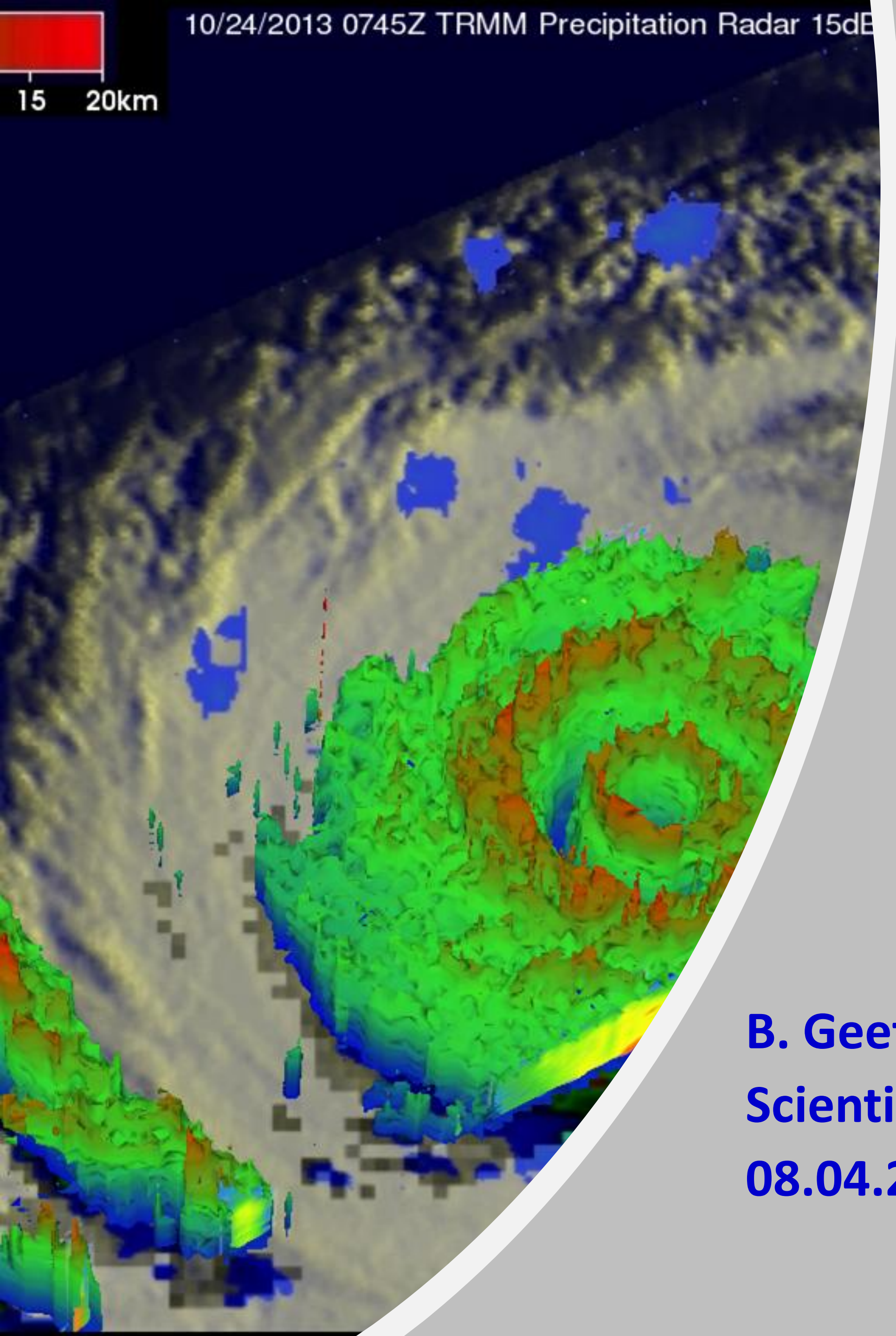



# Training on Tropical cyclones & Storm surge forecasting by RSMC New Delhi

## Characteristics of Heavy rainfall associated with Tropical Cyclones

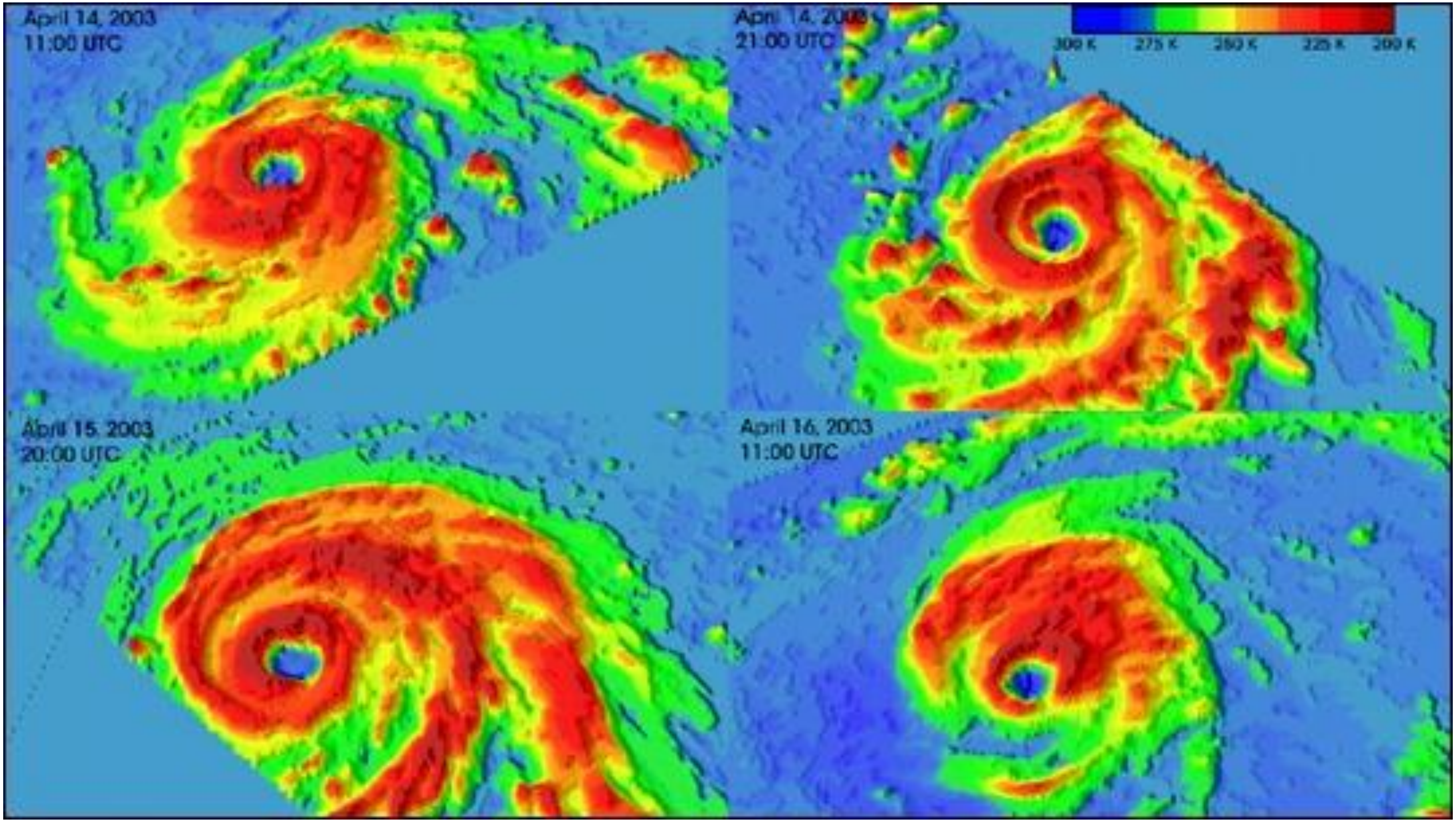
**B. Geetha**
**Scientist-D, IMD Chennai**
**08.04.2022**

# Outline

- ✓ **Precipitation in various areas of a mature TC**
- ✓ **Factors affecting TC rainfall**
- ✓ **Observational features**
- ✓ **Some features observed in TCs over NIO**

# Precipitation structures in TCs

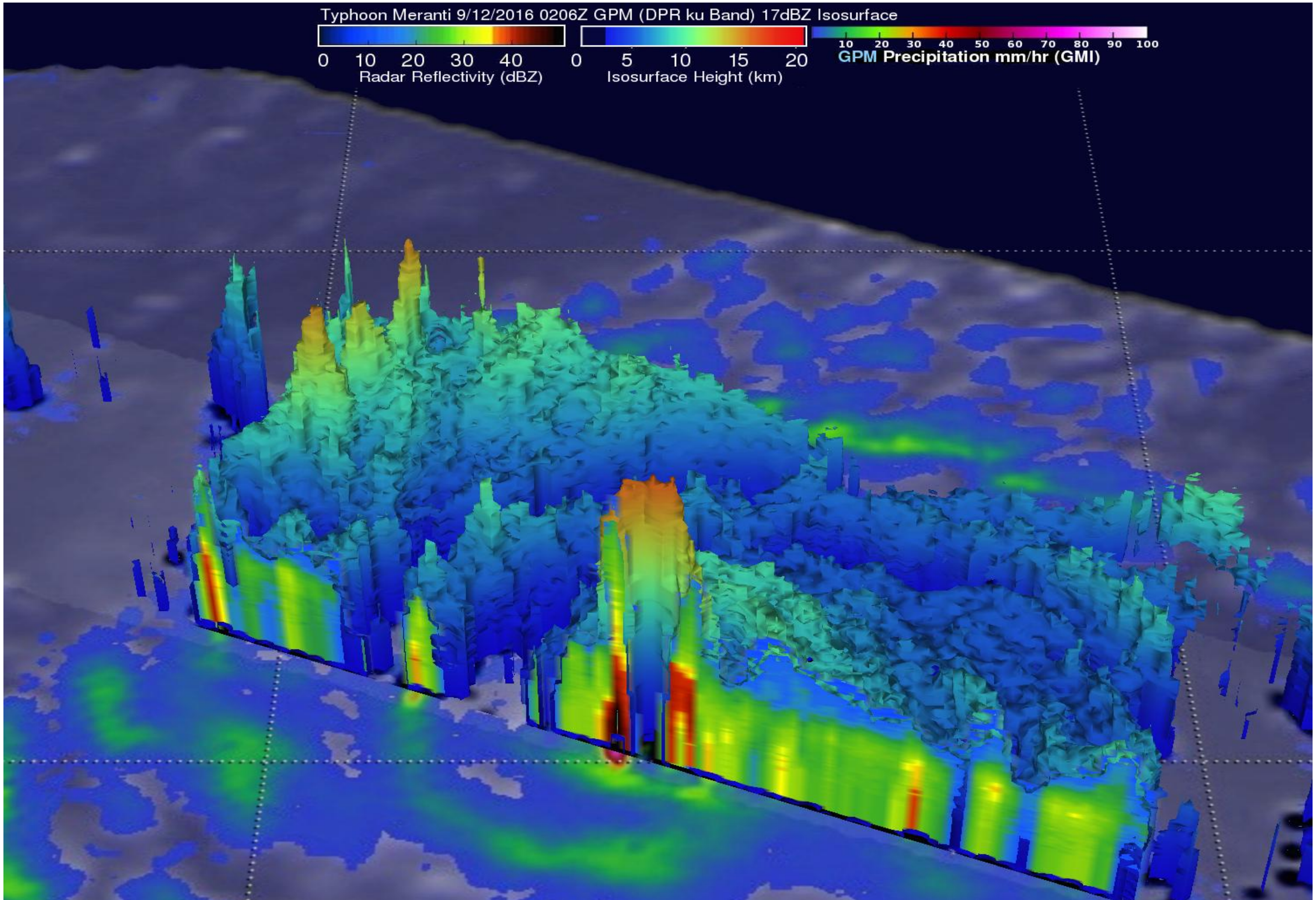
## Radially→four distinct regions of precipitation



# Precipitation structures in TCs

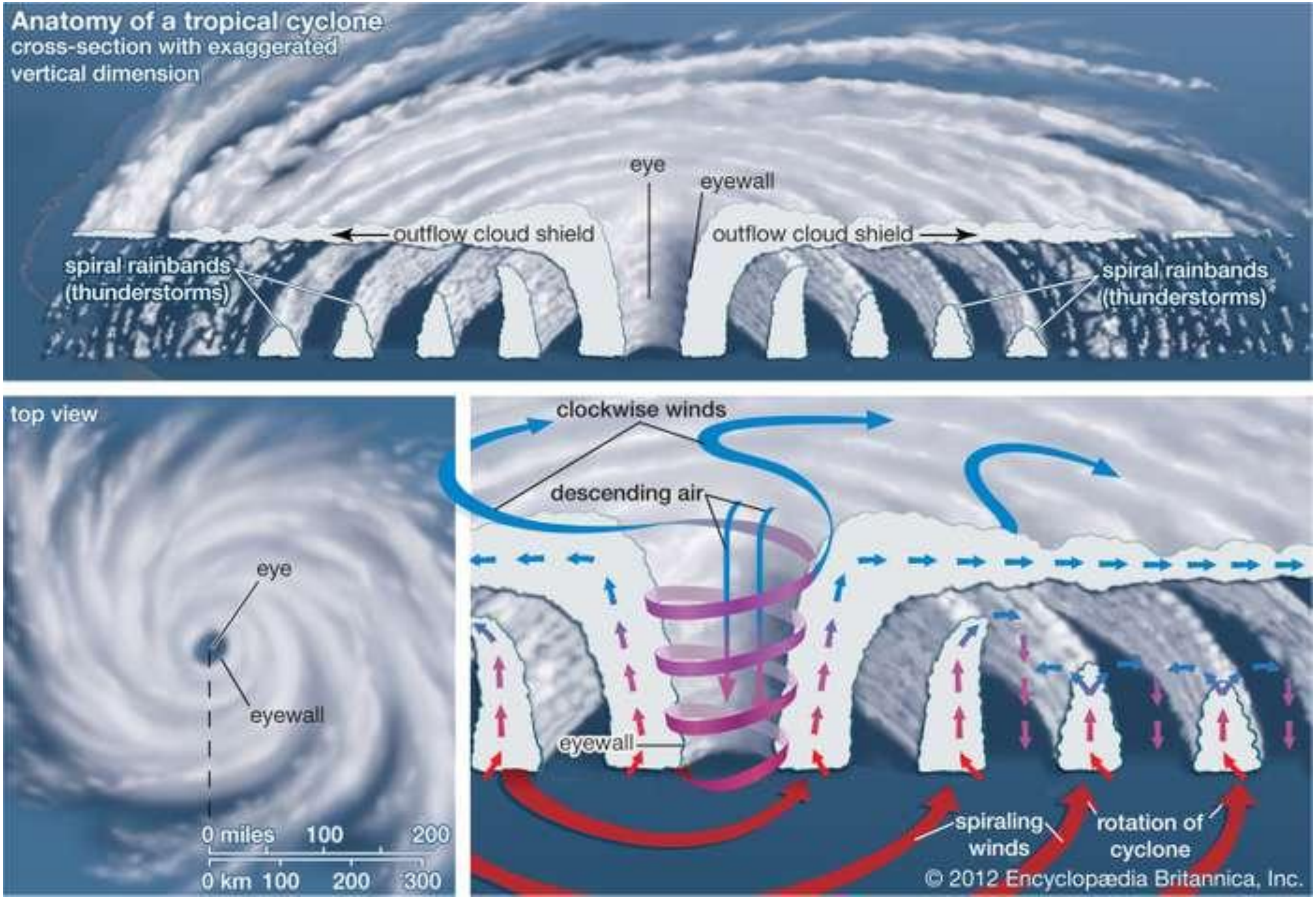
- ✓ There are different dynamical features in different regions of a mature TC.

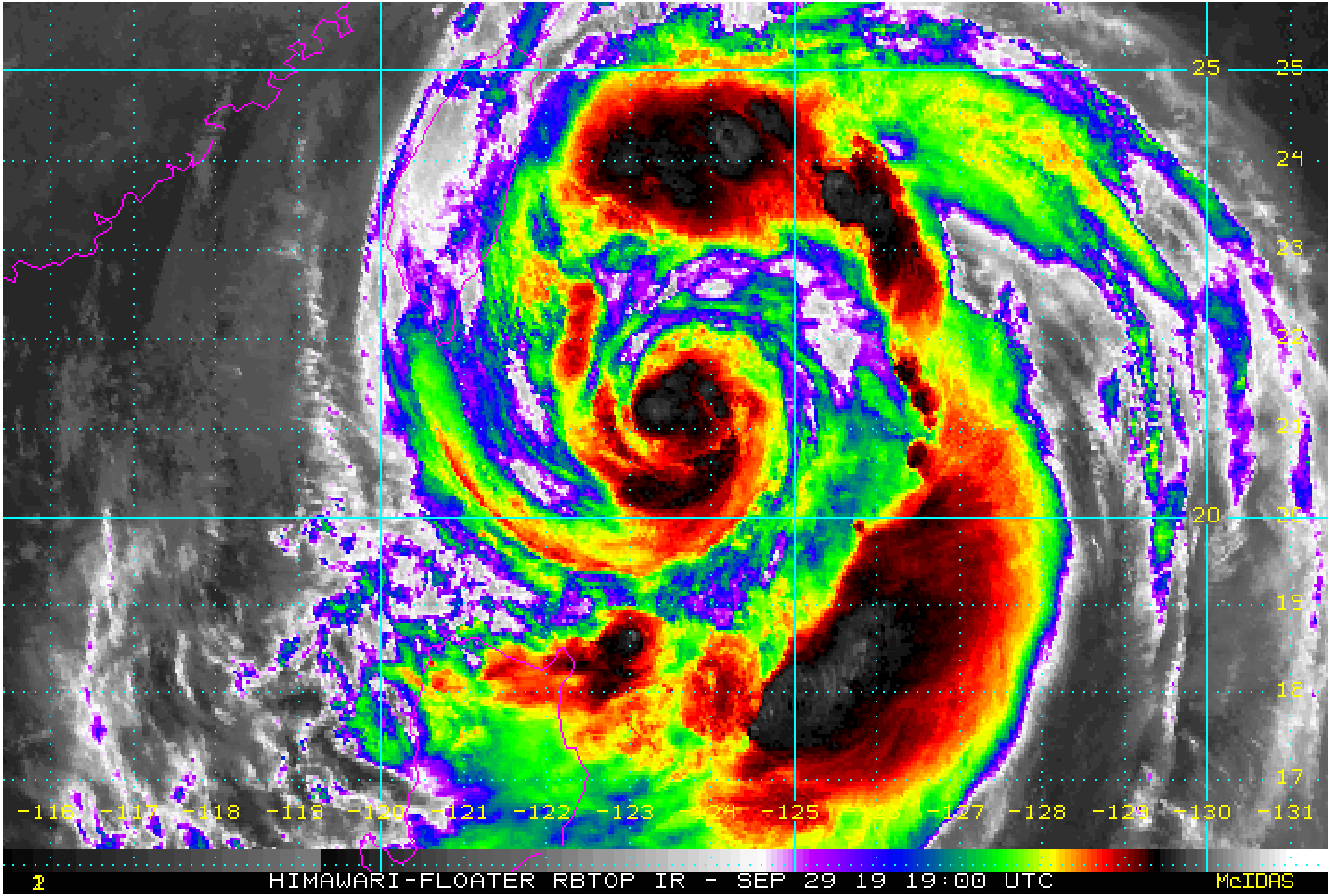
- ✓ EYE→ little precipitation with almost free or weak radar echoes.
- ✓ EYEWALL→ outwardly sloped deep cloud wall, named eyewall, surrounding the eye, with heavy precipitation and strongest swirling winds. RMW and RMR (area of heaviest precipitation) are located in this region.
- ✓ INNER SPIRAL BANDS→ Immediately outside the eyewall, there are often well-organized narrow rainbands, called inner spiral rainbands where high wave number asymmetries are often damped effectively (i.e., symmetric distribution)
- ✓ OUTER SPIRAL BANDS→ Further outside, namely outside of about 2–3 times of the RMW are loosely organized rainbands with embedded strong convective cells. Those rainbands are often referred to as outer spiral rainbands (asymmetric distribution).




**On Sept. 12 2016, at 0206 UTC, GPM DPR data indicated rain was falling at a rate of over 299 mm per hour in powerful storms in the northeastern side of Meranti's eye wall.**

**Credit: NASA/JAXA**


Anatomy of a tropical cyclone
cross-section with exaggerated vertical dimension
eye
eyewall
outflow cloud shield
outflow cloud shield
spiral rainbands (thunderstorms)
spiral rainbands (thunderstorms)
top view
eye
eyewall
0 miles 100 200
0 km 100 200 300
clockwise winds
descending air
eyewall
spiraling winds
rotation of cyclone
© 2012 Encyclopædia Britannica, Inc.



25
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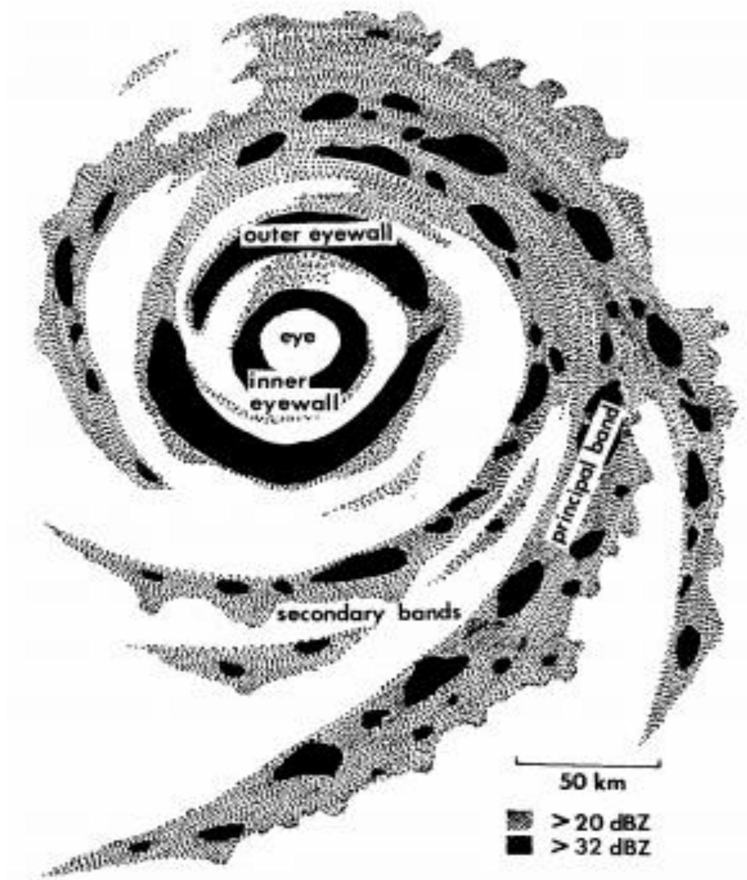
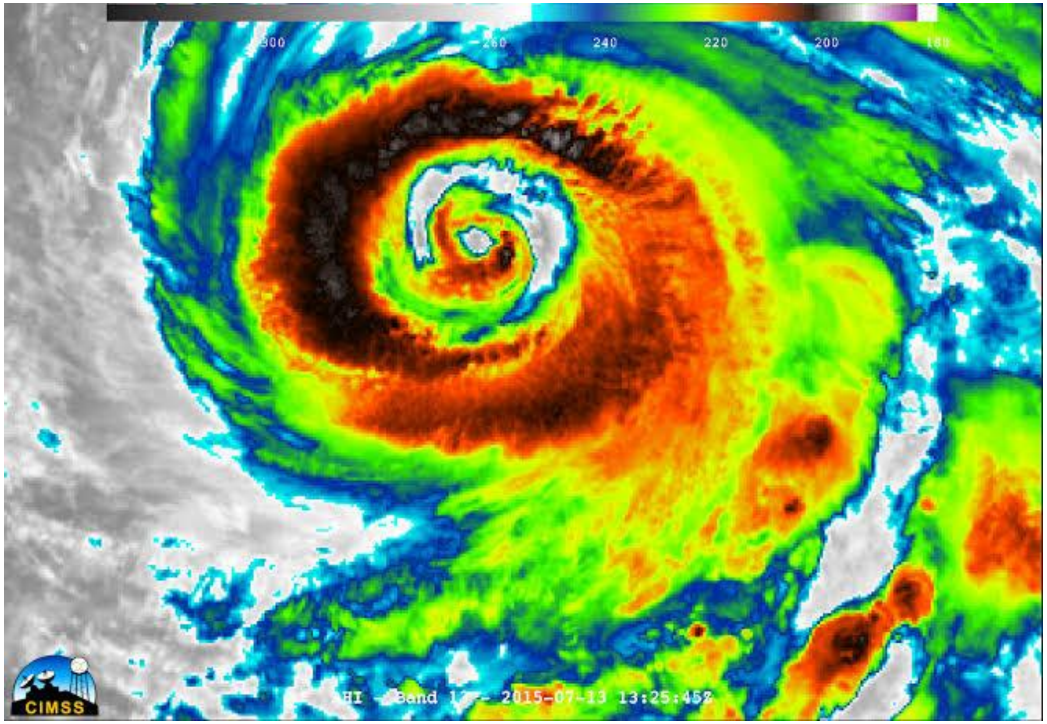
-116 -117 -118 -119 -120 -121 -122 -123 -124 -125 -126 -127 -128 -129 -130 -131
HIMAWARI-FLOATER RBTOP IR - SEP 29 19 19:00 UTC
McIDAS

# Eye wall precipitation




- ✓ **Most intense precipitation associated with TC occurs in eyewall**
- ✓ **Eyewall is colder than the Eye**
- ✓ **Sometimes, double eye wall is also seen**

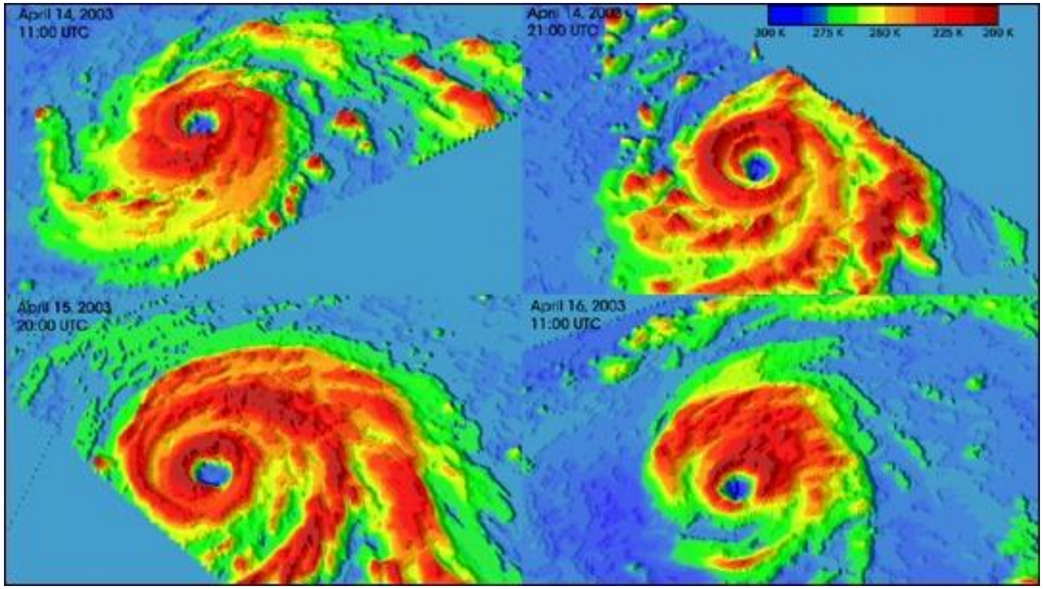
## Spiral bands:

