.00 N
15.00 N
20.00 N
25.00 N
30.00 N
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

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 SATELLITE AND RADAR INPUTS SHOULD 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 D to CS Basin(F): BOB+AS+Land, Period: 1891-2011

Note: Negative value indicates indeterminate probability
Source: Cyclone eAtlas - IMD
Monthly Probability of Intensification of D to SCS Basin(F): BOB+AS+Land, Period: 1891-2011

Seasonal Probability of Intensification of D to SCS Basin(F): BOB+AS+Land, Period: 1891-2011
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.
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)
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.
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.
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.
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)

- 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%.

Mean humidity distribution at 700 hPa level and 500 hPa level on 11 (Weakening mean position 13.8/83.4)
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.
• 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.
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
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. Entrainment 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)
Translational Speed and Intensity

Translational Speed (mps*10) of TC Phailin & TC Hudhud

- VCS Phailin
- VCS Hudhud
- Phailin landfall
- Hudhud landfall

Date/Time in UTC

Month/Date
Time (UTC)
Pressure Drop and intensity
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.
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.
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

(a-i)

(b-i)

(c-i)

Phailin Hudhud

(a-ii)

(b-ii)

(c-ii)

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