- ✓ **Spiral-shaped patterns of precipitation characterize radar and satellite images of tropical cyclones.**

- ✓ **These are typically 5-50 km wide and 100-300 km long.**

- ✓ **The precipitation-free lanes between bands tend to be somewhat wider than the bands.**

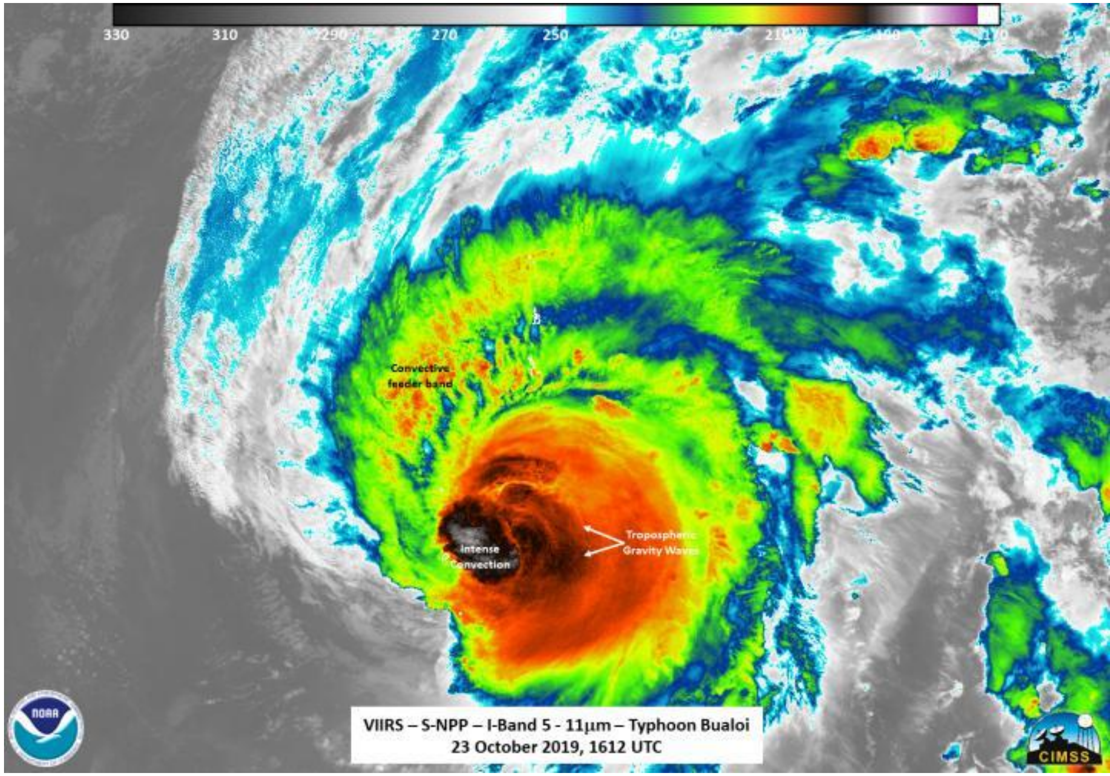
- ✓ **As the tropical cyclone becomes more intense, the inward ends of the bands approach the center less steeply and then approximate arcs of circles.**



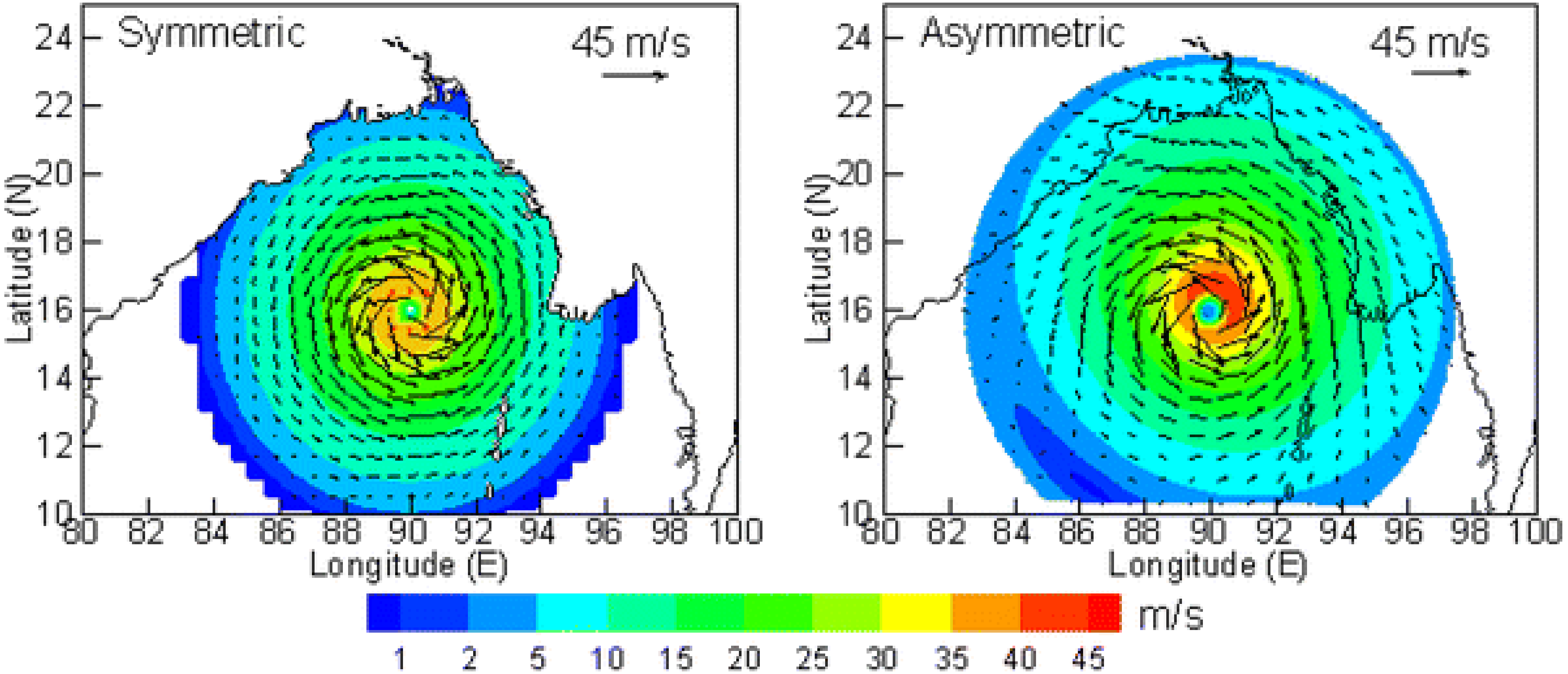
# Asymmetric structure

- ✓ **Although a strong mature TC is highly axisymmetric, considerable asymmetric structure can develop as a result of either internal dynamical instability or external forcing such as env VWS or both.**

- ✓ **Asymmetries are characterised by (i) vortex Rossby waves (VRWs) in the inner core region, (ii) inertia-gravity waves further outside & (iii) mesovortices in the eyewall.**



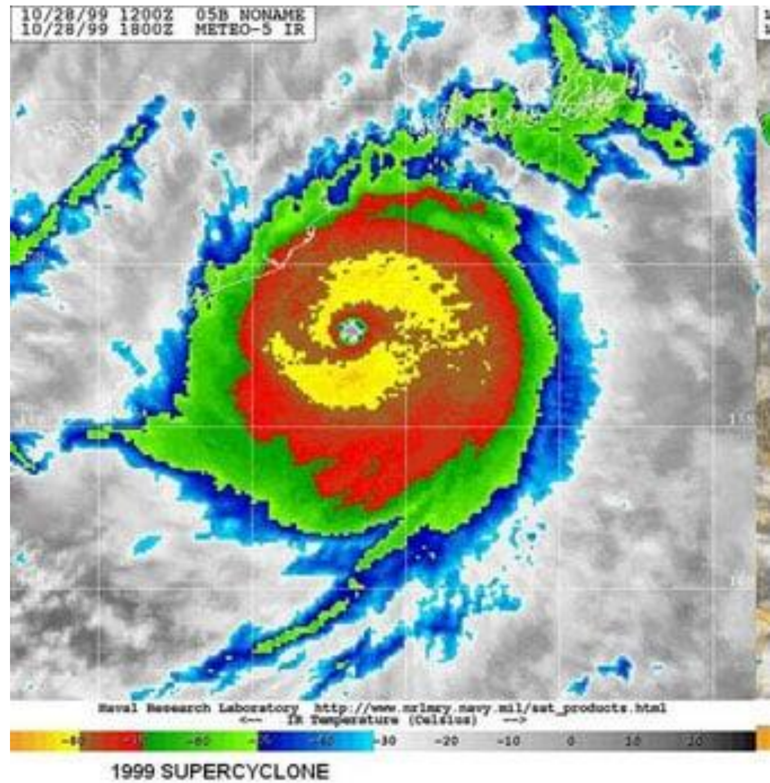
## In the wind field …




(a) Symmetric (b) Asymmetric

# Axi-symmetric inner core structure

- ✓ **In the inner core of the vortex→ an annular region immediately outside the RMW exists.**
- ✓ **In this annular region, most of the high azimuthal wave number asymmetries would be filamented and effectively damped and axi-symmetrized.**
- ✓ **Hence, in the near-core region the primary flow is quasi-axisymmetric and rapidly rotating.**




**Oct 1999 – Odisha Super cyclone**

# Asymmetric structure ....Vortex Rossby Waves

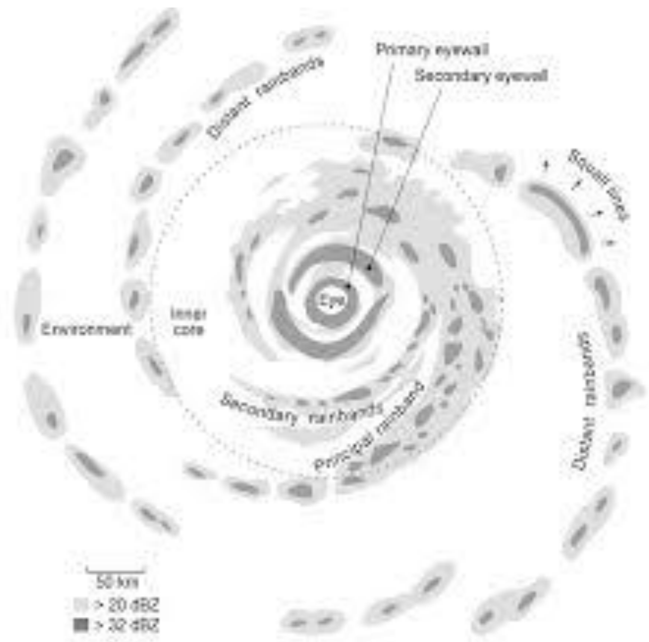
- ✓ As TCs are localized vortices with elevated cyclonic potl vor (PV) concentrated in the inner core region near the RMW with large radial gradients, any radial perturbation of air parcel would experience restoring force due to the presence of PV gradients, and generate edge PV waves.

- ✓ Radial gradient of the vorticity of the cyclonic vortex lead to generation of Vortex Rossby Waves.

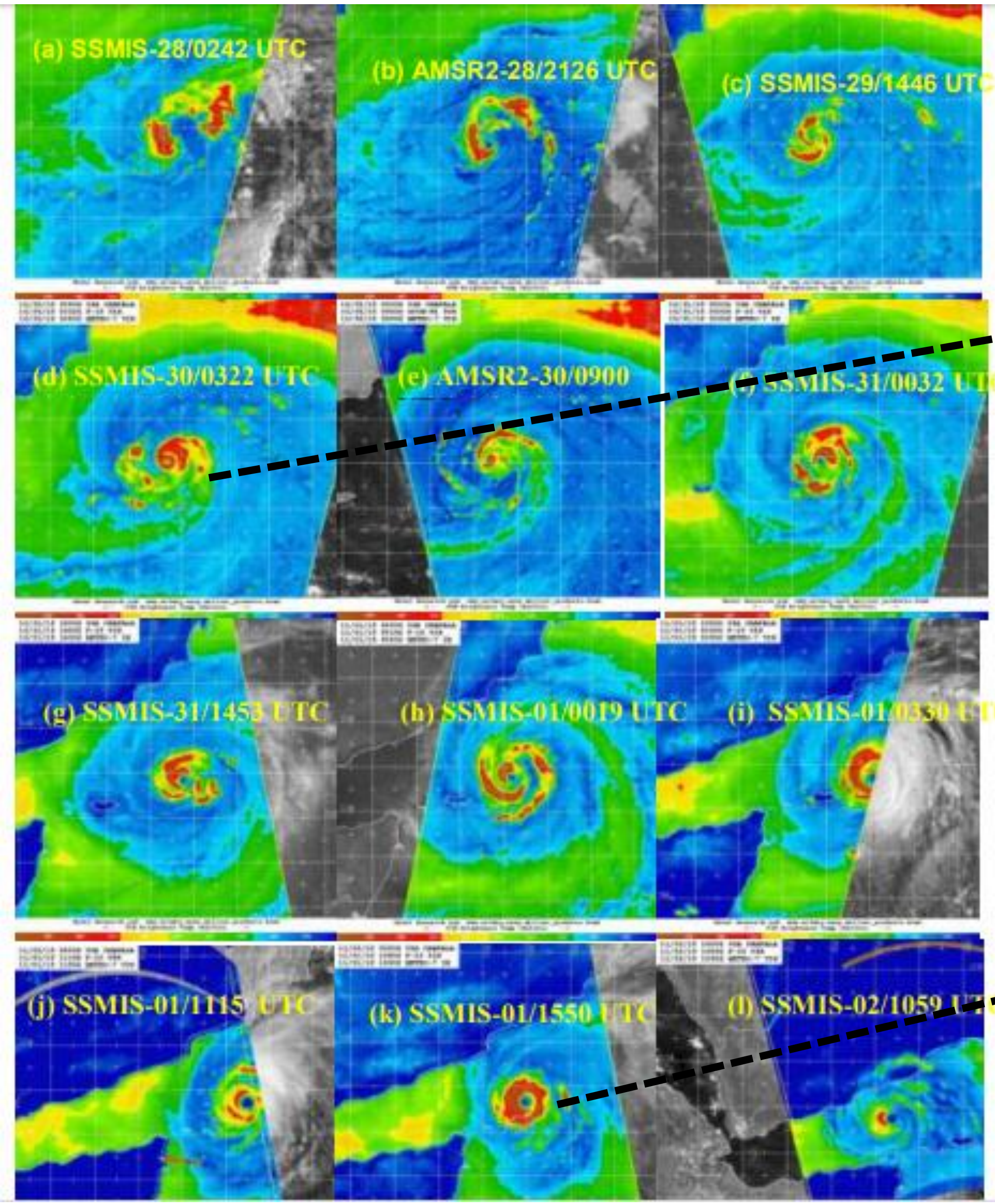
- ✓ VRWs can be forced and driven by convective asymmetries in the eyewall.

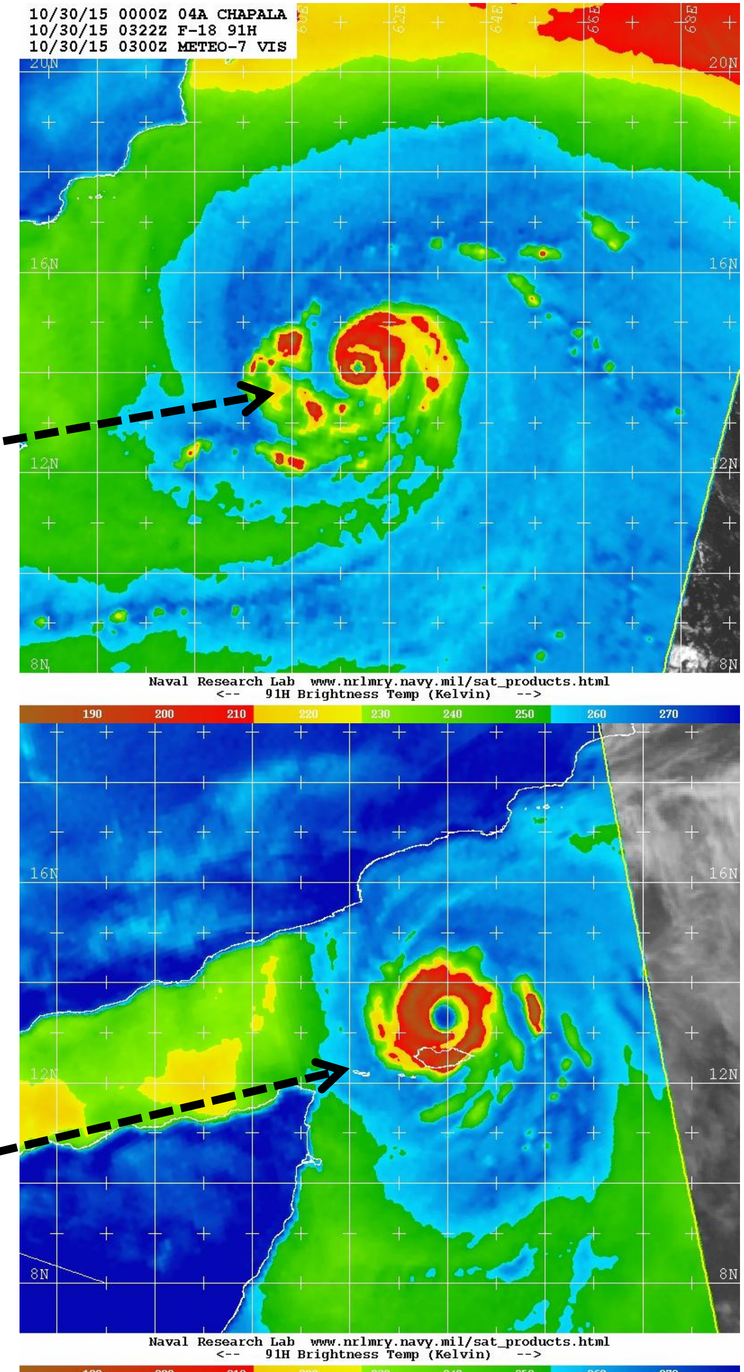
# Double eye wall / Eyewall replacement cycle

- In some strong TCs, some of the outer rainbands may strengthen and organize into a ring of convection, named as outer eyewall or a secondary eyewall that slowly moves inward and robs the original eyewall or the inner eyewall of its needed moisture and angular momentum. This usually causes the weakening of the inner eyewall and the TC during this phase. Eventually, the outer eyewall replaces the inner one and the storm may re-intensify.
- Axisymmetrization of spiral rainbands is considered to be a plausible process causing the secondary eyewall formation (SEF).
- In some cases, eddy angular momentum flux associated with an upper tropospheric trough may initiate deep convection outside the eyewall and trigger major outer spiral rainbands and the SEF.



# ERC: ESCS Chapala over AS during 28 Oct - 4 Nov 2015



## Asymmetric structures - Observational features

# Spatial rainfall distribution - Studies on convective asymmetries

- ✓ **Case studies on Rainfall asymmetries of Hurricanes Alicia, Elena Allen –Burphee&Black, MWR, Oct 1989**

- ✓ **RF asymmetry w.r.t VWS - Case study of Hurricane Bonnie (1998) – Rogers et al, MWR, Aug 2003**

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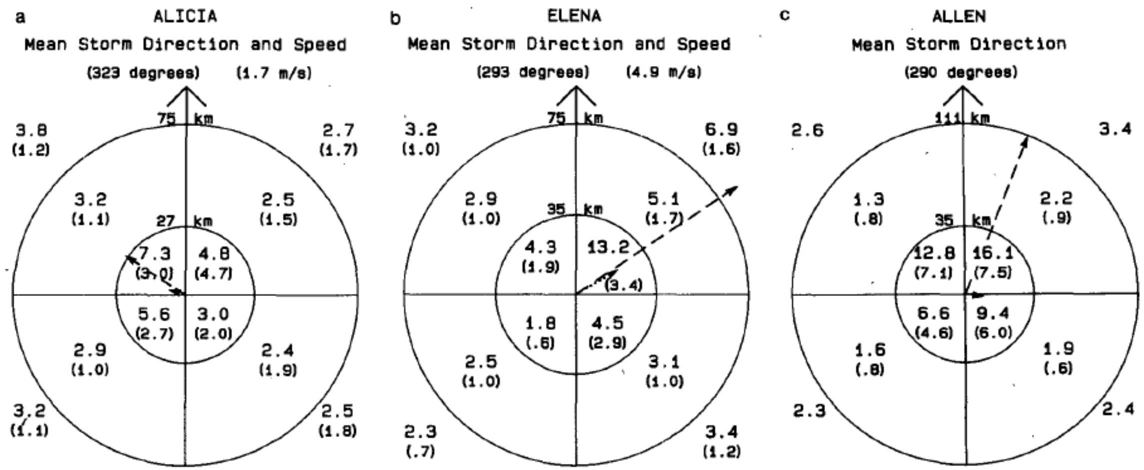



FIG. 6. Mean rain rate (mm h$^{-1}$) and standard deviation (in parentheses) are given by quadrant, relative to the storm motion, for the eyewall and rainband regions of (a) Alicia, (b) Elena, and (c) Allen. The numbers outside the larger circle are mean rain rates and standard deviations by quadrant for the total area. Dashed and dotted arrows indicate the azimuth of the maximum rain rate for wavenumber 1 in the eyewall and rainband regions, respectively. The amplitude of wavenumber 1 is proportional to the length of the arrow. An arrow with an amplitude of 5 mm h$^{-1}$ has a length equal to the radius of the larger circle. The Allen data are reproduced from Marks (1985) and are averaged for his six composites from 5–9 August 1980.

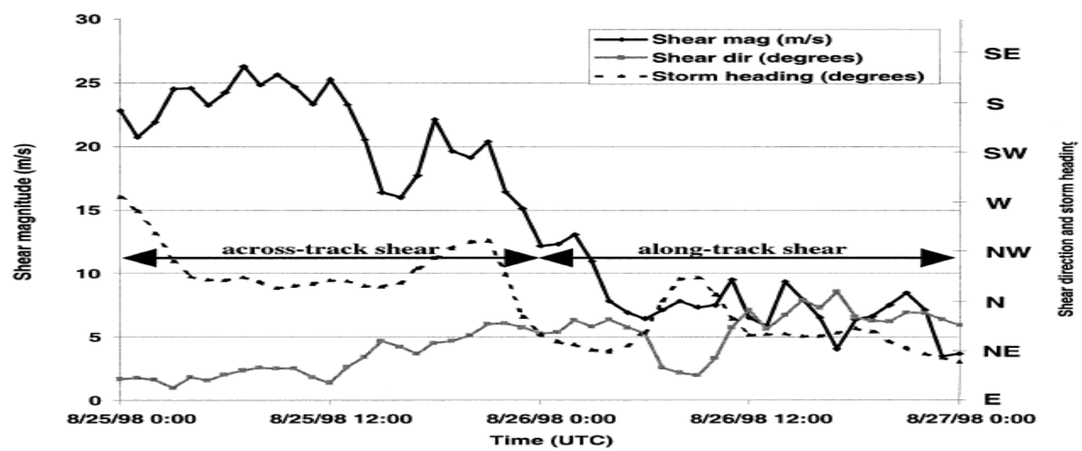


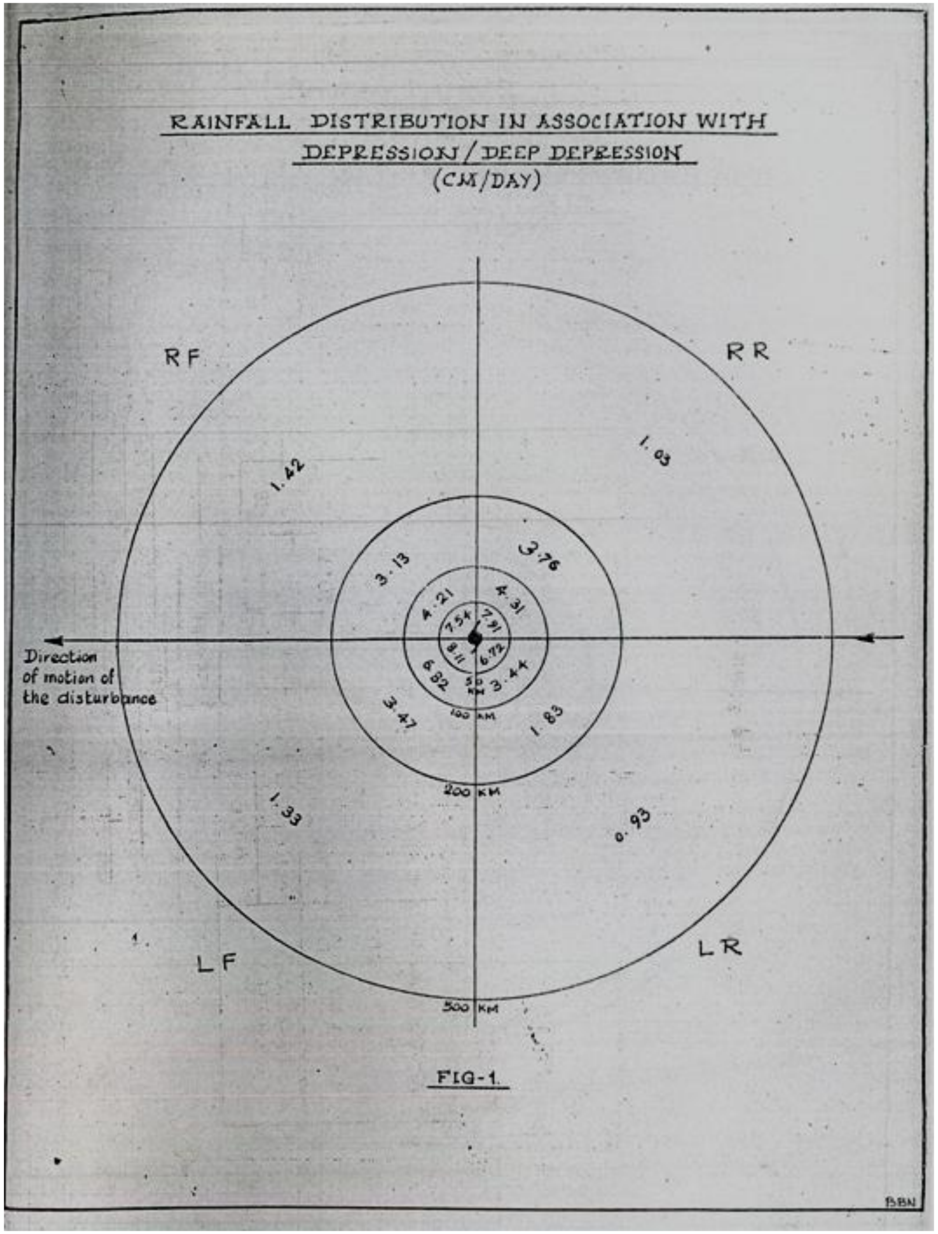

FIG. 8. Time series between 0000 UTC 25 Aug and 0000 UTC 27 Aug of the magnitude of 900–400-hPa wind shear (solid line; m s$^{-1}$), direction of 900–400-hPa wind shear (gray line; E means shear vector points toward the east, NW means shear vector points toward the northwest, etc.), and storm heading (dashed line; E means storm is heading toward the east, etc.) Periods of storm motion encountering across-track or along-track shear are indicated by arrows.

# Radial and azimuthal variation in TC rainfall over NIO

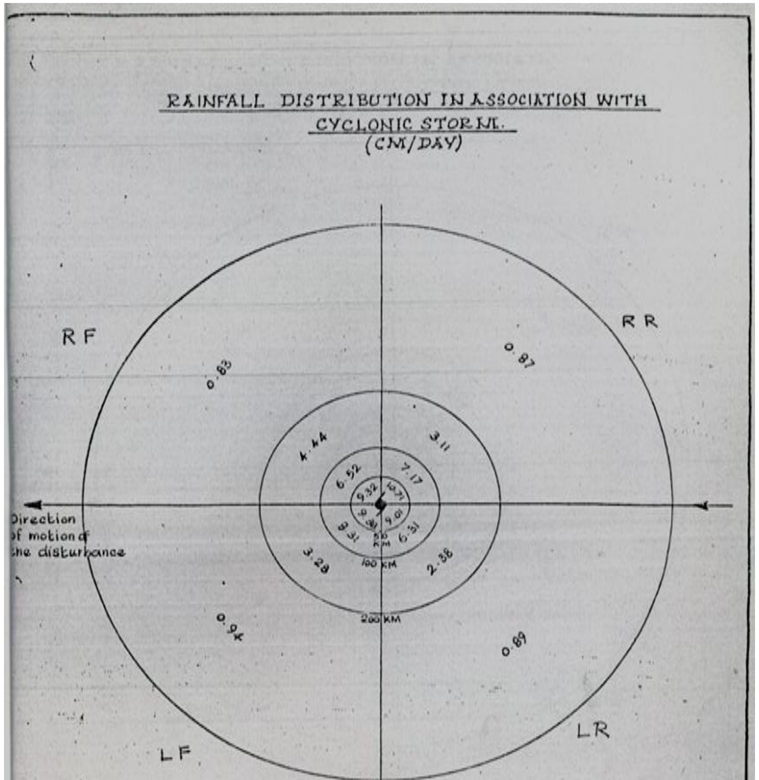
- ✓Based on Rain gauge observations for systems during 1877-1984 when the system was near the coast
- ✓Rainfall due to severe TCs→ high only within 200 km
- ✓Beyond 200 km→ D give more rainfall than SCS

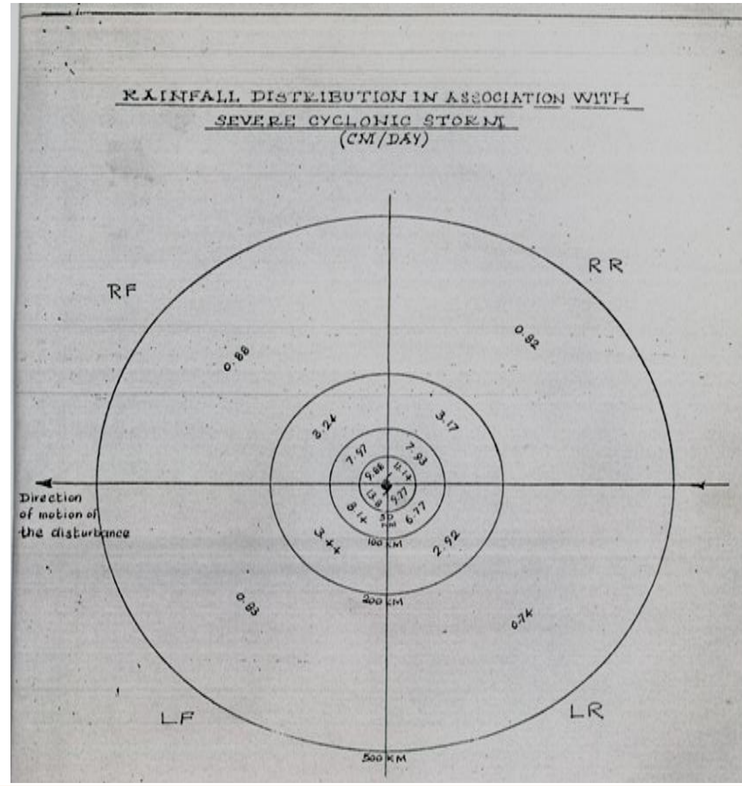
| D/DD stage |
| --- |
| Max concentration→ within 50 km; FL asymm followed by RR quadrant - (8 cm/day) |
| 50-100 km→ 4-7 cm/day; FL asymm→ 7 cm/day |
| Beyond 200 km→ about 1 cm/day |

**Jayanthi N & Sen Sarma A.K., IMD, PPSR No. 87/2 dated Sep 1987**



# Radial and azimuthal variation in TC rainfall distribution ...



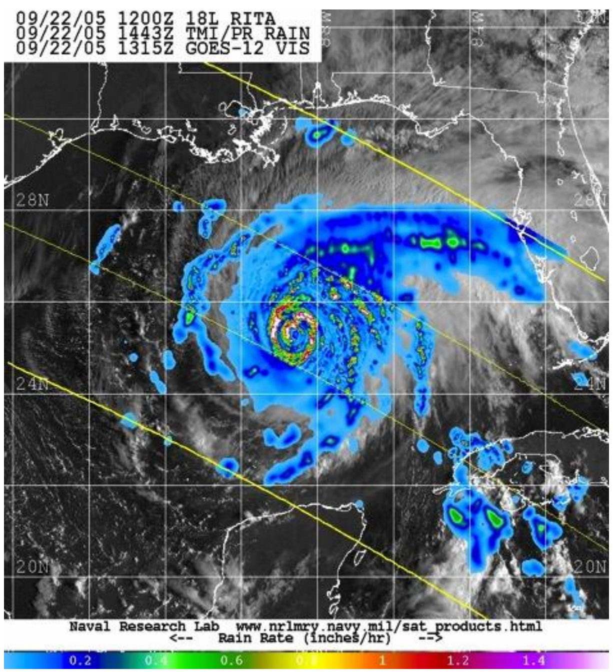

| CS stage |
|---|
| Max concentration→ within 50 km (9-10 cm/day); asymm max→ RR followed by FL quadrant |
| 50-100 km→ 6-8 cm/day; FL asymm→ 8 cm/day; RR→ 7 cm/day |
| 100-200 km→ about 2-4 cm/day; Right asymm; Beyond 200 km→ 0.8 cm/day |

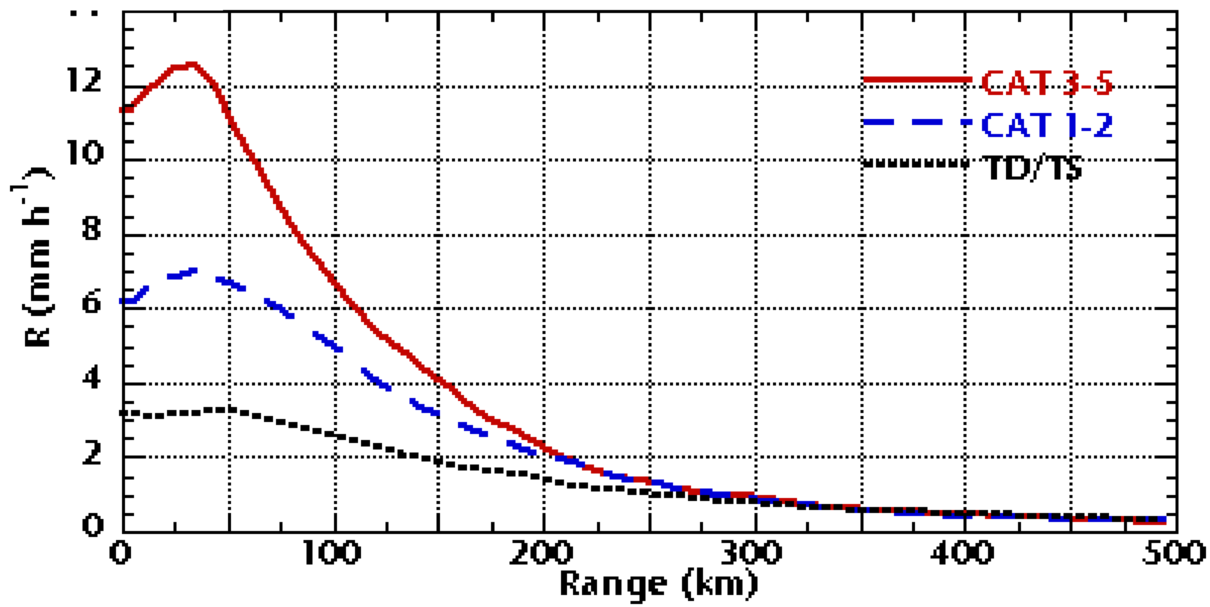
| SCS stage |
|---|
| Max concentration→ within 50 km; asymm max→ FL (13.8 cm/day) followed by RR quadrant (11 cm/day) |
| 50-100 km→ 5-6 cm/day; Asymmetry→ not pronounced |
| 100-200 km→ about 3 cm/day; Right asymm; Beyond 200 km→ 0.8 cm/day |

# Characteristics of TC precipitation - global perspective

- NASA Tropical Rainfall Measuring Mission (TRMM)
  - TRMM Microwave Imager (TMI)
  - Precipitation Radar (PR)
- Strength global coverage with single instrument
- Improve understanding of TC rain from rain climatology, globally
- 1 Jan 1998–31 Dec 2000, 260 TCs globally →2121 TMI observations

tropical storms (TSs) are defined as systems with wind speed[1] from 18 to 33 m s$^{-1}$, category 1–2 (CAT12) systems with wind between 34 and 48 m s$^{-1}$, and category 3–5 (CAT35) systems with wind >49 m s$^{-1}$. The




Lonfat et al, 2004, MWR, 132, 1645-1660

↑

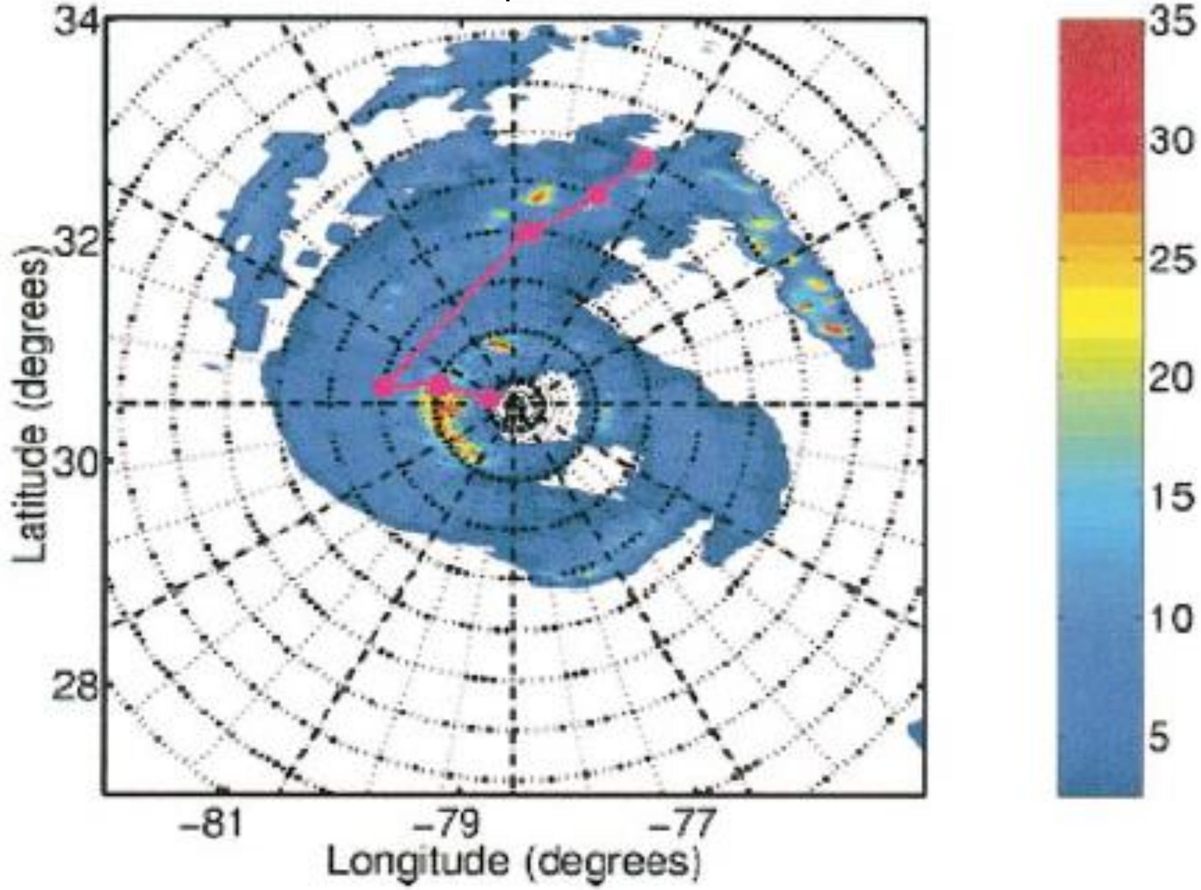
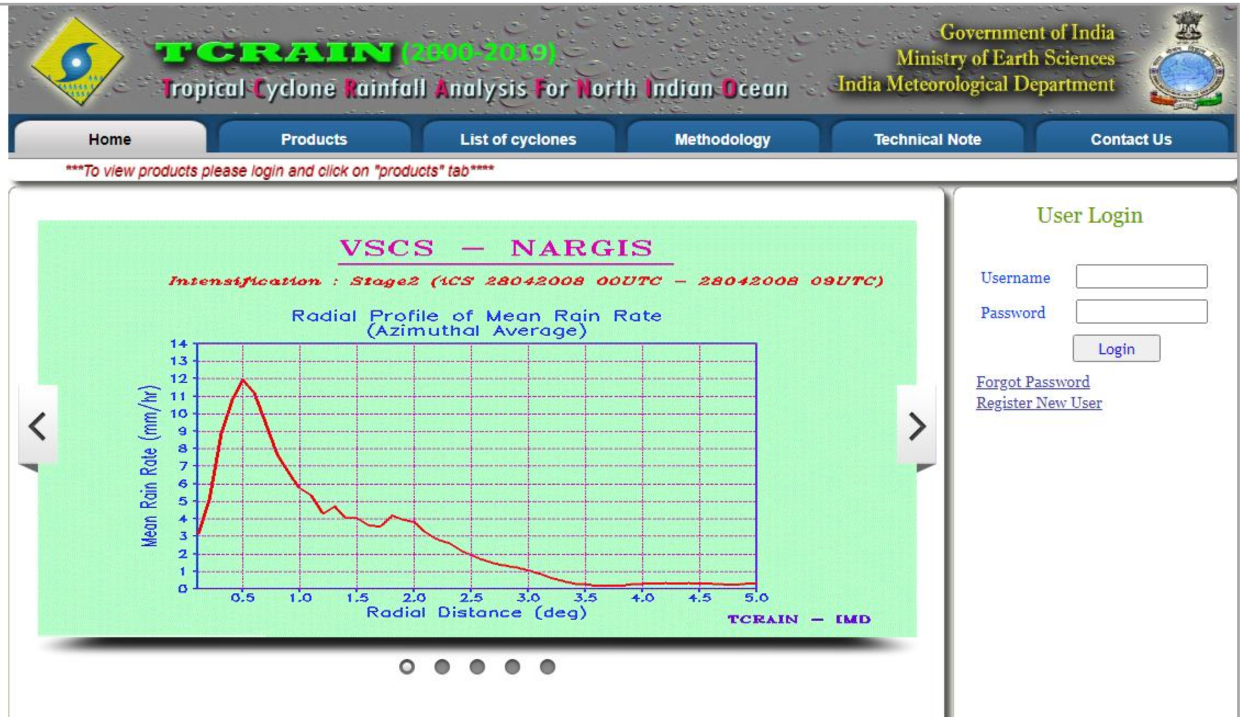


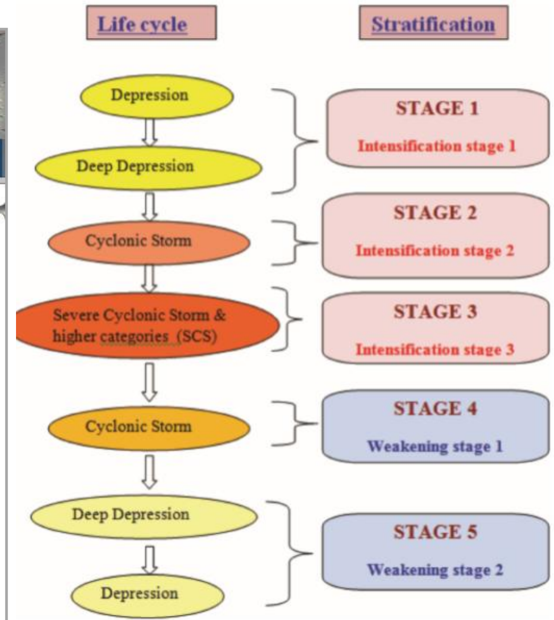

FIG. 4. TMI surface rainfall (in mm $h^{-1}$) of Hurricane Dennis, on 28 Aug 1999. The dots indicate the location of the phase max of the rainfall asymmetry as a function of the distance to the storm center. The circles (broken lines) are drawn at 50-km radial increments.

**Lonfat et al, 2004, MWR, 132, 1645-1660**

# TC rainrate distribution – NIO (TRMM data)




**imdchennai.gov.in → Cyclone Rainfall Atlas (under Tools & applications tab)**




**Rainfall distribution in the TC field based on 3-hrly TRMM / GPM data for about 80 cyclones**

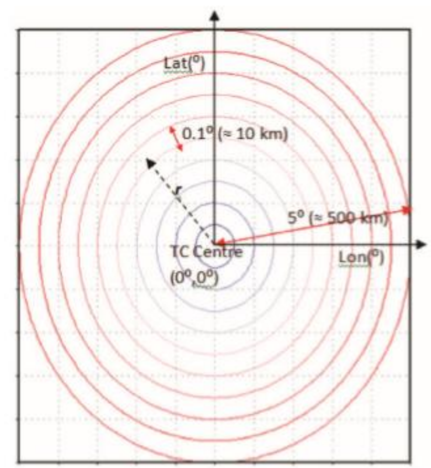



FIG. 3a. Schematic representation of steps for determination of azimuthally averaged radial profile of mean rain rate

**Balachandran et al,** *Tropical cyclone Research & Review,* 2014, **3**, 2, 122-129)

# TC Rainrate distribution –NIO …

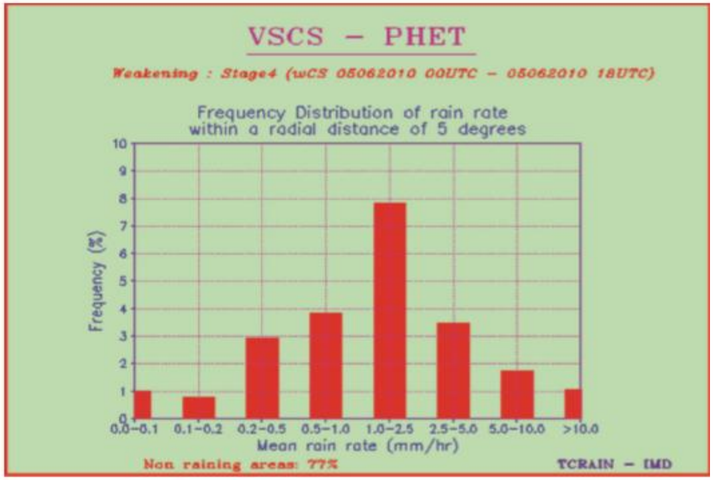



FIG. 2. Sample product of Frequency distribution of rain rates within 5° radial distance

**Frequency distribution of rain rates within 5° radial distance from the TC centre**

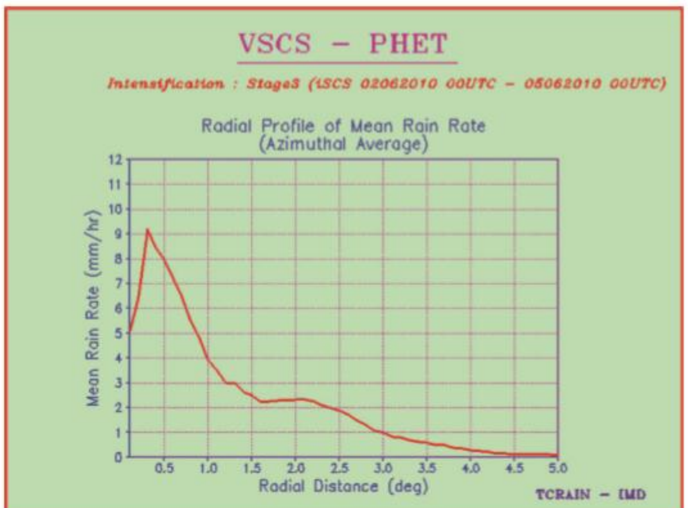



FIG. 3b. A sample product of Radial Profile of rain rates within 5° radial distance

**Radial profile of azimuthally averaged mean rain rates within 5° radial distance from the TC centre**

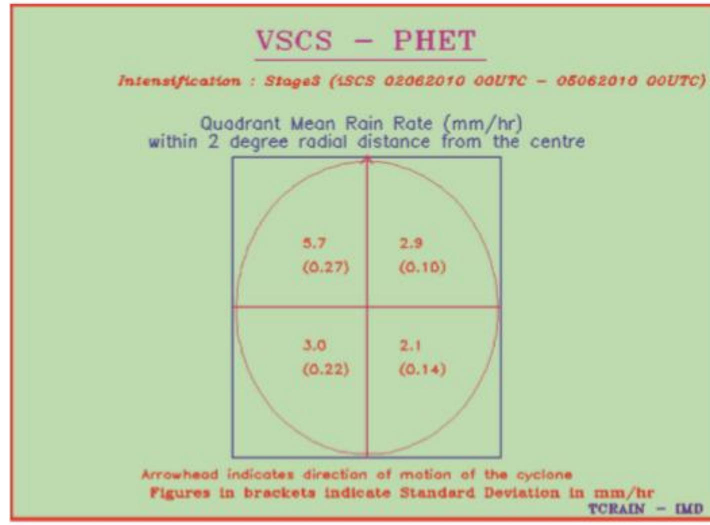



FIG. 4b. A sample product of quadrant mean rain rates within 2° radial distance

**Quadrant mean rain rates within 2° radial distance from the TC centre**

**Balachandran et al,** *Tropical cyclone Research & Review,* 2014, **3**, 2, 122-129)

# TRMM based TC rainfall distribution ….

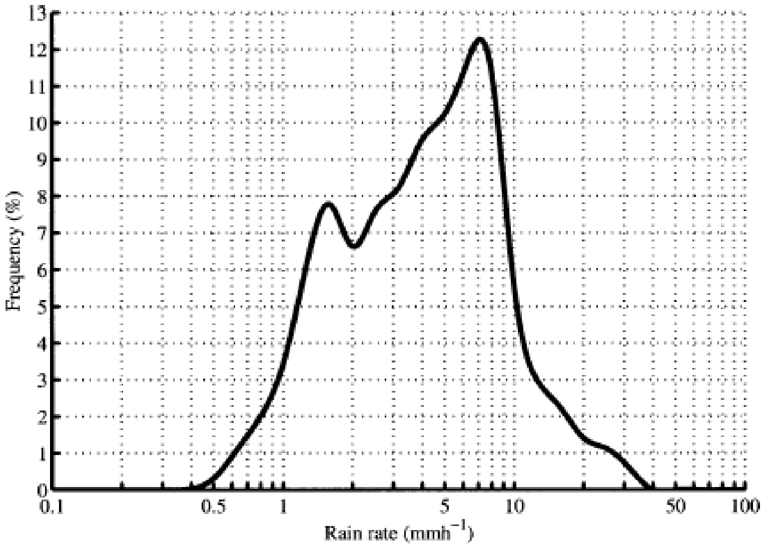
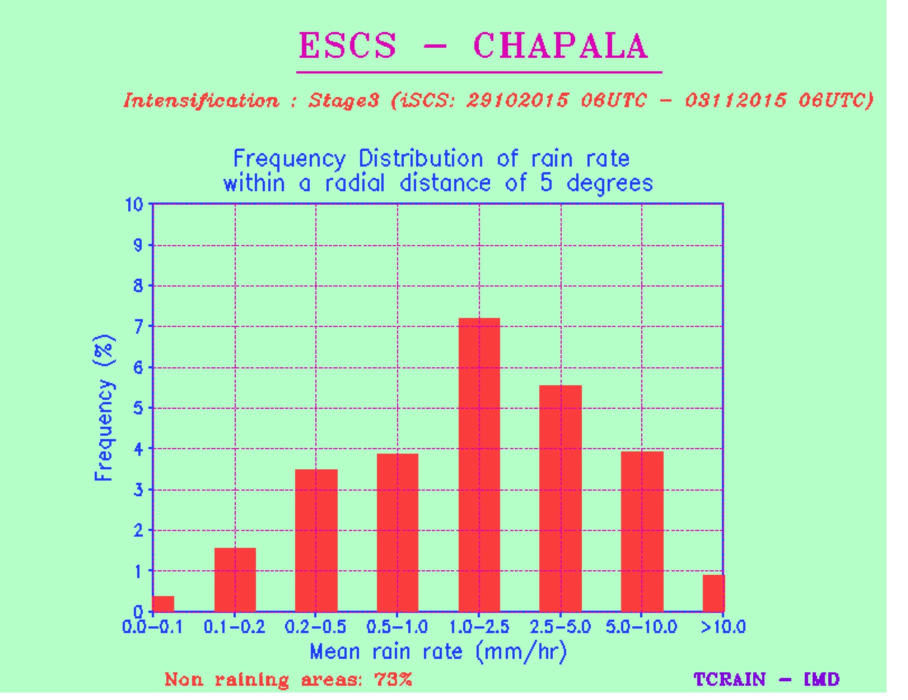
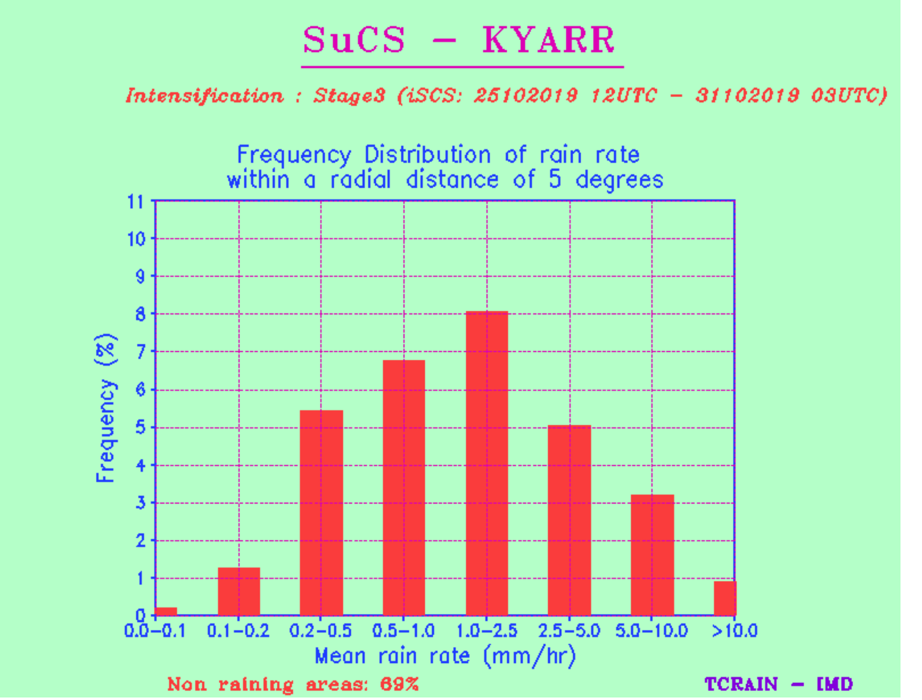


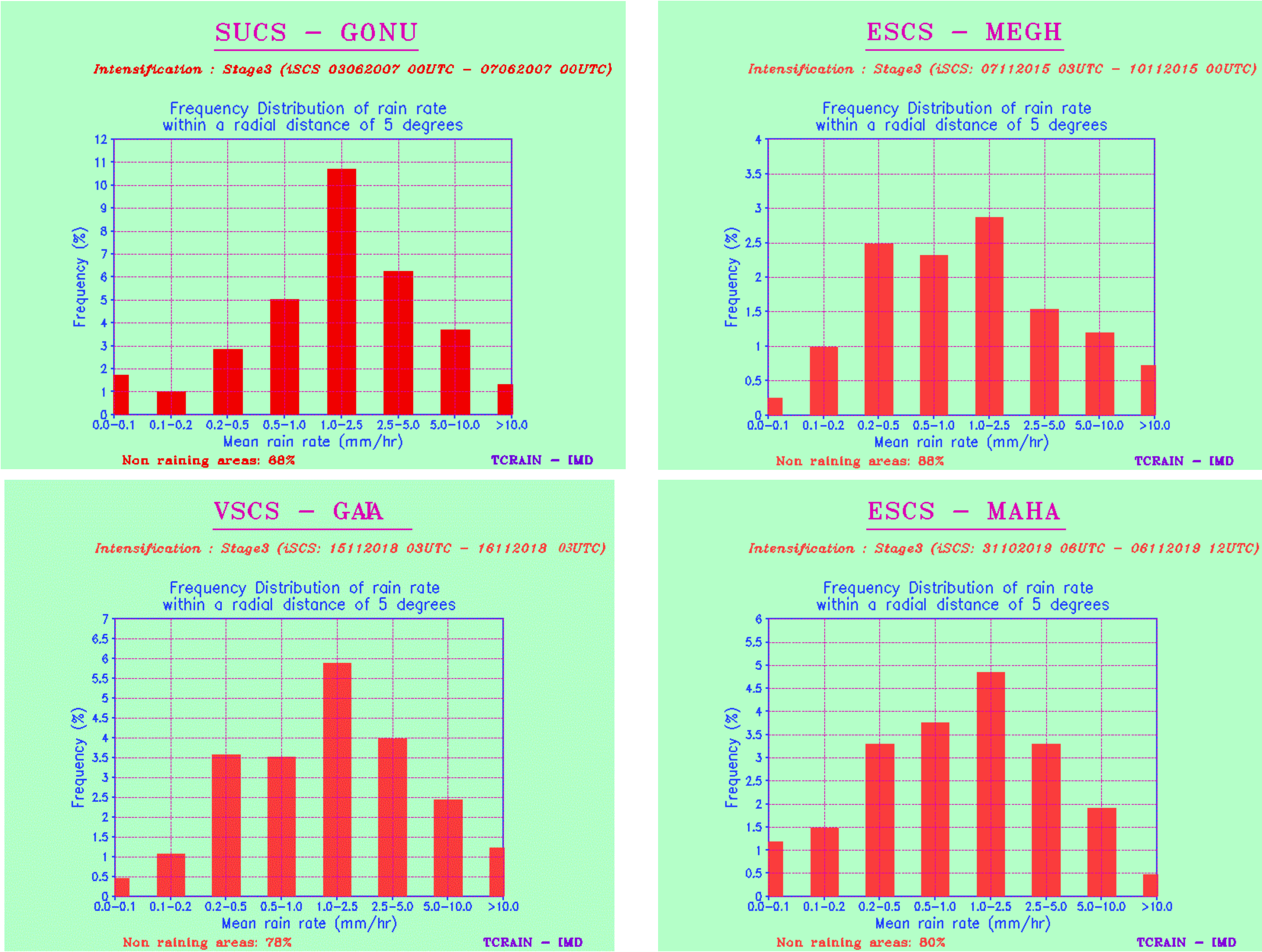

FIG. 6. PDF of rainfall for Dennis within 300-km radius of the storm center.

**Rainfall covers only 25% of the total area within 500 km of the storm center.**
**Rain rates → 0.4 and 40 mm/hr.**
**91% of the rainfall within 500 km →1 -10 mm/hr.**
**Mode →7 mm/hr; Secondary max→ near 1.5 mm/hr.**
**The stratiform rain area in the rainbands contributed the most to the 7 mm/hr peak.**
**The total distribution is skewed toward higher rates, which shows that convective-type rainfall from the eyewall and rainband dominates the distribution.**

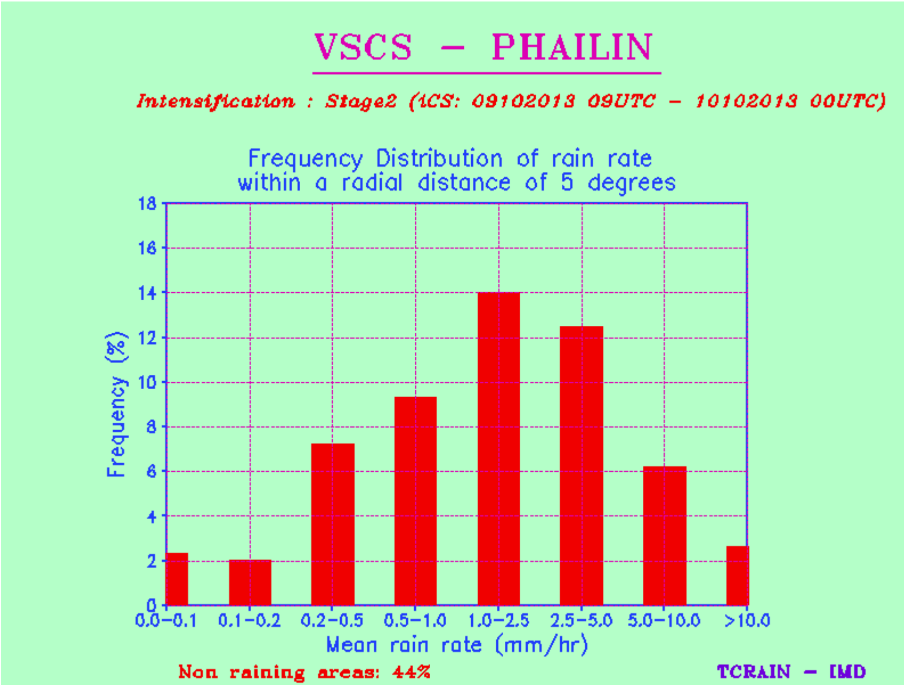
**Lonfat et al, 2004, MWR, 132, 1645-1660**

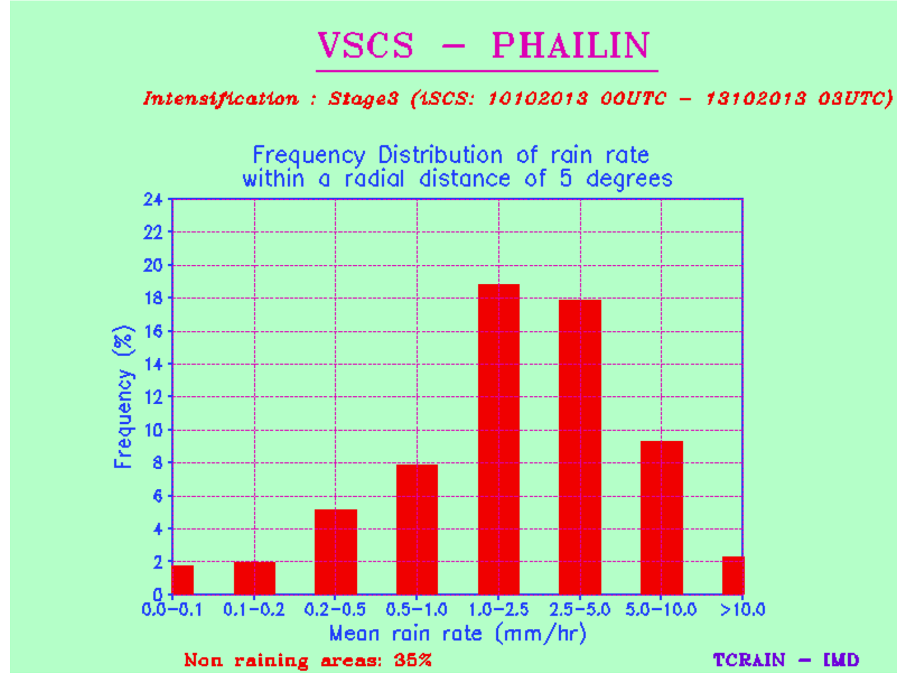


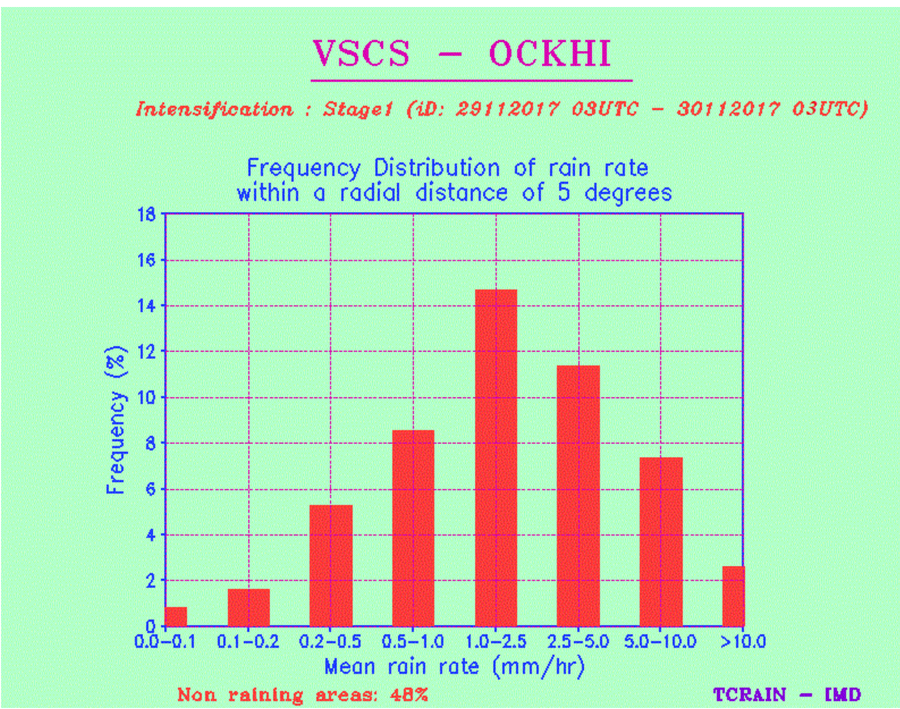



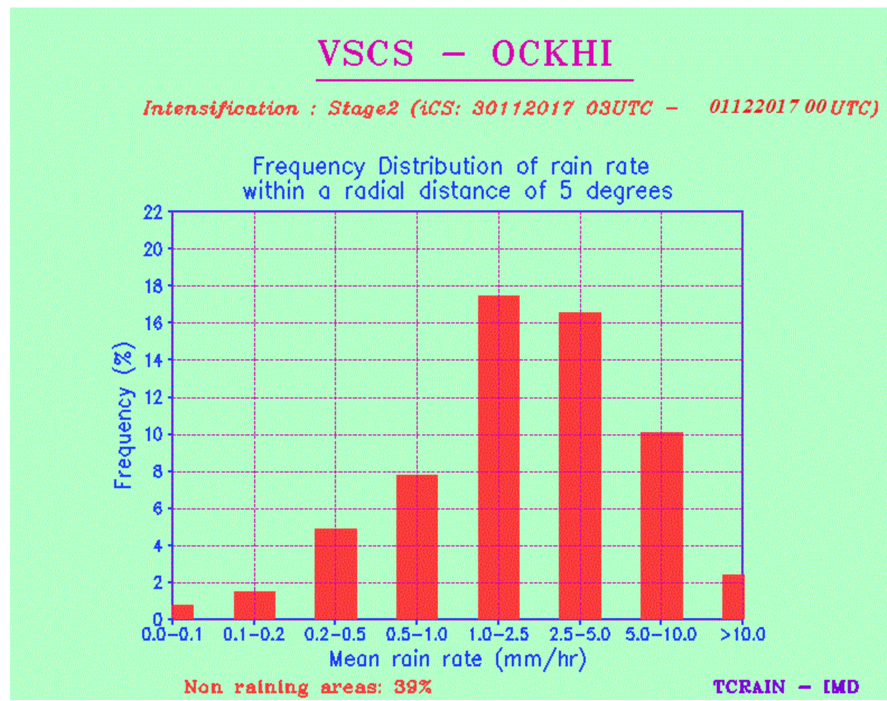


SUCS – GONU
Intensification : Stage3 (iSCS 03062007 00UTC – 07062007 00UTC)
Frequency Distribution of rain rate
within a radial distance of 5 degrees
Frequency (%)
Mean rain rate (mm/hr)
0.0–0.1 0.1–0.2 0.2–0.5 0.5–1.0 1.0–2.5 2.5–5.0 5.0–10.0 >10.0
Non raining areas: 68%
TCRAIN – IMD
ESCS – MEGH
Intensification : Stage3 (iSCS: 07112015 03UTC – 10112015 00UTC)
Frequency Distribution of rain rate
within a radial distance of 5 degrees
Frequency (%)
Mean rain rate (mm/hr)
0.0–0.1 0.1–0.2 0.2–0.5 0.5–1.0 1.0–2.5 2.5–5.0 5.0–10.0 >10.0
Non raining areas: 88%
TCRAIN – IMD
VSCS – GAJA
Intensification : Stage3 (iSCS: 15112018 03UTC – 16112018 03UTC)
Frequency Distribution of rain rate
within a radial distance of 5 degrees
Frequency (%)
Mean rain rate (mm/hr)
0.0–0.1 0.1–0.2 0.2–0.5 0.5–1.0 1.0–2.5 2.5–5.0 5.0–10.0 >10.0
Non raining areas: 78%
TCRAIN – IMD
ESCS – MAHA
Intensification : Stage3 (iSCS: 31102019 06UTC – 06112019 12UTC)
Frequency Distribution of rain rate
within a radial distance of 5 degrees
Frequency (%)
Mean rain rate (mm/hr)
0.0–0.1 0.1–0.2 0.2–0.5 0.5–1.0 1.0–2.5 2.5–5.0 5.0–10.0 >10.0
Non raining areas: 80%
TCRAIN – IMD


VSCS – PHAILIN
Intensification : Stage2 (iCS: 09102013 09UTC – 10102013 00UTC)
Frequency Distribution of rain rate
within a radial distance of 5 degrees
Frequency (%)
0.0–0.1 0.1–0.2 0.2–0.5 0.5–1.0 1.0–2.5 2.5–5.0 5.0–10.0 >10.0
Mean rain rate (mm/hr)
Non raining areas: 44%
TCRAIN – IMD


VSCS – PHAILIN
Intensification : Stage3 (iSCS: 10102013 00UTC – 13102013 03UTC)
Frequency Distribution of rain rate
within a radial distance of 5 degrees
Frequency (%)
0.0–0.1 0.1–0.2 0.2–0.5 0.5–1.0 1.0–2.5 2.5–5.0 5.0–10.0 >10.0
Mean rain rate (mm/hr)
Non raining areas: 35%
TCRAIN – IMD


VSCS – OCKHI
Intensification : Stage1 (iD: 29112017 03UTC – 30112017 03UTC)
Frequency Distribution of rain rate
within a radial distance of 5 degrees
Frequency (%)
0.0–0.1 0.1–0.2 0.2–0.5 0.5–1.0 1.0–2.5 2.5–5.0 5.0–10.0 >10.0
Mean rain rate (mm/hr)
Non raining areas: 48%
TCRAIN – IMD


VSCS – OCKHI
Intensification : Stage2 (iCS: 30112017 03UTC – 01122017 00 UTC)
Frequency Distribution of rain rate
within a radial distance of 5 degrees
Frequency (%)
0.0–0.1 0.1–0.2 0.2–0.5 0.5–1.0 1.0–2.5 2.5–5.0 5.0–10.0 >10.0
Mean rain rate (mm/hr)
Non raining areas: 39%
TCRAIN – IMD

# TC Rainrate distribution –NIO …

**Composite rainrate distribution based on 43 TCs of NIO during 2000-2010 using 3-hrly TRMM data;**

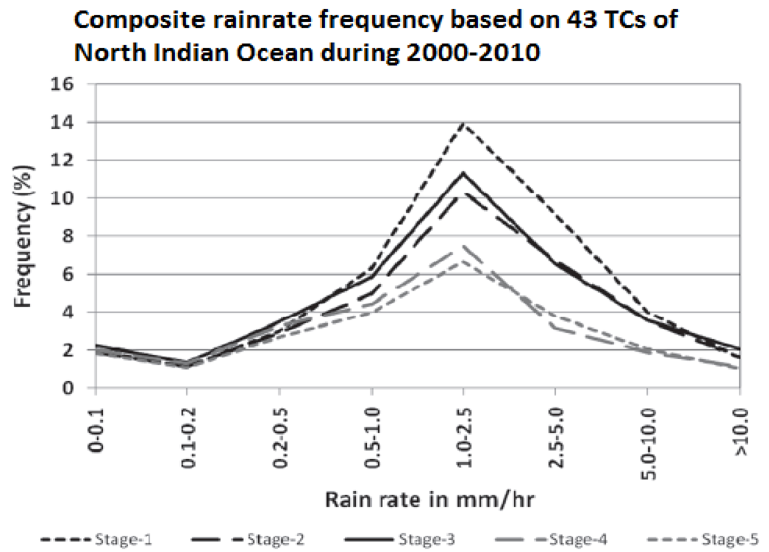



FIG. 5. Frequency distribution of rain rates around TCs of NIO upto 5° radial distance and for various intensity stages. (black shade: intensification stages; gray shade: weakening stages)

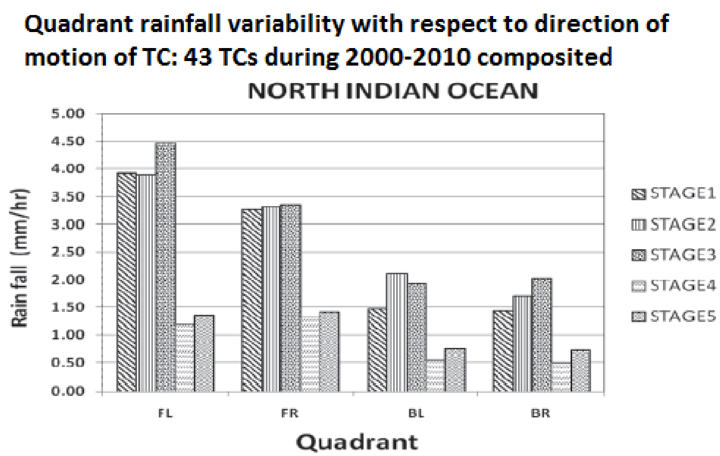



FIG. 6a. Quadrant mean rain rates during various stages of intensity of TCs of NIO. FL: front left, FR: front right, BL: back left and BR: back right quadrants

**Frequency distribution of rain rates within 5° radial distance from the TC centre**

**1-2.5 mm/hr is the most frequent rain rate for all intensity classes**

**Balachandran et al,** *Tropical cyclone Research & Review,* 2014, **3**, 2, 122-129)

**Quadrant mean rain rates within 2° radial distance from the TC centre**

**FL → Intensification stages**
**FR→ weakening stages**

# Azimuthal mean rain rates as a function of the radial distance

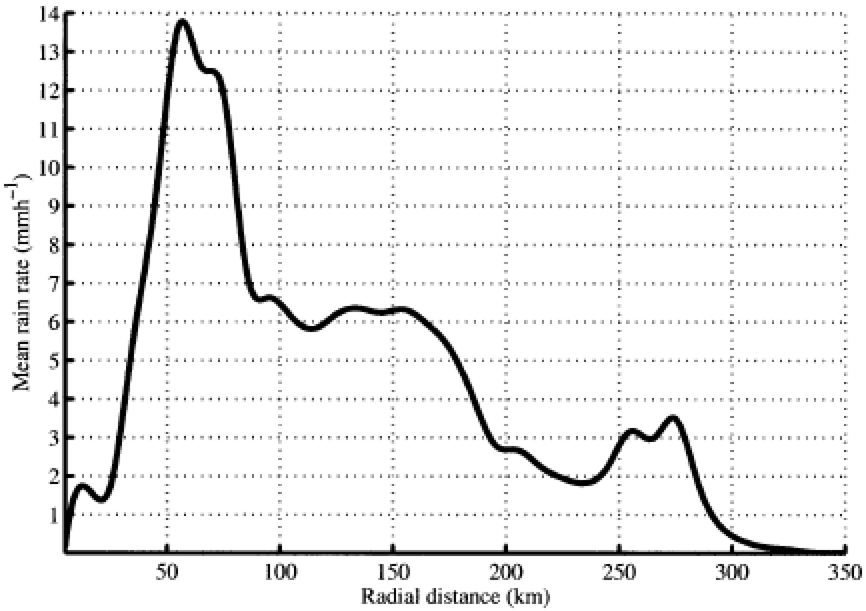



FIG. 5. Radial profile of azimuthally averaged rain rates for Dennis on 28 Aug 1999.

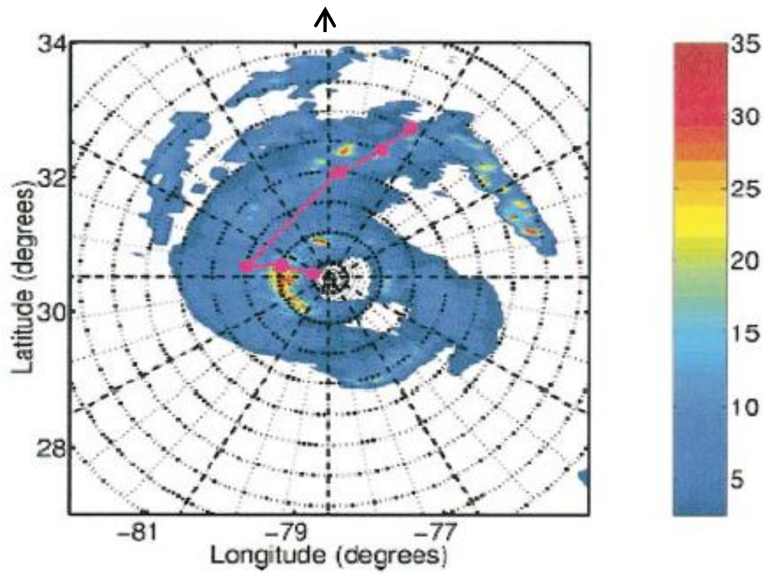
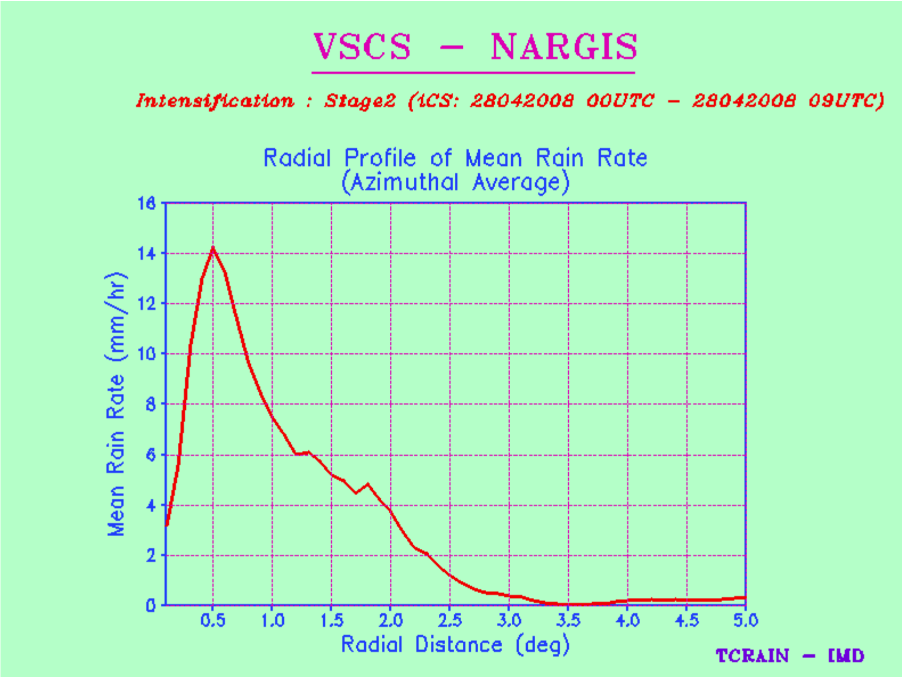
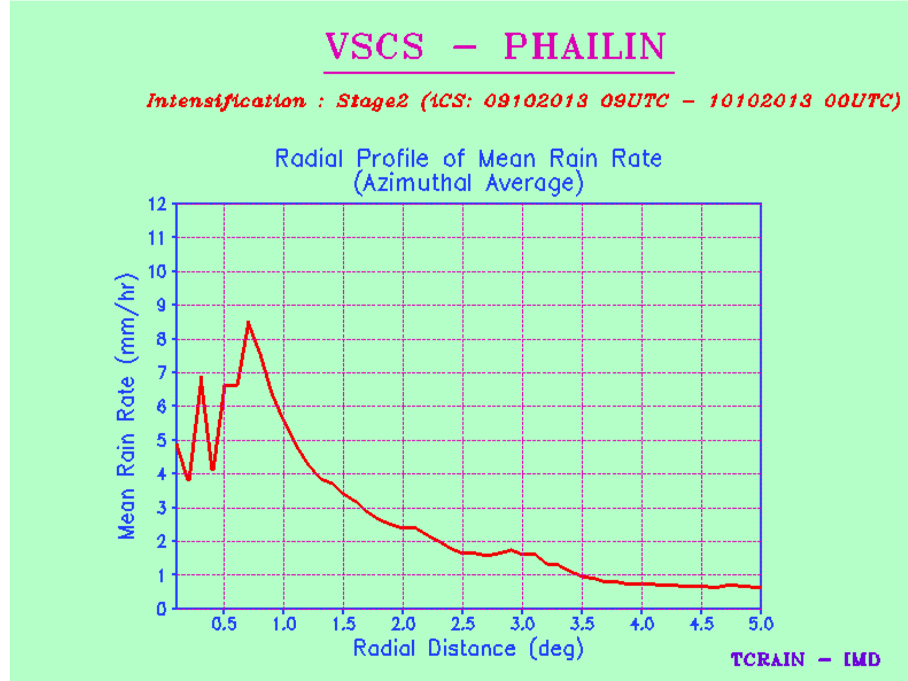


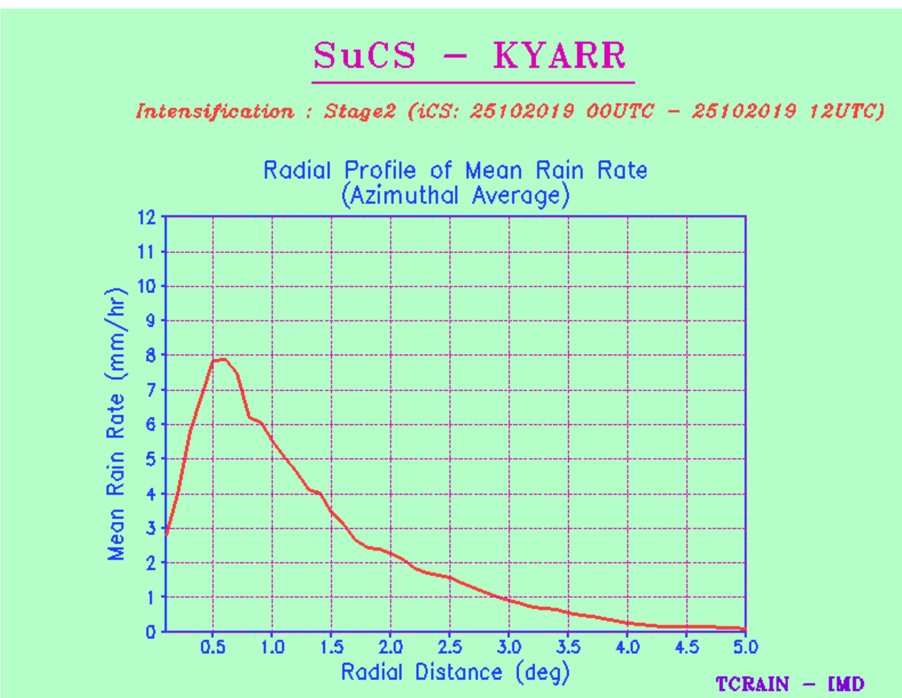

FIG. 4. TMI surface rainfall (in mm $h^{-1}$) of Hurricane Dennis, on 28 Aug 1999. The dots indicate the location of the phase max of the rainfall asymmetry as a function of the distance to the storm center. The circles (broken lines) are drawn at 50-km radial increments.

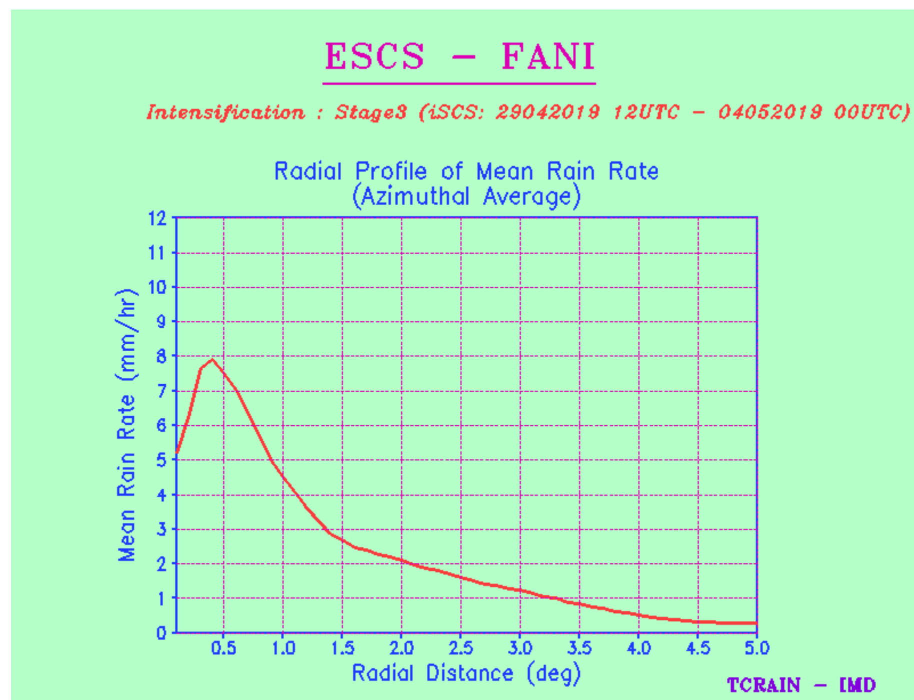
- ✓Peak rain → located 60 km from the center (about 13.5 mm/hr)
- ✓ Several secondary peaks at 150- and 275-km radii, corresponding to a broad zone of precipitation in the F-L quadrant of the storm, and a more intense but narrower region farther to the F-R quadrant of the storm.
- ✓The eyewall is well defined in the precipitation distribution, at 60 km from the center.
- ✓The eye is not totally clear of rain.

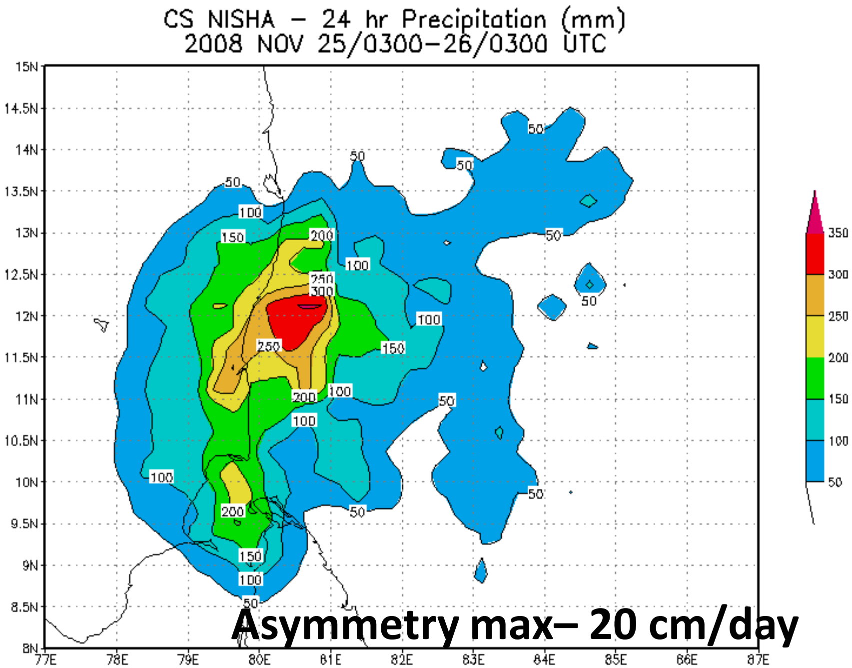
Lonfat et al, 2004, MWR, 132, 1645-1660


VSCS – NARGIS
Intensification : Stage2 (iCS: 28042008 00UTC – 28042008 09UTC)
Radial Profile of Mean Rain Rate
(Azimuthal Average)
Mean Rain Rate (mm/hr)
0
2
4
6
8
10
12
14
16
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Radial Distance (deg)
TCRAIN – IMD

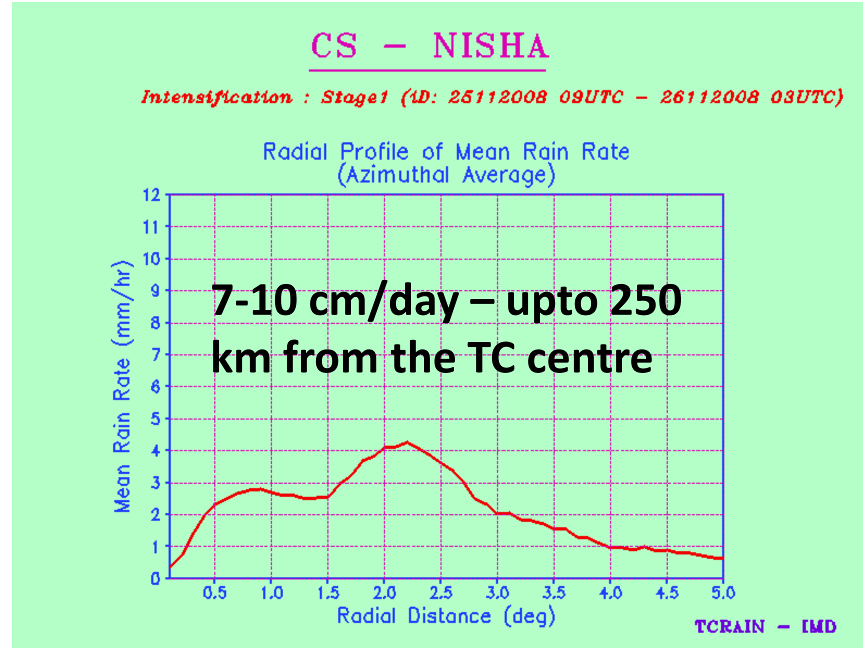

VSCS – PHAILIN
Intensification : Stage2 (iCS: 09102013 09UTC – 10102013 00UTC)
Radial Profile of Mean Rain Rate
(Azimuthal Average)
Mean Rain Rate (mm/hr)
0
1
2
3
4
5
6
7
8
9
10
11
12
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Radial Distance (deg)
TCRAIN – IMD


SuCS – KYARR
Intensification : Stage2 (iCS: 25102019 00UTC – 25102019 12UTC)
Radial Profile of Mean Rain Rate
(Azimuthal Average)
Mean Rain Rate (mm/hr)
0
1
2
3
4
5
6
7
8
9
10
11
12
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Radial Distance (deg)
TCRAIN – IMD

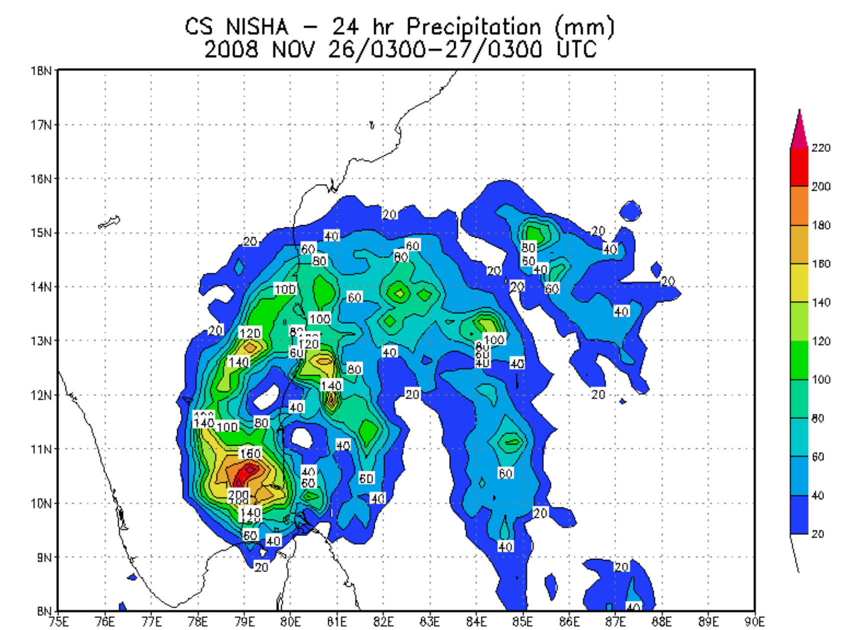

ESCS – FANI
Intensification : Stage3 (iSCS: 29042019 12UTC – 04052019 00UTC)
Radial Profile of Mean Rain Rate
(Azimuthal Average)
Mean Rain Rate (mm/hr)
0
1
2
3
4
5
6
7
8
9
10
11
12
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Radial Distance (deg)
TCRAIN – IMD

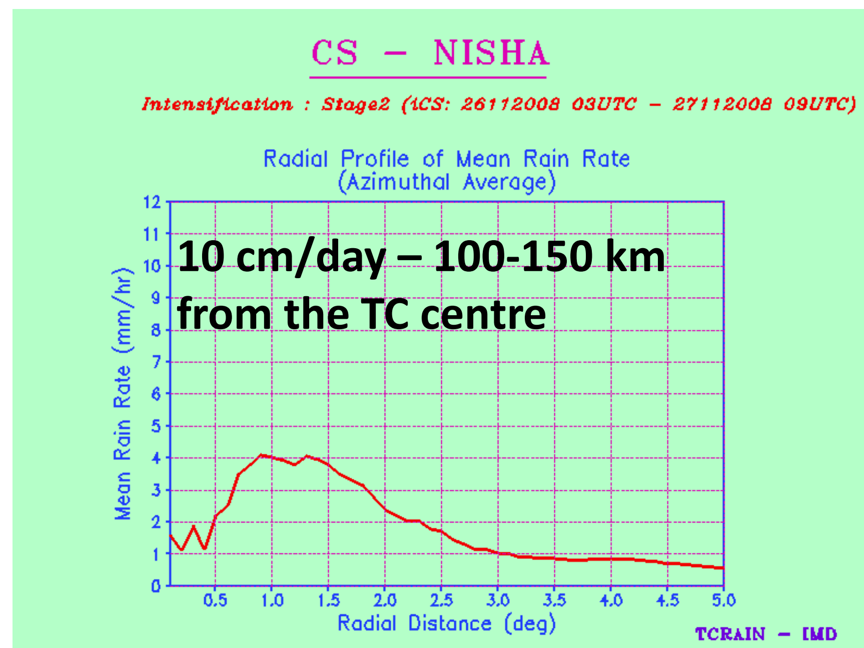



**Asymmetry max– 20 cm/day**




**7-10 cm/day – upto 250 km from the TC centre**




**10 cm/day – 100-150 km from the TC centre**

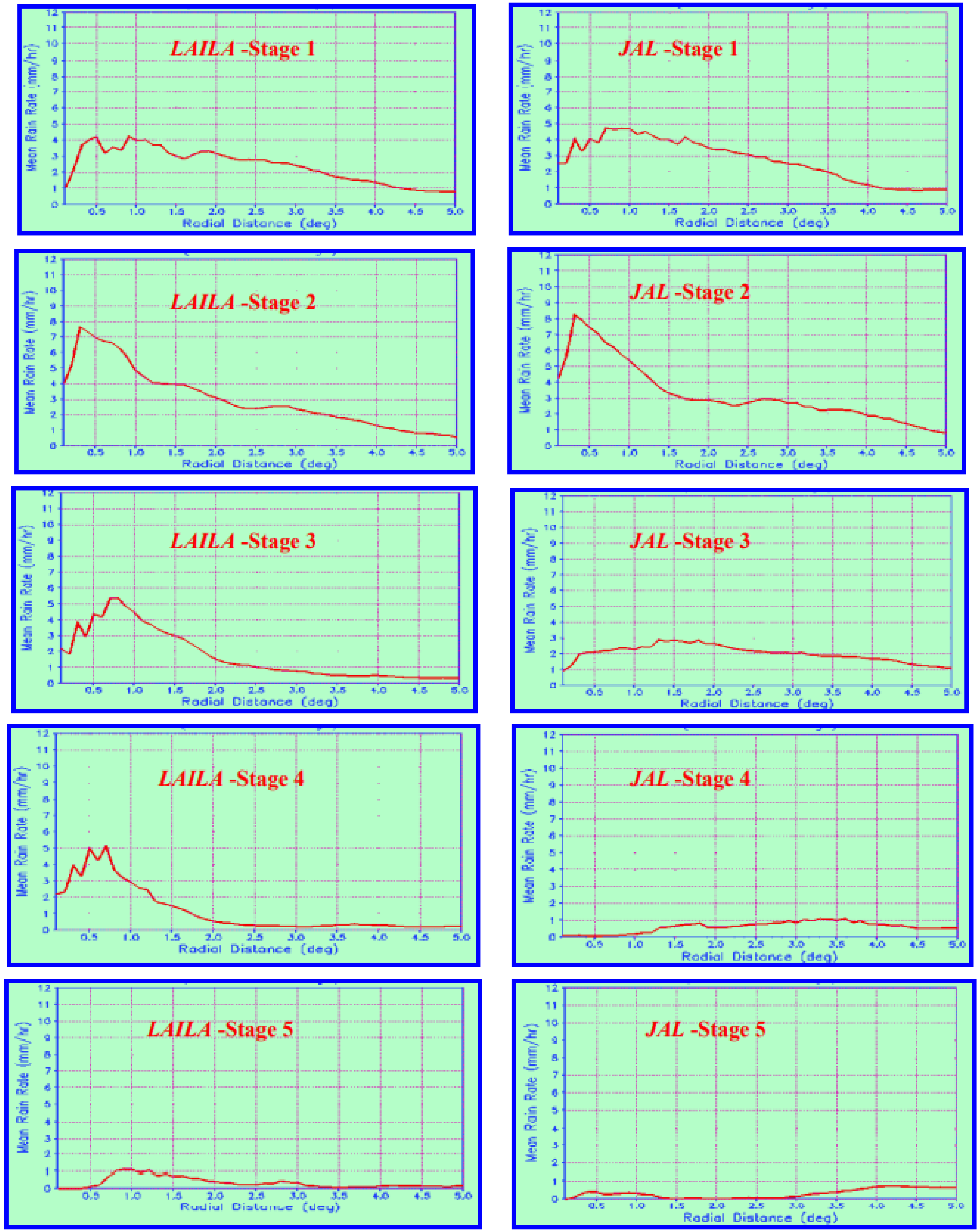
D

CS

SCS

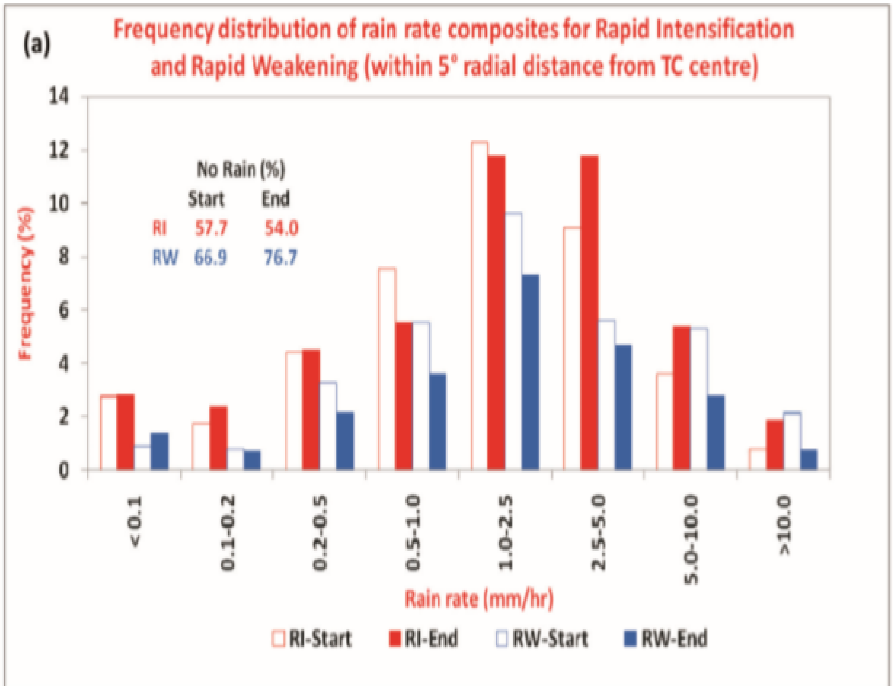
CS

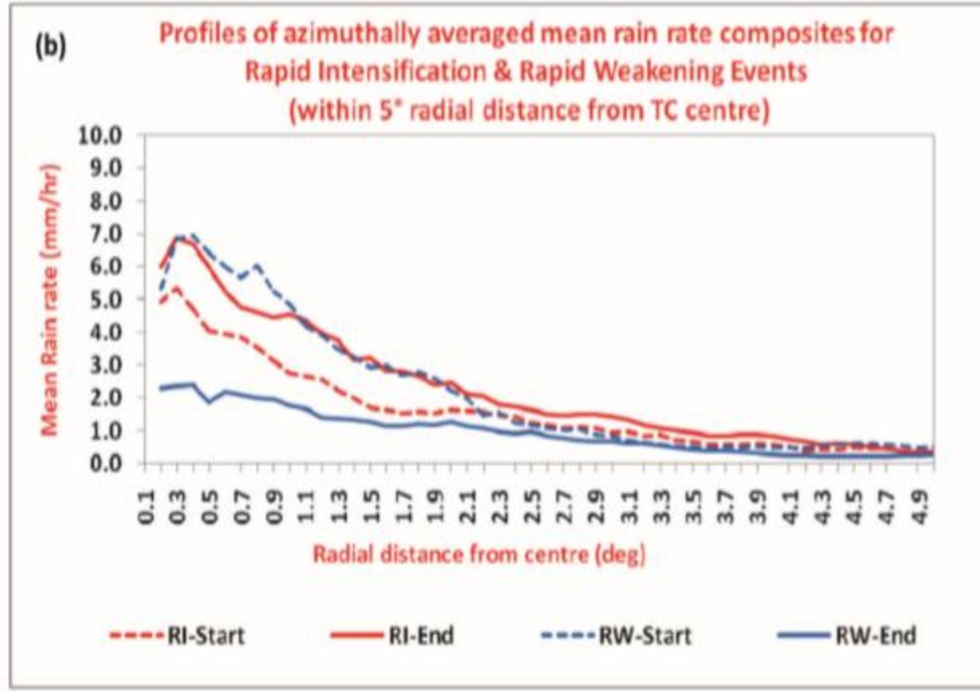
D



LAILA -Stage 1
JAL -Stage 1
LAILA -Stage 2
JAL -Stage 2
LAILA -Stage 3
JAL -Stage 3
LAILA -Stage 4
JAL -Stage 4
LAILA -Stage 5
JAL -Stage 5
Mean Rain Rate (mm/hr)
Radial Distance (deg)

# Variation in rainrates during RI & RW




Frequency distribution of rain rates within 5° radial distance from the TC centre

Radial profile of azimuthally averaged mean rain rates within 5° radial distance from the TC centre

✓RI→ Most frequent rainrate increases from 1-2.5 mm/hr to 2.5-5 mm/hr

✓RI → About 2 mm/hr increase in rainrate upto 200 km from the TC centre

✓RW→ About 2-5 mm/hr decrease in rainrate upto 150 km from the TC centre

**Geetha & Balachandran,** *Tropical cyclone Research & Review,* 2016, 5, 1-2, 32-46)

# Asymmetry analysis of TC precipitation

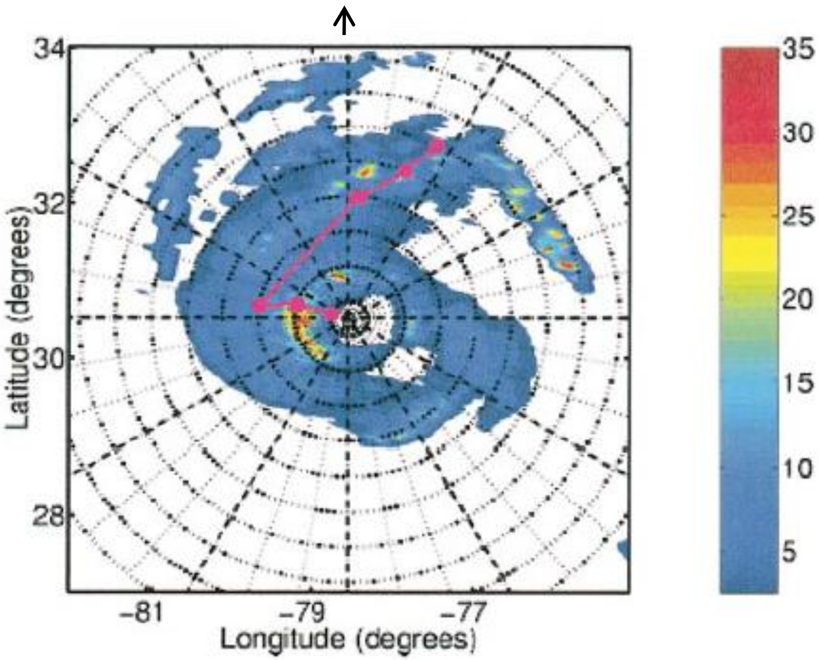



FIG. 4. TMI surface rainfall (in mm h⁻¹) of Hurricane Dennis, on 28 Aug 1999. The dots indicate the location of the phase max of the rainfall asymmetry as a function of the distance to the storm center. The circles (broken lines) are drawn at 50-km radial increments.

## Fourier first-order wave number -1 asymmetry

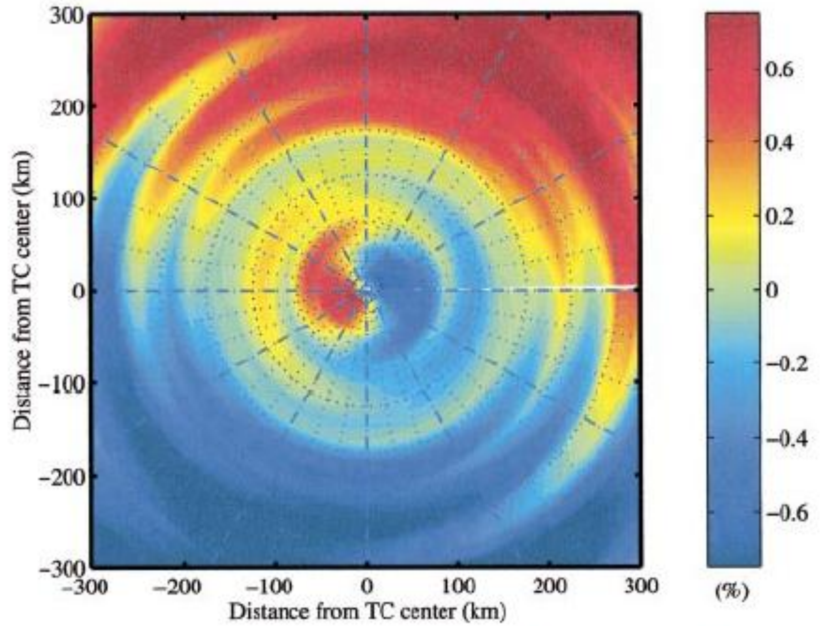



FIG. 9. Normalized phase maximum of the first-order rainfall asymmetry in Hurricane Dennis, as a function of the distance from the storm center. The first-order Fourier coefficients are calculated relative to the storm motion direction.

✓**Rain in the inner 150 km → mostly on the L and F-L of the storm center.**
✓**Outer region → rainfall mainly located in a strong rainband on the F and F-R of the storm center.**

**Lonfat et al, 2004, MWR, 132, 1645-1660**

# Convective structure - Asymmetry Analysis

## Fourier First Order Wave Number One Asymmetry

**[TRMM-3-hrly, 0.25 $^{0}$X0.25$^{0}$ rainfall dataset (3B42v6/7)]**

- ✓**Asymmetry is defined <u>relative to the storm motion</u>.**
- ✓**Direction of the storm motion → determined from the best track.**
- ✓**Mean *Rain rate computations* → <u>10-km-wide annuli</u> *around the* TC center are used to compute the spatial rainfall asymmetry.**
- ✓**In each annulus, the first-order Fourier coefficients (a,b) are computed using all rain estimates**

$$a_i = \sum_i \left[ R_i \cos \theta_i \right] \qquad b_i = \sum_i \left[ R_i \sin \theta_i \right]$$

**where *$R_i$ is each individual rain estimate* and *$\theta_i$ the phase* angle of the estimate relative to the storm motion.**

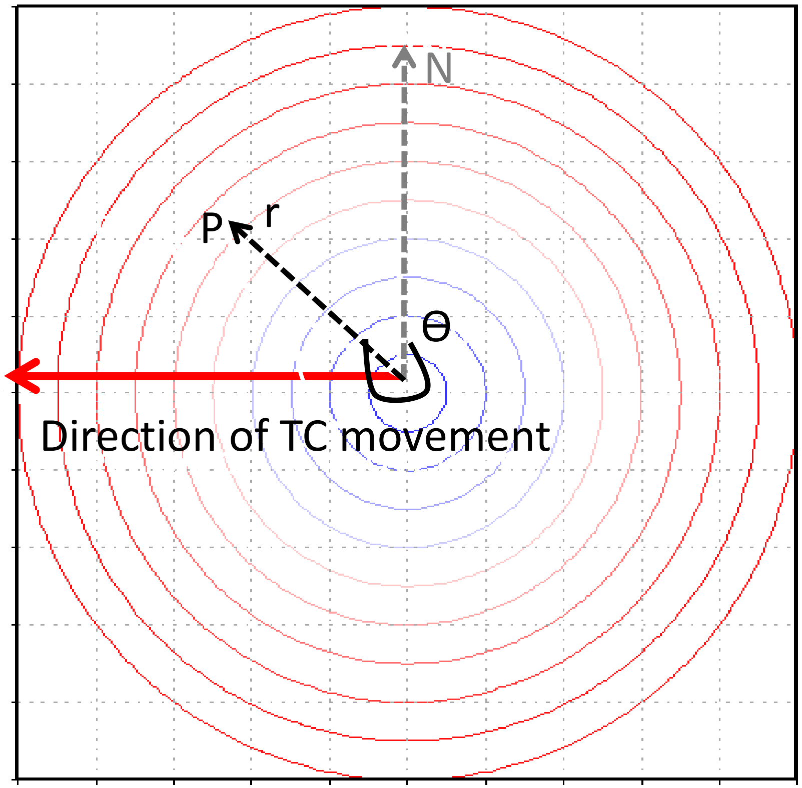
- ✓**The spatial structure of the first-order asymmetry (*$M_1$*) *can* be represented by**

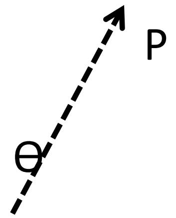
$$M_1 = \frac{\left| a_1 \cos \theta + b_1 \sin \theta \right|}{R}$$

**where *R is the mean rain rate calculated over the entire* annulus.**

- ✓**The first-order asymmetry is computed at 6-hrly intervals and analysed**

# Computations→ carried out in storm-relative Lagrangian Co-ord system (w.r.t TC centre)



## Asymmetry in TC rainfall distrubition in various oceanic basins:

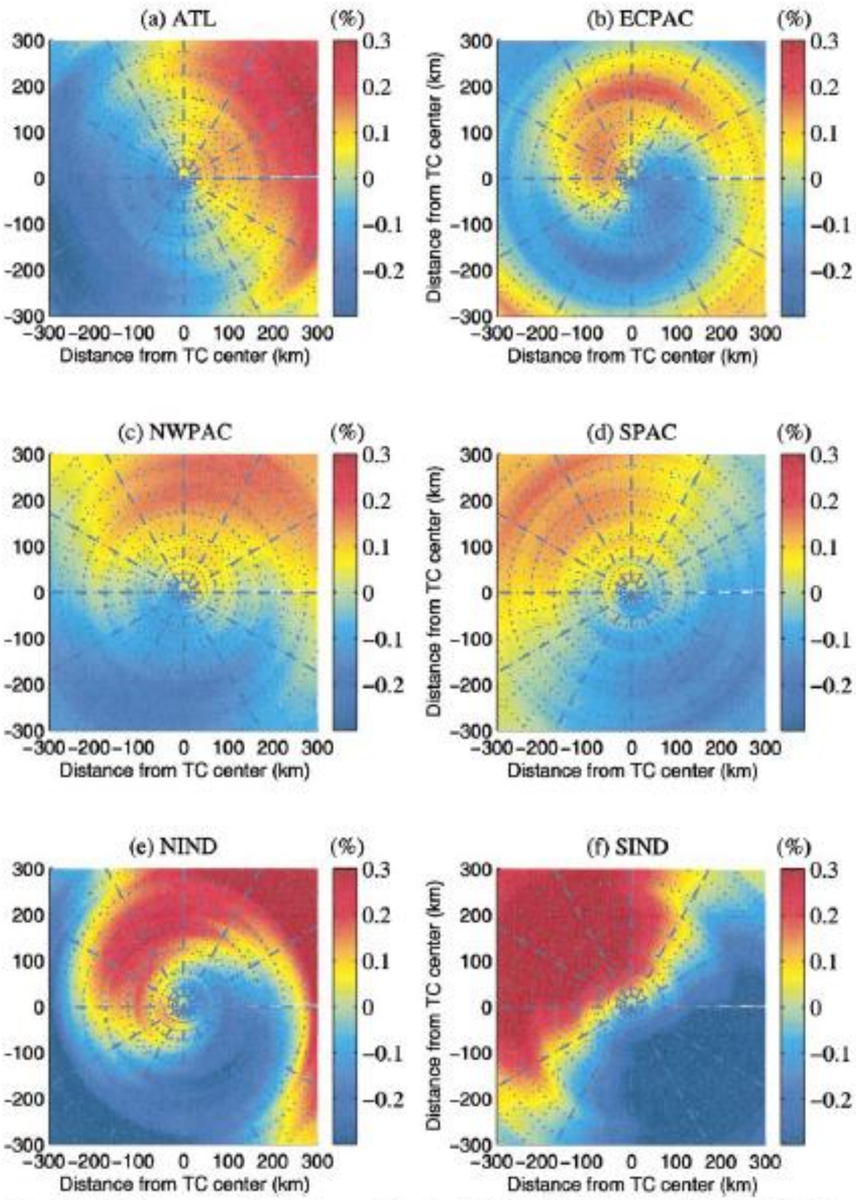



FIG. 18. Rainfall asymmetry for the six oceanic basins: (a) ATL, (b) ECPAC, (c) NWPAC, (d) SPAC, (e) NIND, and (f) SIND.

✓In all basins → *M1* max →front quad
✓Large differences--among different basins.
✓TCs in SH→ *M1 max in the F-L quad*
✓In NH→ *M1* peak in the F-R quad (ATL)

✓Asym amp increase outward from the center in all basins.
✓TCs in NWPAC and SPAC → smallest asym
✓Indian Ocean TCs have largest asym

✓Amp of rainfall asym → small in hurricanes (less than 15% of the ambient mean rain amount within the inner 300 km).

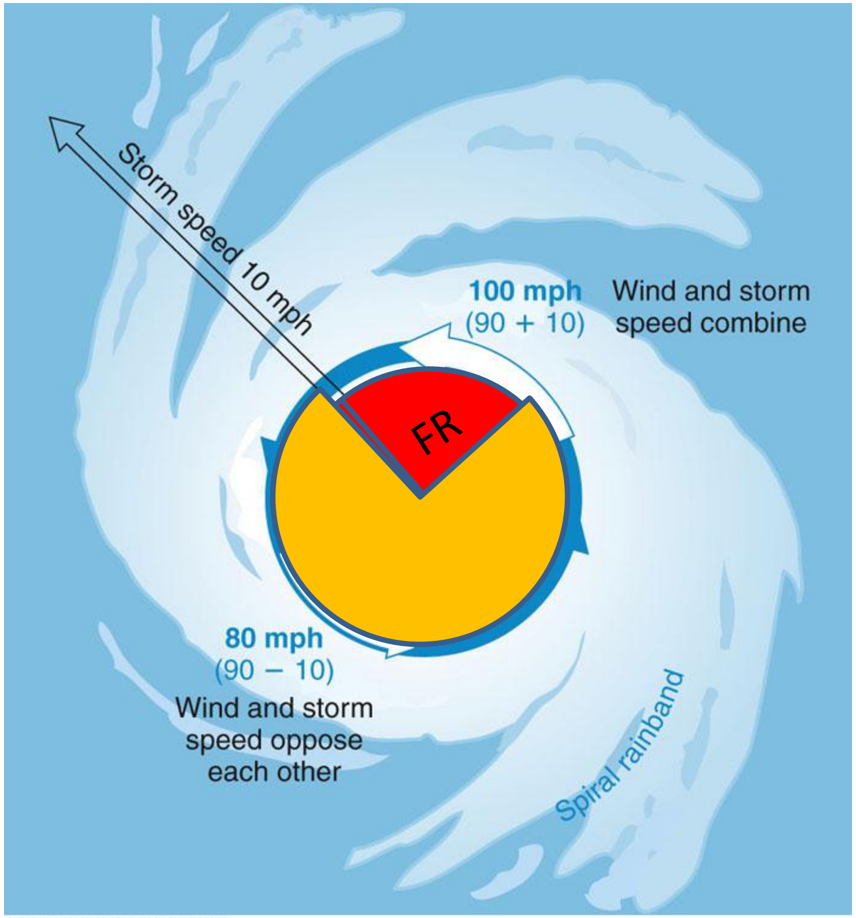
Distinct patterns of rf asym for diff ocean basins → indicate both friction induced low-level convergence and VWS must play a role

Lonfat et al, 2004, MWR, 132, 1645-1660

# Factors affecting TC rainfall asymmetry

- ✓TC motion
- ✓VWS
- ✓Friction-induced convergence in the boundary layer

# Asymmetry due to TC Motion





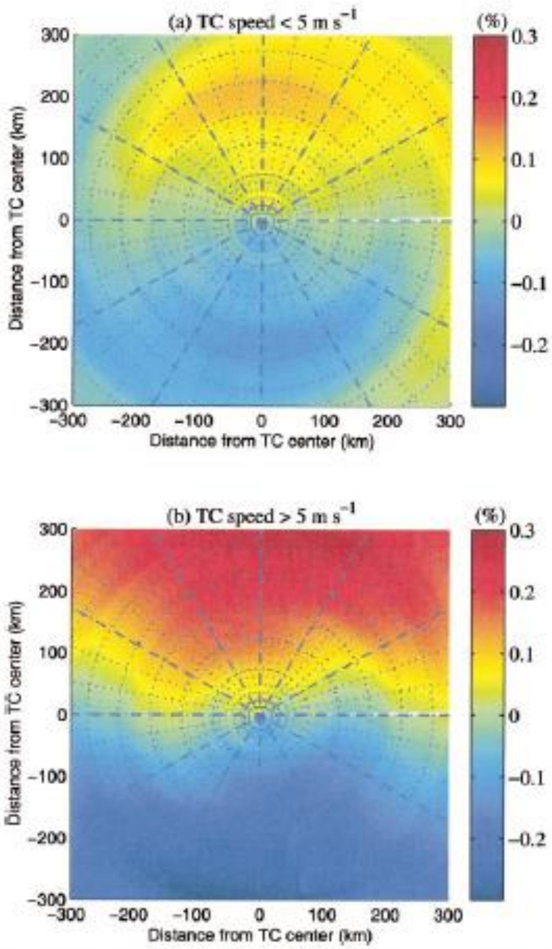
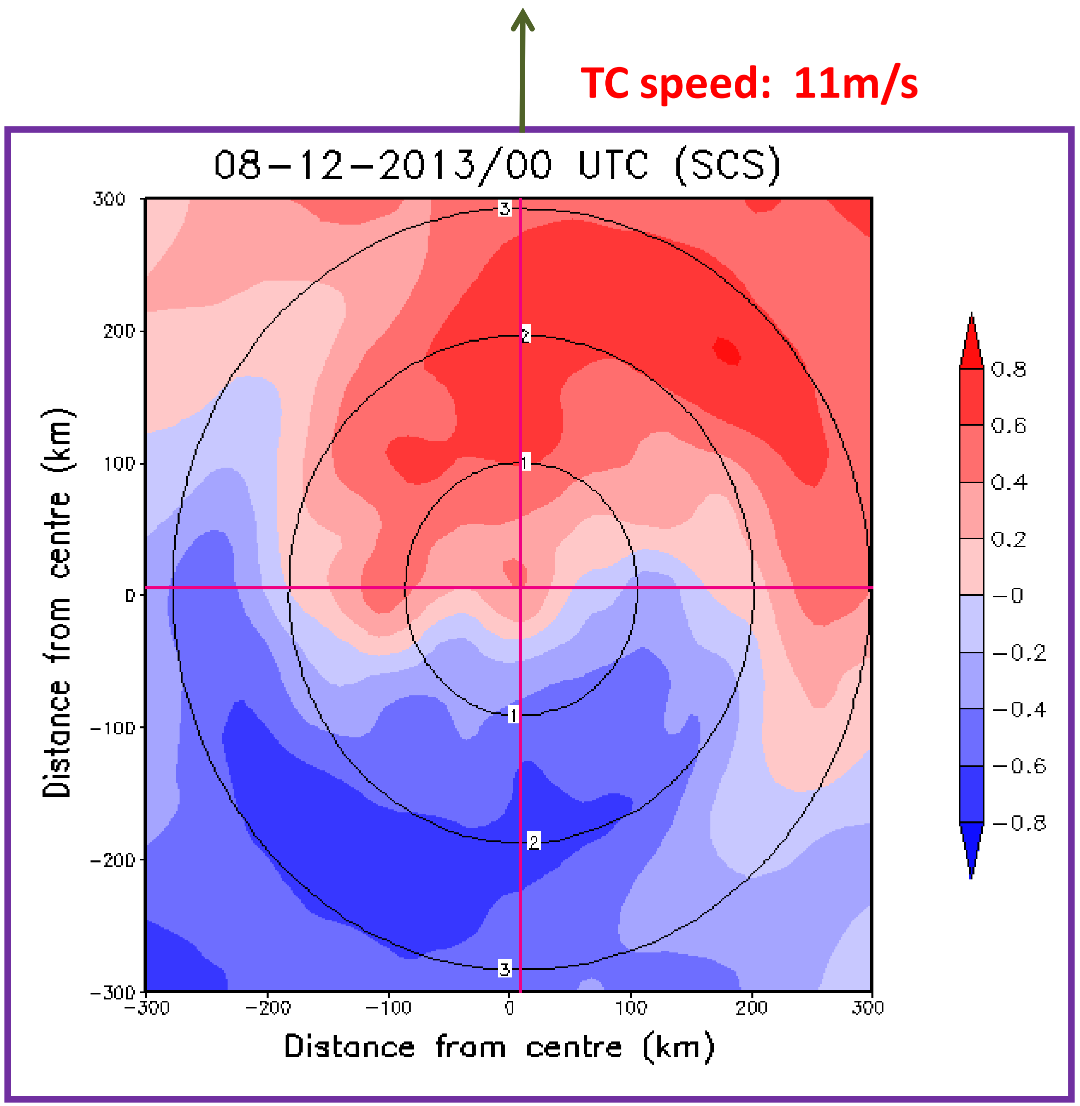




Fig. 19. Rainfall asymmetry as a function of the storm translation speed: (a) $v < 5$ m s$^{-1}$, and (b) $v > 5$ m s$^{-1}$.

- ✓**Under weak shear conditions, TC motion contributes to asymmetry.**
- ✓**R/F maxima is in FR quadrant**
- ✓**Asymmetry amplitude increases with TC speed**

# Asymmetry due to TC Motion –VSCS Madi (Dec 2013)



# Asymmetry pattern during TC intensification – VSCS Madi (Dec 2013)

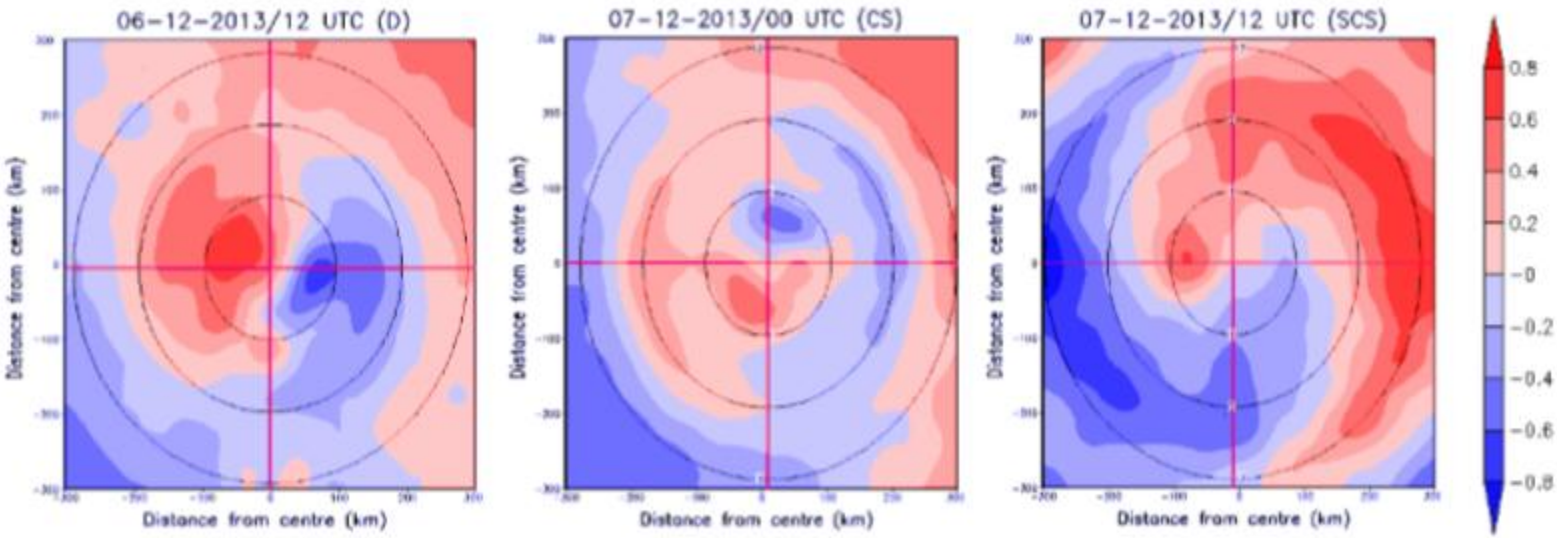



**Fig.7 Asymmetry in radial rainfall distribution during the intensification phase of VSCS *MADI* (06th/12 UTC, 7th/00 UTC and 7th/12 UTC).** Intensity at the respective times are indicated in brackets

✓**Cyclonic shift of wave number-1 asymmetry maximum during intensification phase D→ CS→ SCS**

✓**Magnitude of asymmetry max decreases in the inner core during intensification → lead to axi-symmetrisation of the vortex**

# VWS & TC rainfall asymmetry

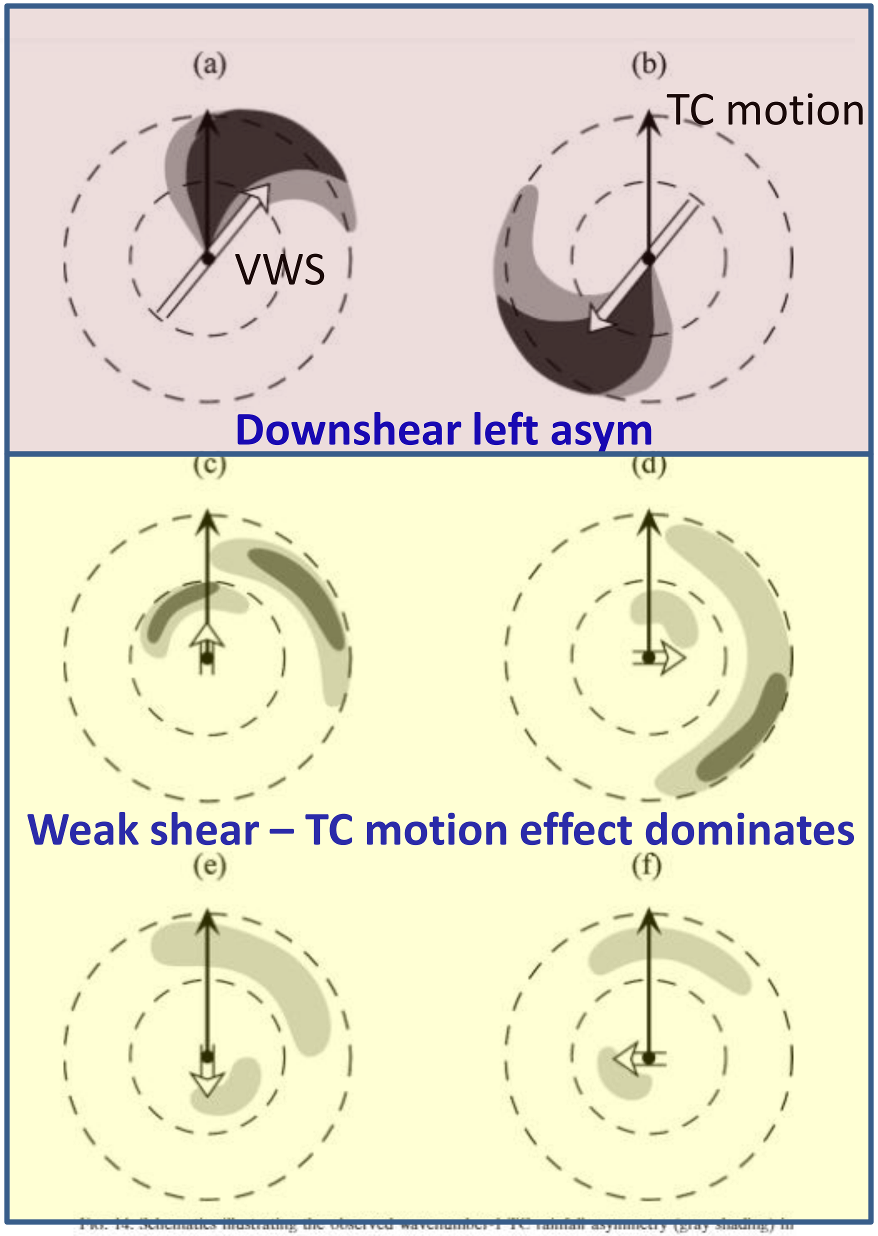
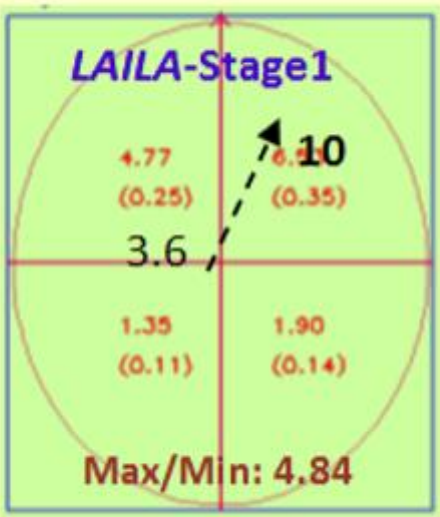
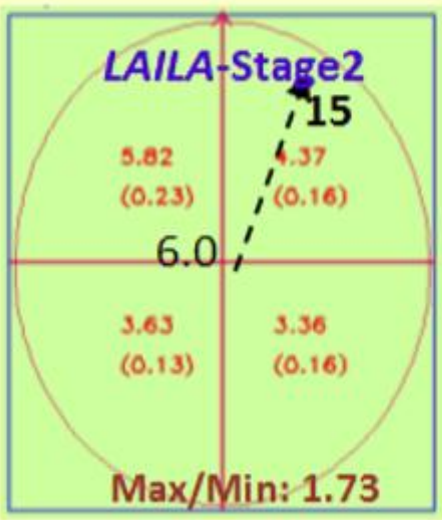


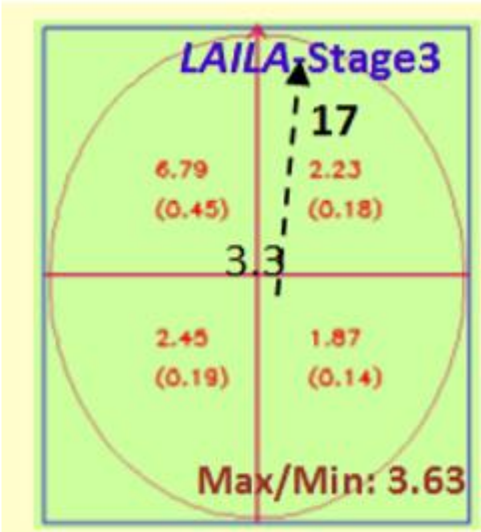

FIG. 14. Schematics illustrating the observed wavenumber-1 TC rainfall asymmetry (gray shading) in relation to the environmental vertical wind shear (wide white arrow) and TC motion (narrow black arrow) for the Northern Hemisphere. The length of the white arrow indicates the magnitude of shear. (a), (b) The strong shear environment (>7.5 m $s^{-1}$), where the shear is a dominant factor in determining the rainfall asymmetries. (c)–(f) The relatively weak shear environment, where the TC motion becomes more important in determining the rainfall asymmetries.

S.S.Chen, J.A.Knaff & F.D.Marks, MWR, 2006

# Asymmetry due to VWS –SCS Laila (May 2010)



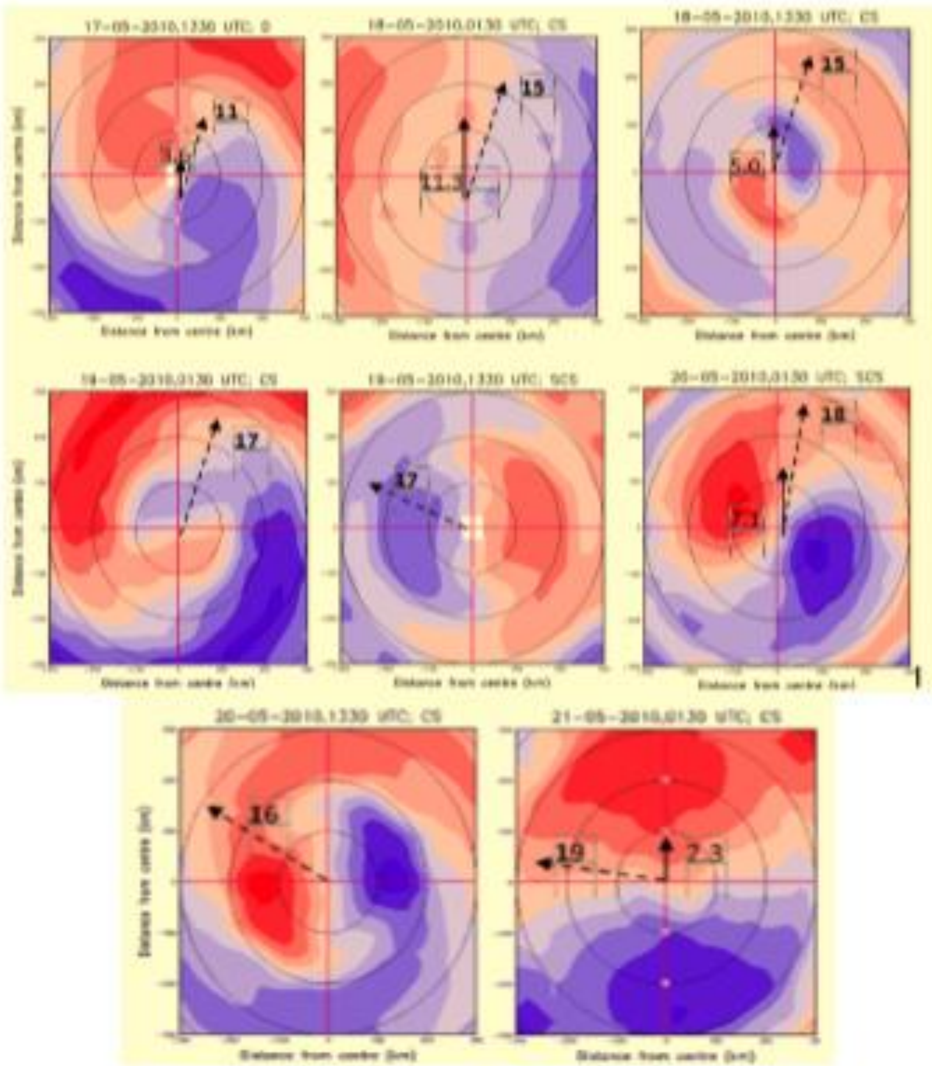
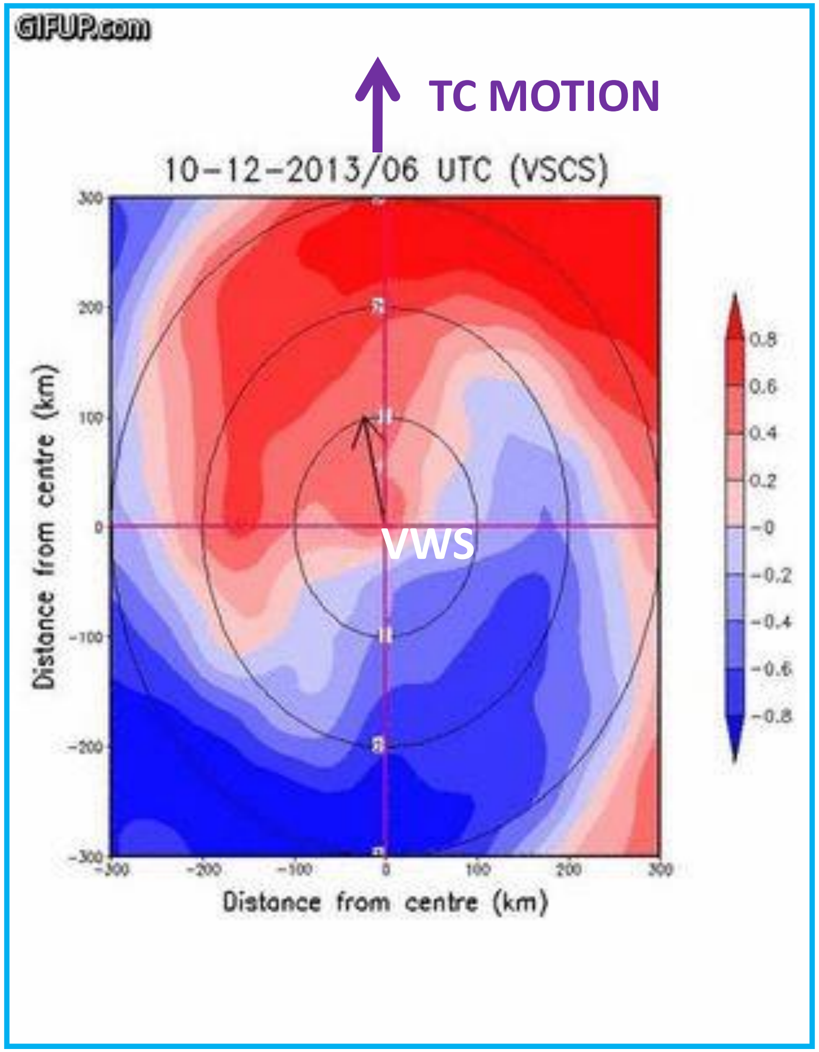




Fig. 6(a). Wave number–1 rainfall asymmetry normalised by the azimuthal mean (wave number - 0) in the case of SCS LAILA at 12 hourly intervals from 17/1330 UTC to 21/0130 UTC, May 2010. TC motion is aligned with positive Y-direction (shown by arrow head at the top). TC translational speed (m/s) is indicated in bold figure near the centre. (TC movement is not indicated for the instances when the TC remained stationary). Dotted arrows indicate the direction of storm relative vertical wind shear and bold figures beside the arrow head correspond to magnitude of the wind shear

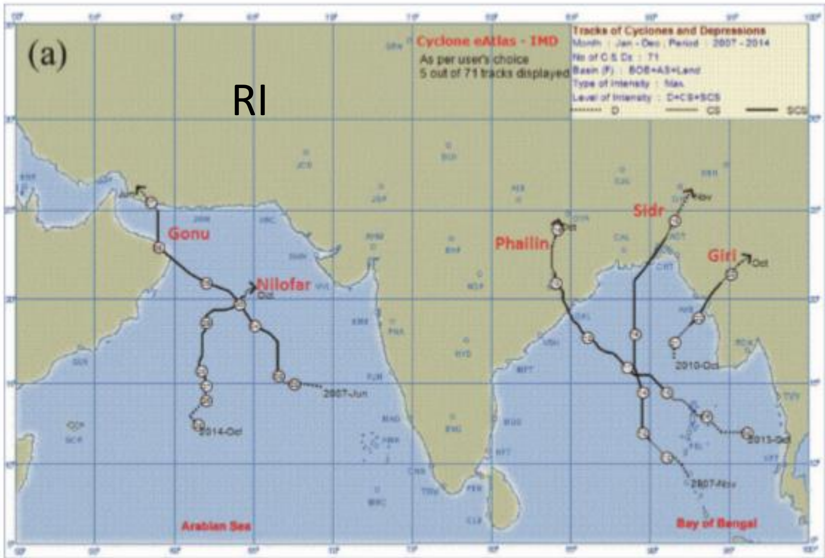
- ✓ **Generally, downshear Left asym**

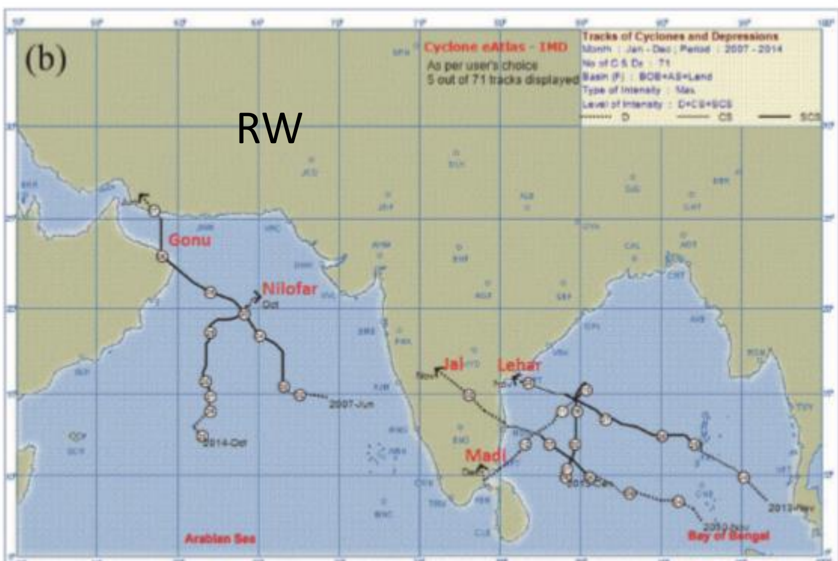
# Asymmetry w.r.t TC movement and VWS during recurvature




- During Recurvature, there was change in orientation between shear and TC motion vectors And the R/F maximum was noted in down shear – left quadrant

# Convective asymmetries during RI & RW



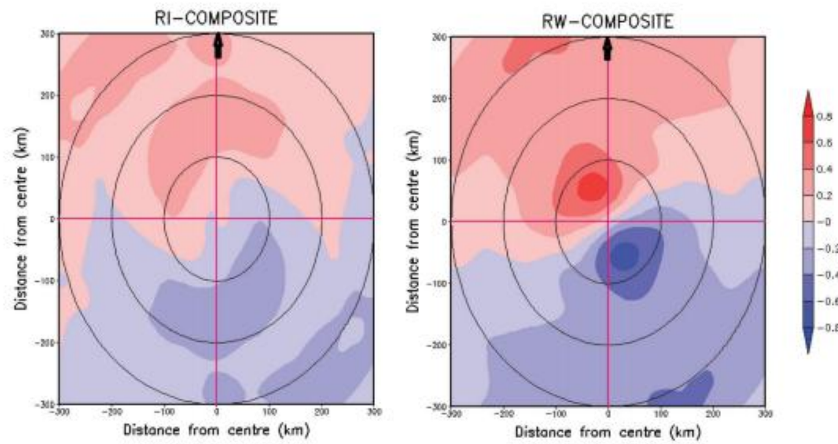




Fig. 6c. Fourier first order wave number -1 asymmetry composites for RI and RW events. The asymmetry amplitude values are the fraction of wavenumber 1 to wavenumber 0 (azimuthal average) asymmetry, i.e., a value of 0.2 indicates that the wavenumber-1 asymmetry is 20% of the azimuthal mean value. Arrow head indicates the direction of TC movement.

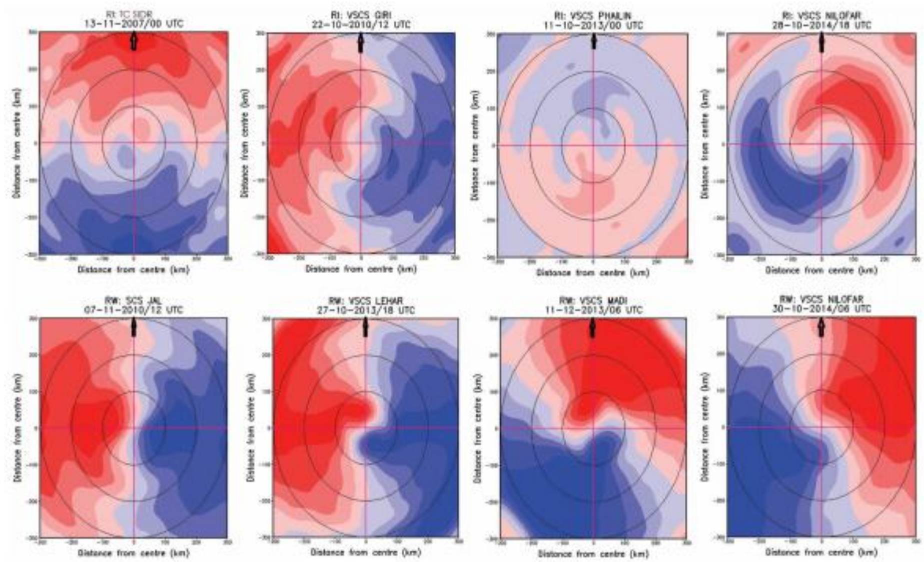
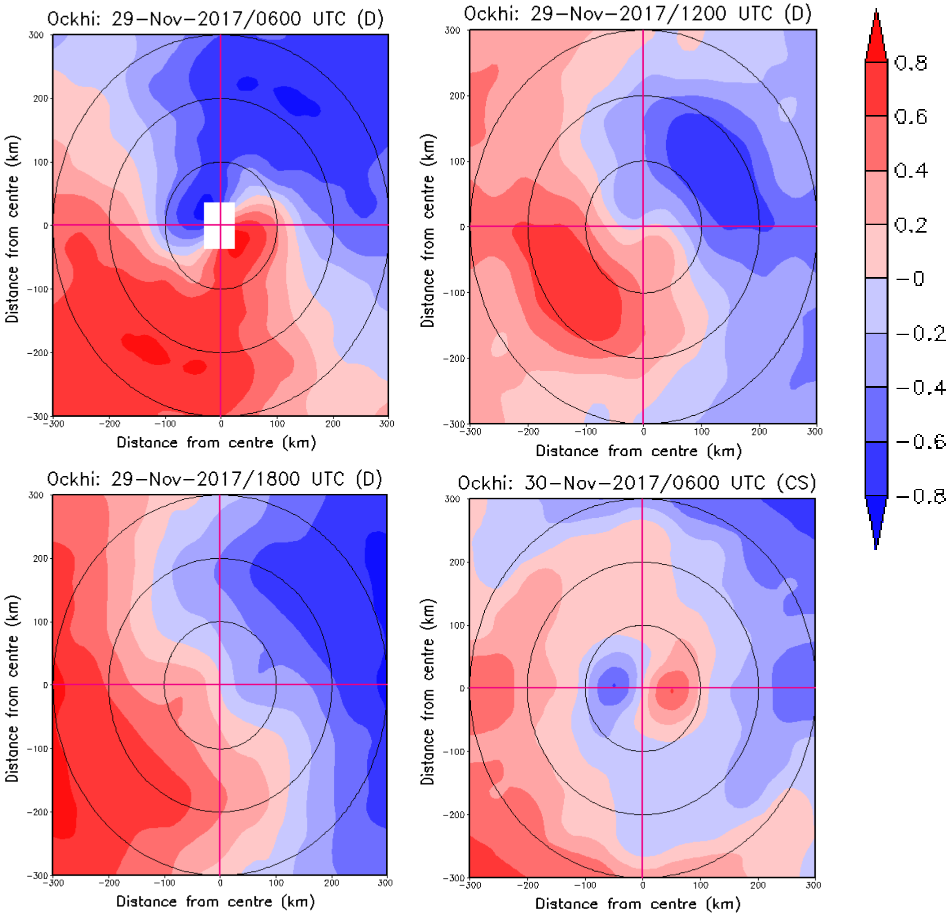
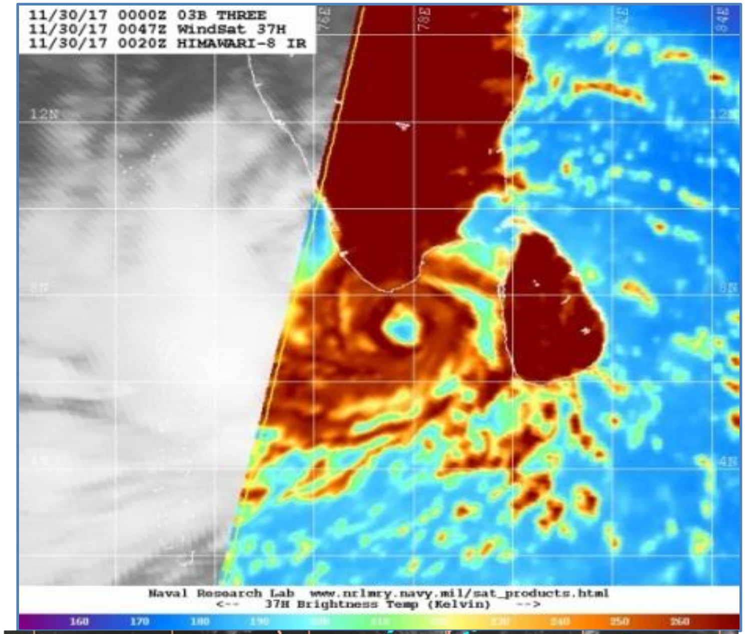


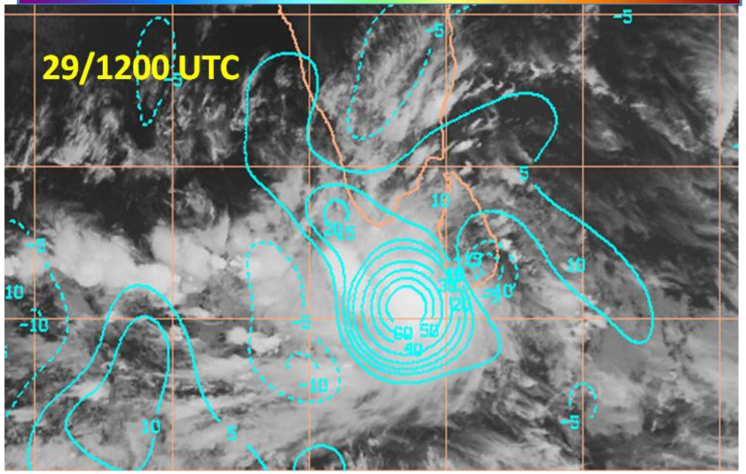

Fig. 6d. Fourier first order wave number -1 asymmetry in the case of individual RI and RW instances. Arrow head indicates the direction of TC movement.

Geetha & Balachandran, TCRR, 2016,32-46.

# TC Ockhi (29 Nov-04 Dec 2017)
# Axi-symmetrisation during development phase
# ( 29/0300 – 30/0300 UTC)




- ✓Asymmetry max in the inner core→ pushed outward
- ✓Asymmetry mixing in the inner core
- ✓Axi-symmetrisation of the inner core

**Geetha & Balachandran, JASR, 2020**

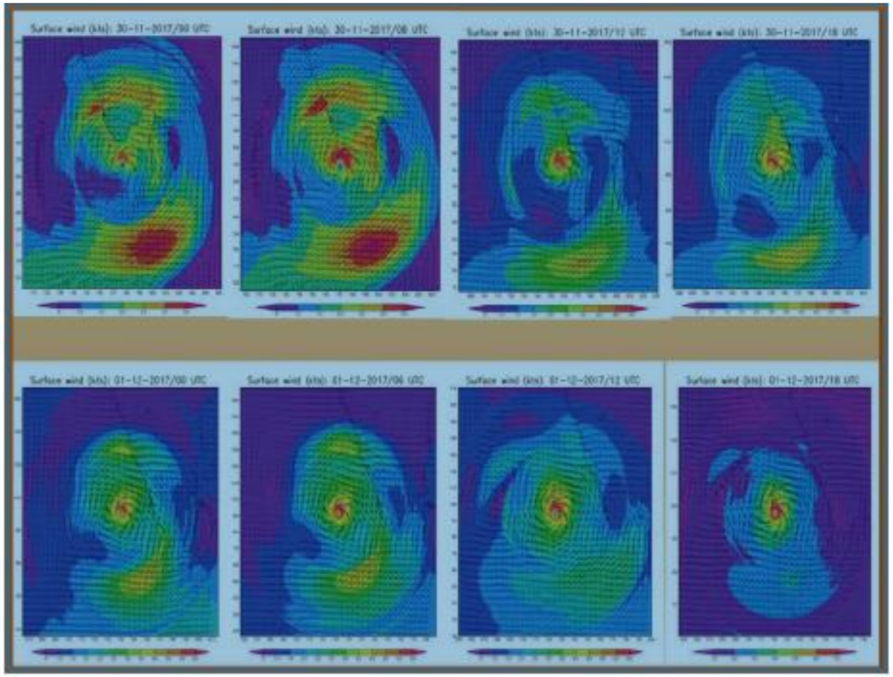


**Figure 4d.** Plots of satellite based NOAA-NESDIS-MTCSWA wind around the TC OCKHI at 6-hrly intervals on 30 Nov and 01 Dec 2017

**Geetha & Balachandran, JASR, 2020**

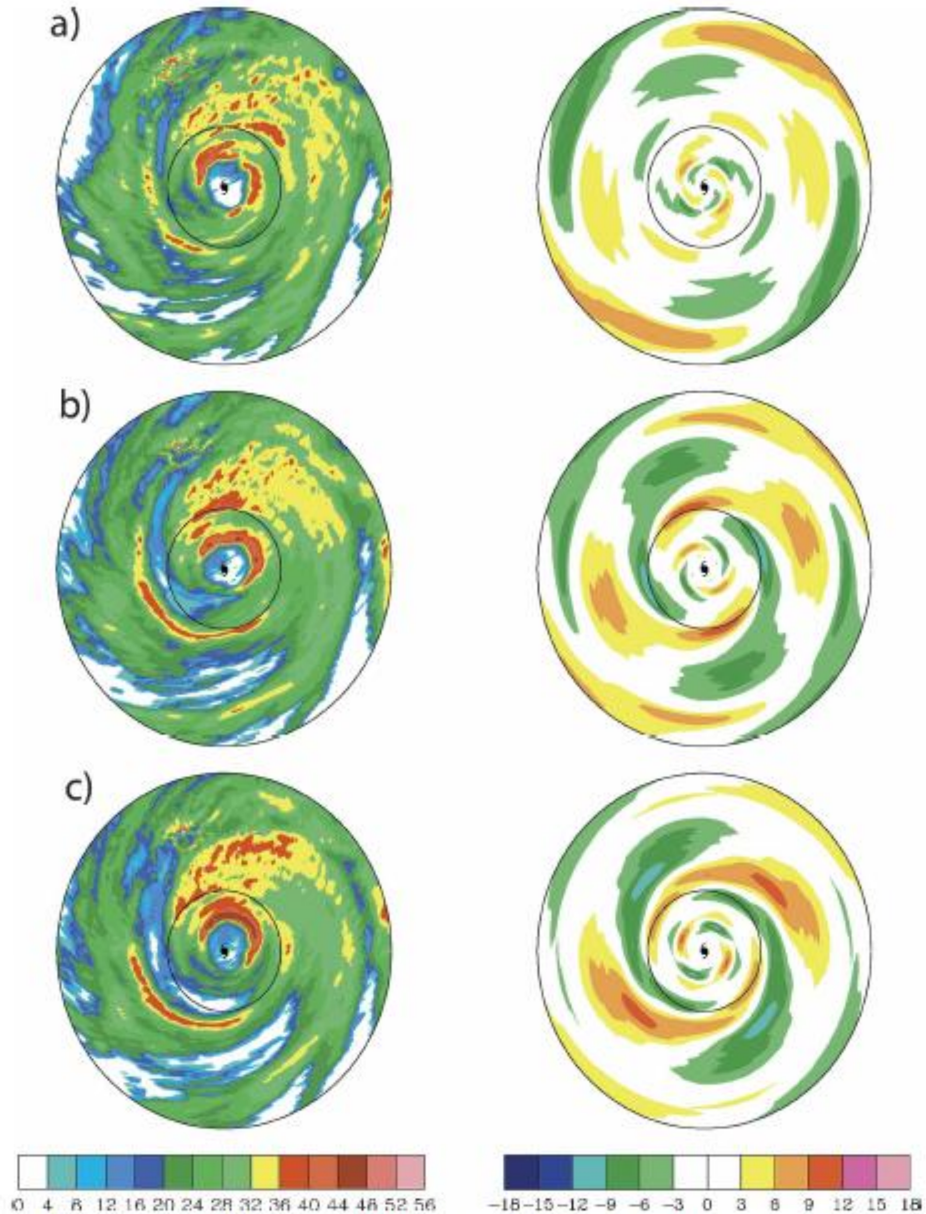



FIG. 7. Apalachicola (left) radar reflectivity and (right) wavenumber 2 asymmetry of Elena at (a) 1600, (b) 1620, (c) 1640, (d) 1700, (e) 1720, and (f) 1740 UTC 1 Sep. The inner and outer circles are the 50- and 150-km radii, respectively.

Previous numerical modeling and observational studies have shown that VRWs could be the result of the expulsion of high vorticity from the eyewall during asymmetric mixing and vorticity rearrangement in the vortex due to barotropic instability (Schubert et al. 1999; Kossin et al. 2000). As detailed above, the evolu-

**Corboseiro et al, MWR (2006)**

# Diurnal rainfall variation in TCs

# Diurnal rainfall variation in TCs

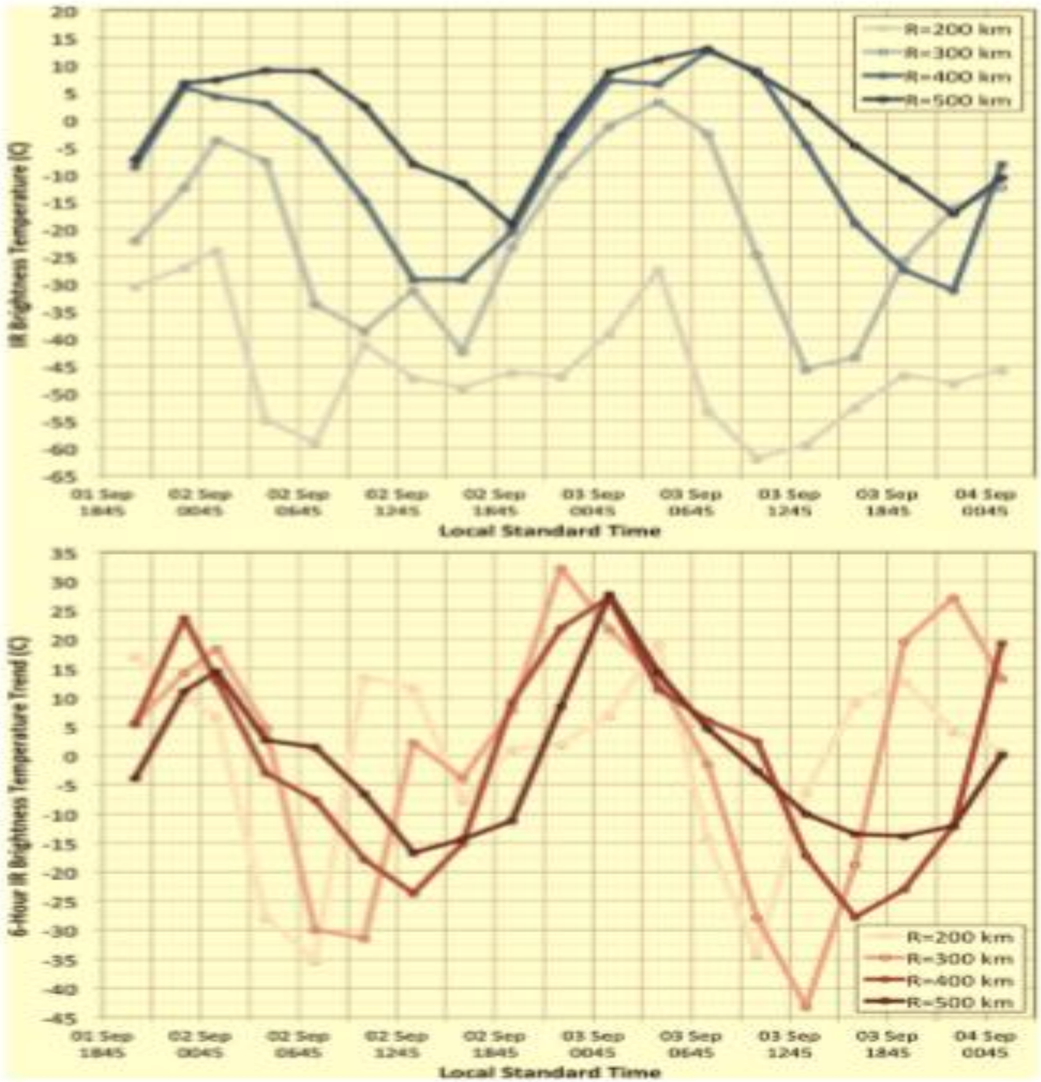
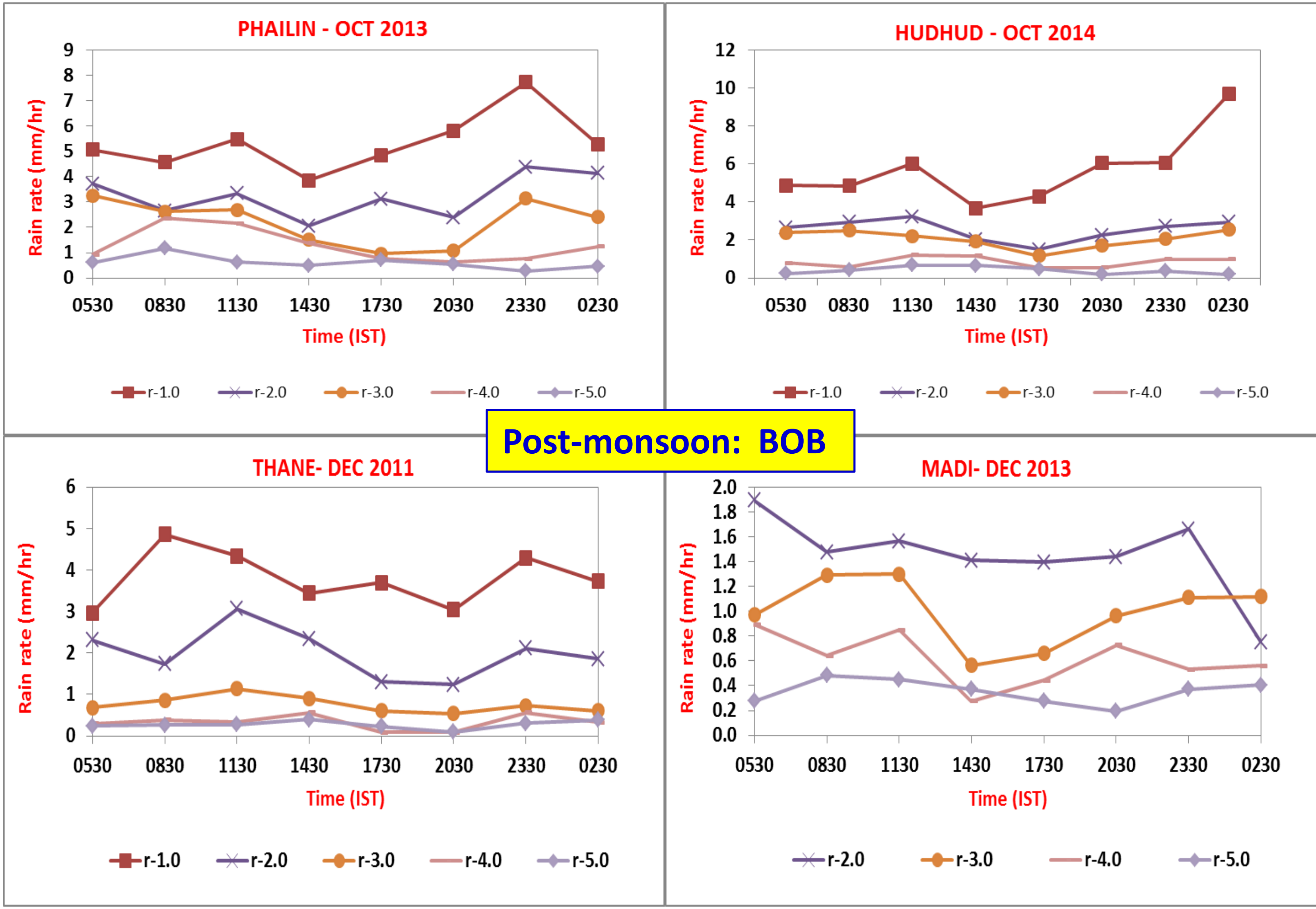



FIG. 3. Azimuthally averaged 3-hourly GOES (top) IR brightness temperatures and (bottom) 6-h brightness temperature trends at 200-, 300-, 400-, and 500-km radii around 2007 Hurricane Felix from 2045 LST 1 Sep to 0145 LST 4 Sep.

- ✓Diurnal pulse propagation from the inner core to the outer radii
- ✓Symmetry in propagation→ propagation of gravity wave feature

Dunion et al, 2014, MWR, 142, 3900-3919

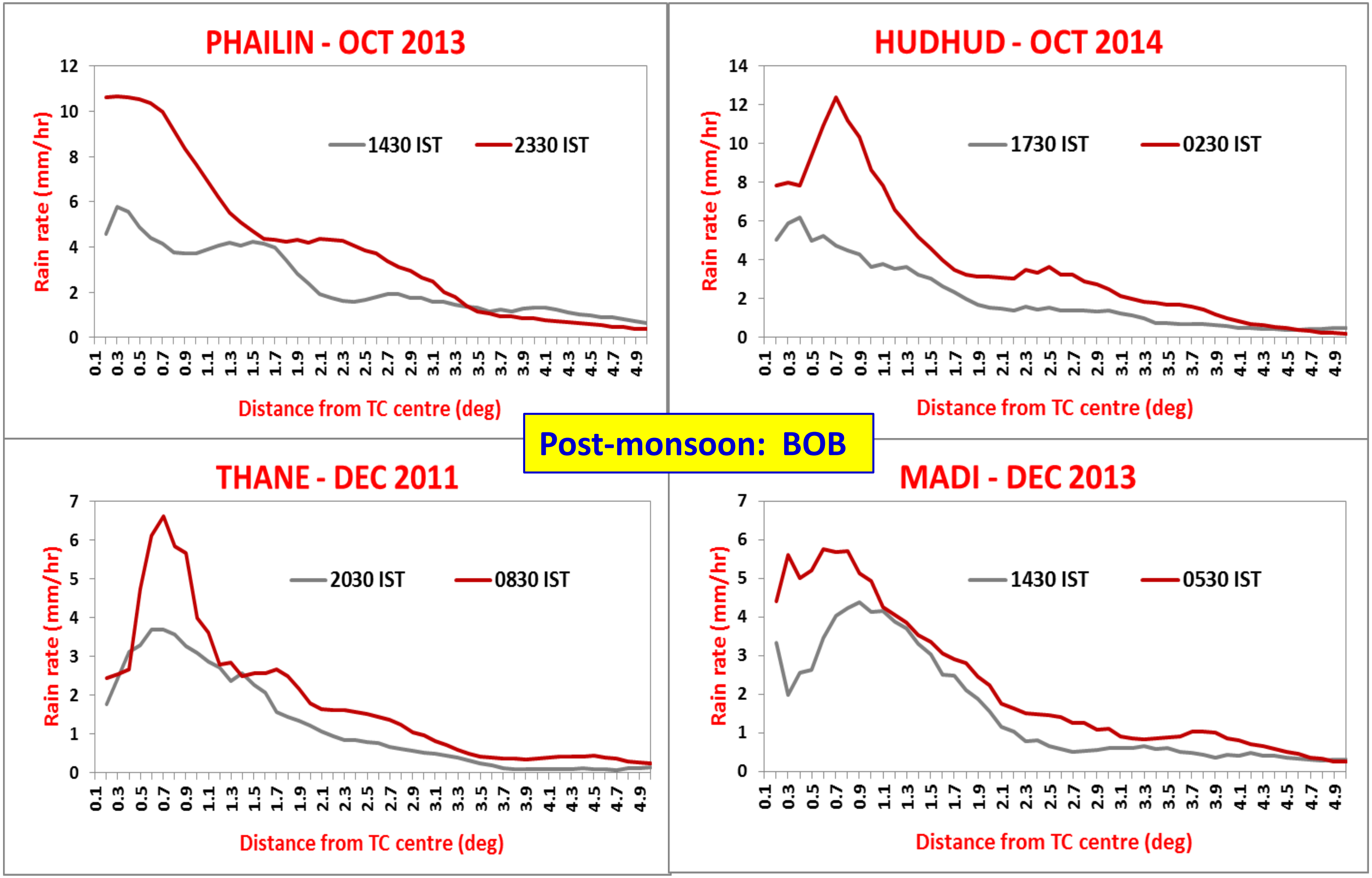



✓2 peaks – 1 late night peak (2330 – 0230 IST) due to TC diurnal cycle

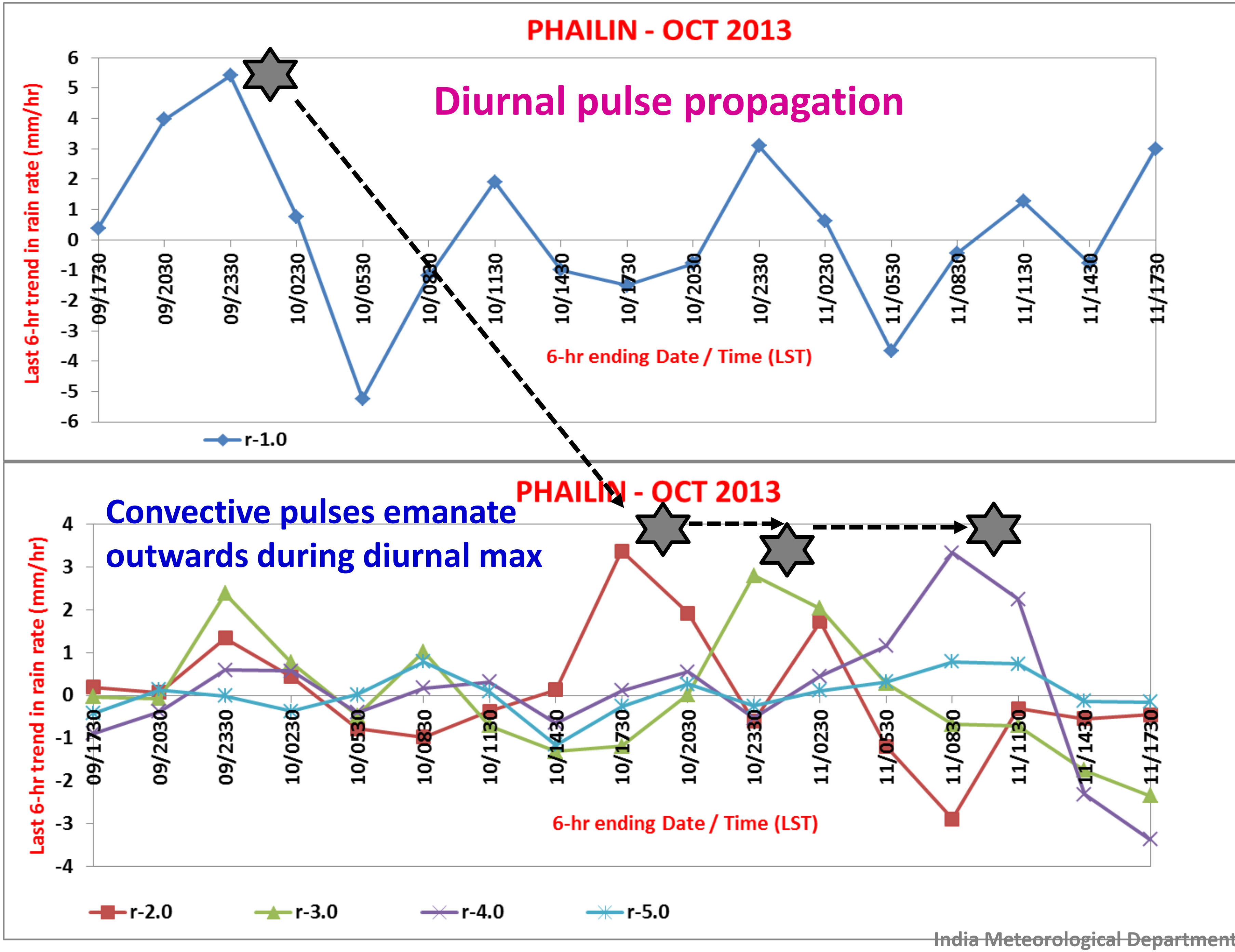
✓Another early morning peak (0530-1130 IST) associated with NEM diurnal cycle

✓Afternoon minimum (1430-1730 IST)

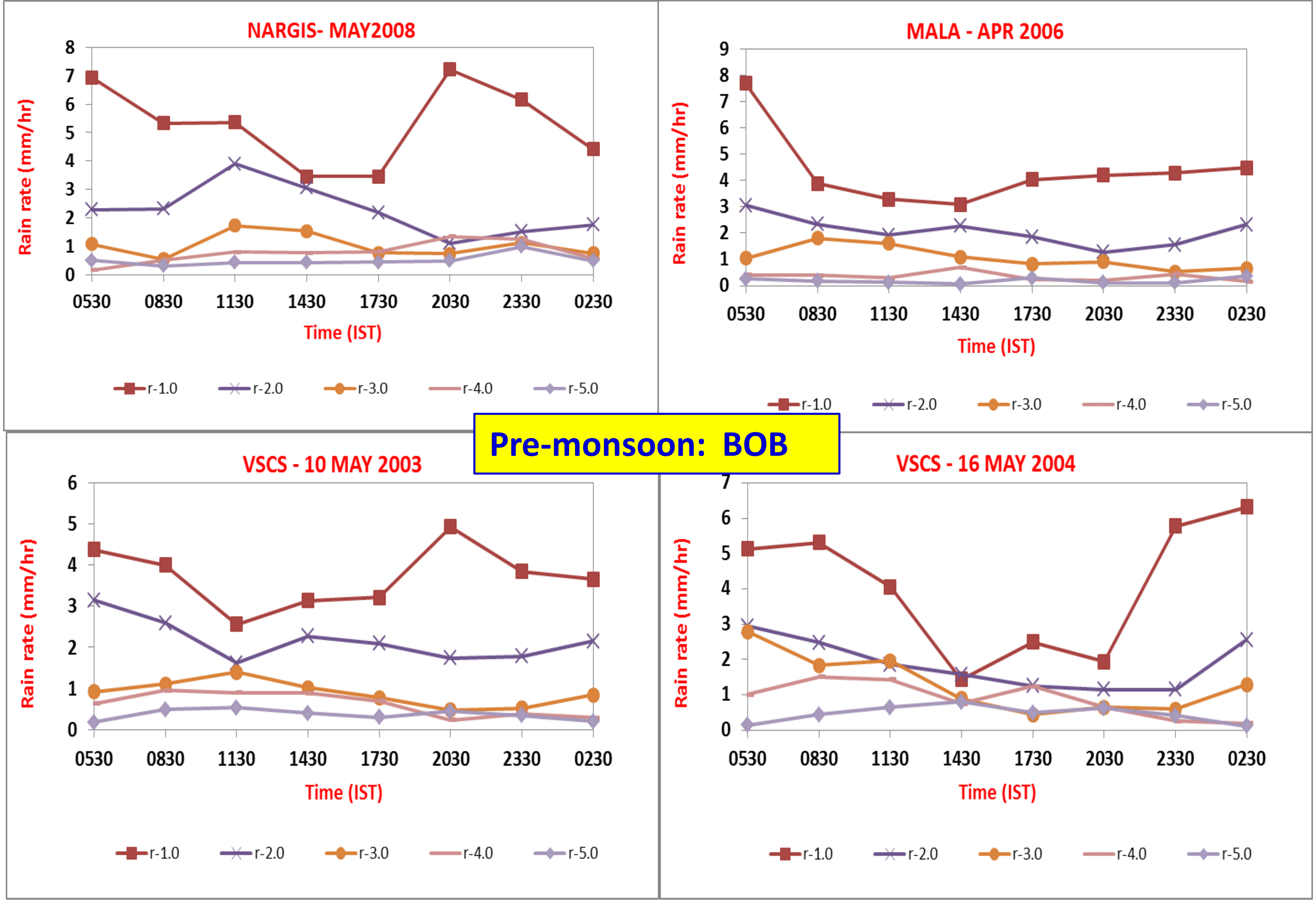
# Radial profiles of rain rates during the Diurnal Max & Min




- ✓Large differences of about 4-6 mm/hr upto about 150 km from the TC centre
- ✓1-2 mm/hr difference beyond 150 km from the TC centre

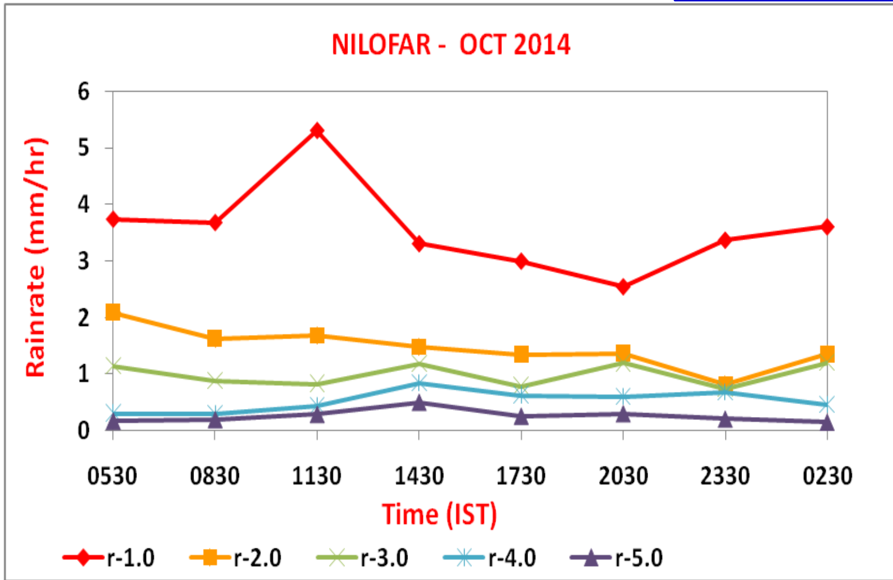


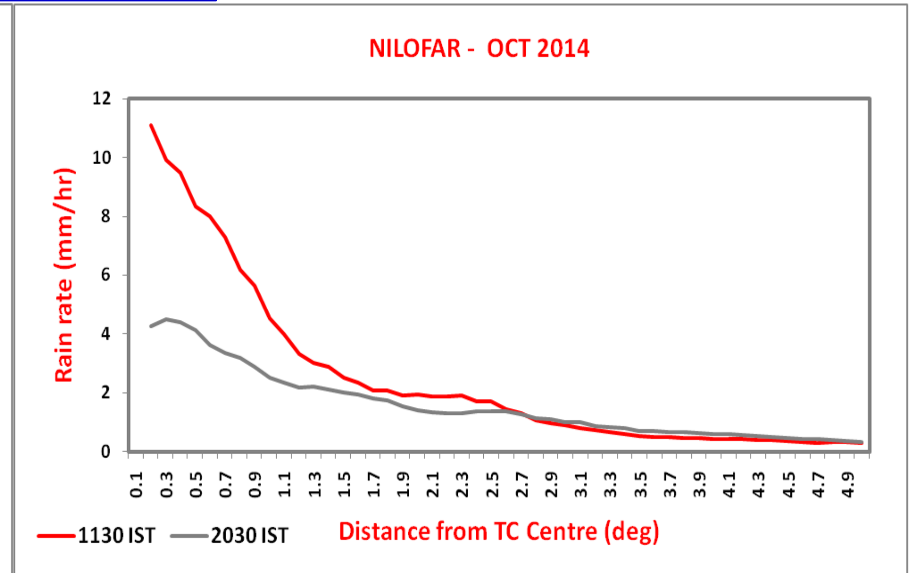
PHAILIN - OCT 2013
Diurnal pulse propagation
Last 6-hr trend in rain rate (mm/hr)
6-hr ending Date / Time (LST)
09/1730
09/2030
09/2330
10/0230
10/0530
10/0830
10/1130
10/1430
10/1730
10/2030
10/2330
11/0230
11/0530
11/0830
11/1130
11/1430
11/1730
r-1.0
PHAILIN - OCT 2013
Convective pulses emanate
outwards during diurnal max
Last 6-hr trend in rain rate (mm/hr)
6-hr ending Date / Time (LST)
r-2.0
r-3.0
r-4.0
r-5.0
India Meteorological Department

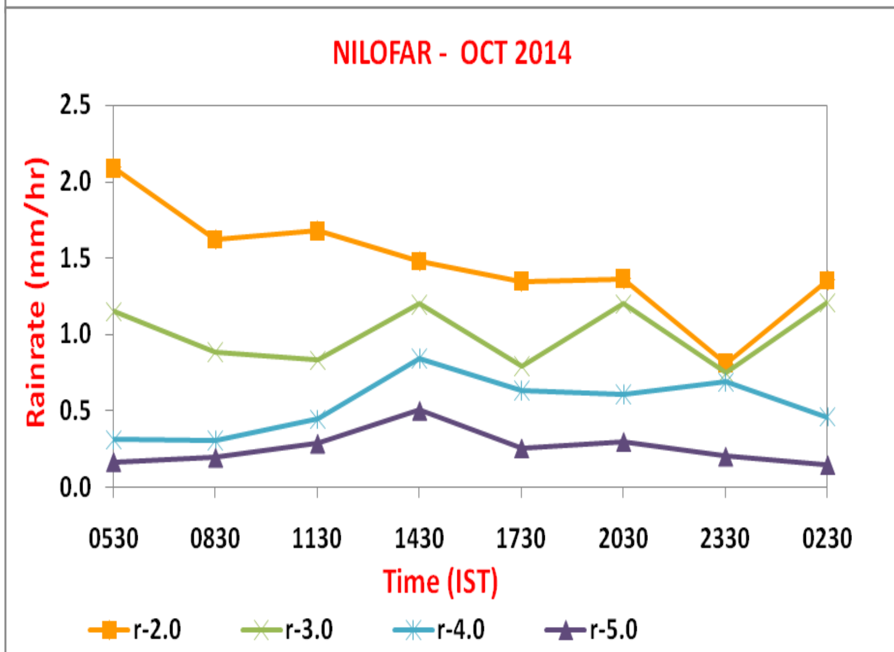



- ✓**TC diurnal cycle pre-dominant in the inner core (r=1.0$^{o}$) with max during night-early morning (2030-0530 IST) and minimum in the afternoon (1430-1730)**
- ✓**No discernible diurnal cycle pattern in the outer region (r≥ 2.0 $^{o}$)**

# Post-monsoon: AS

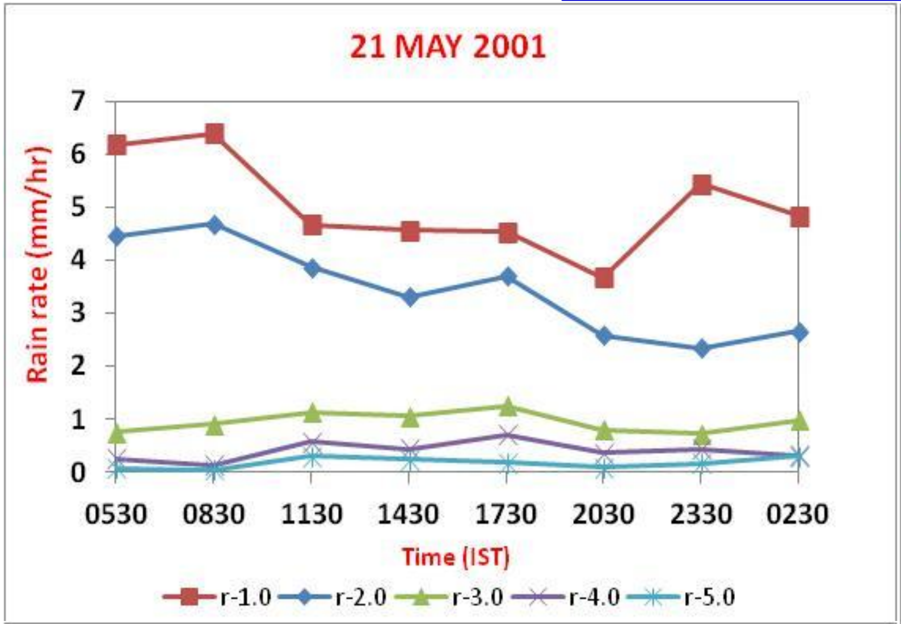


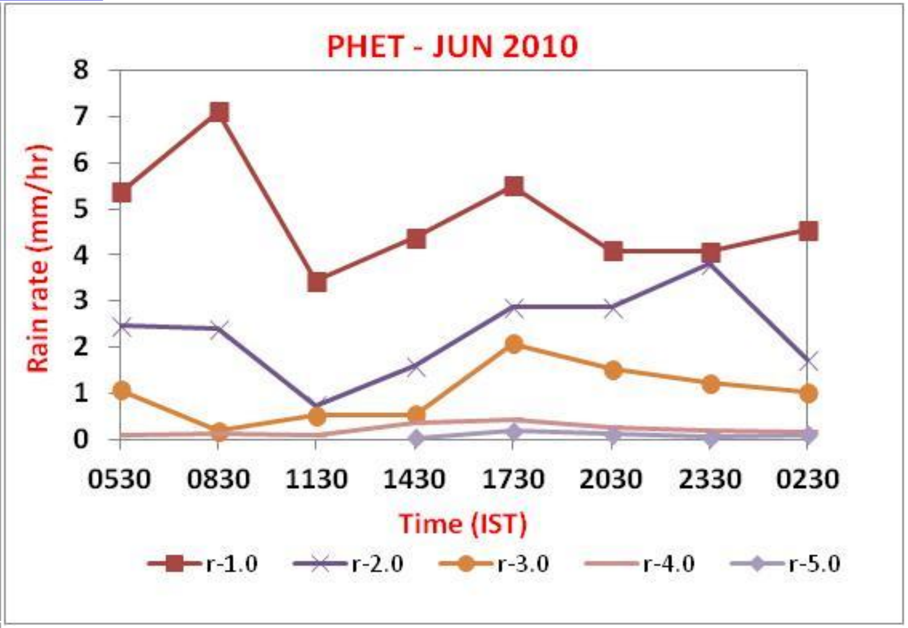



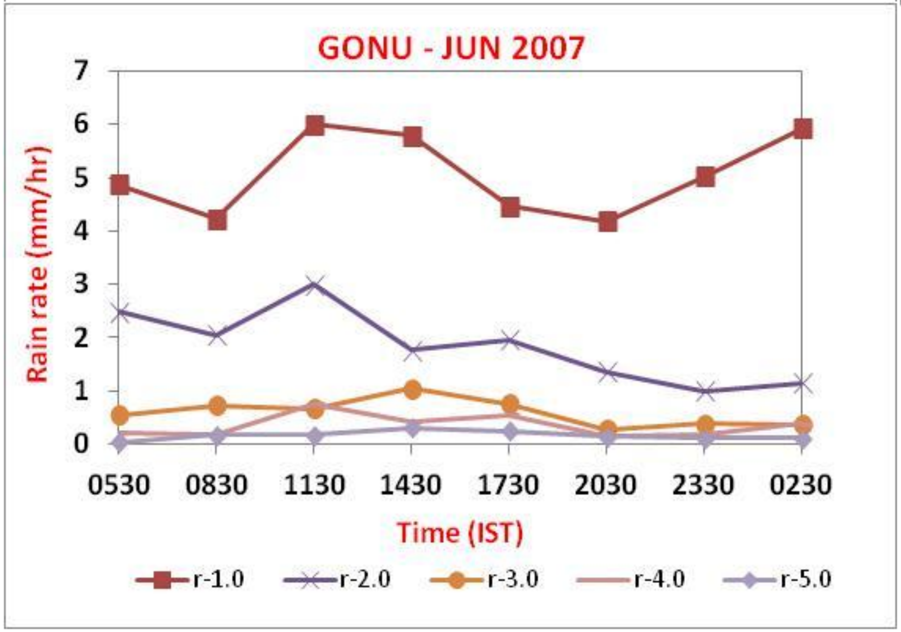




- ✓ **Inner core (r=1°) – Afternoon minimum followed by gradual increase from night to morning**
- ✓ **No discernible diurnal cycle pattern in the outer region**

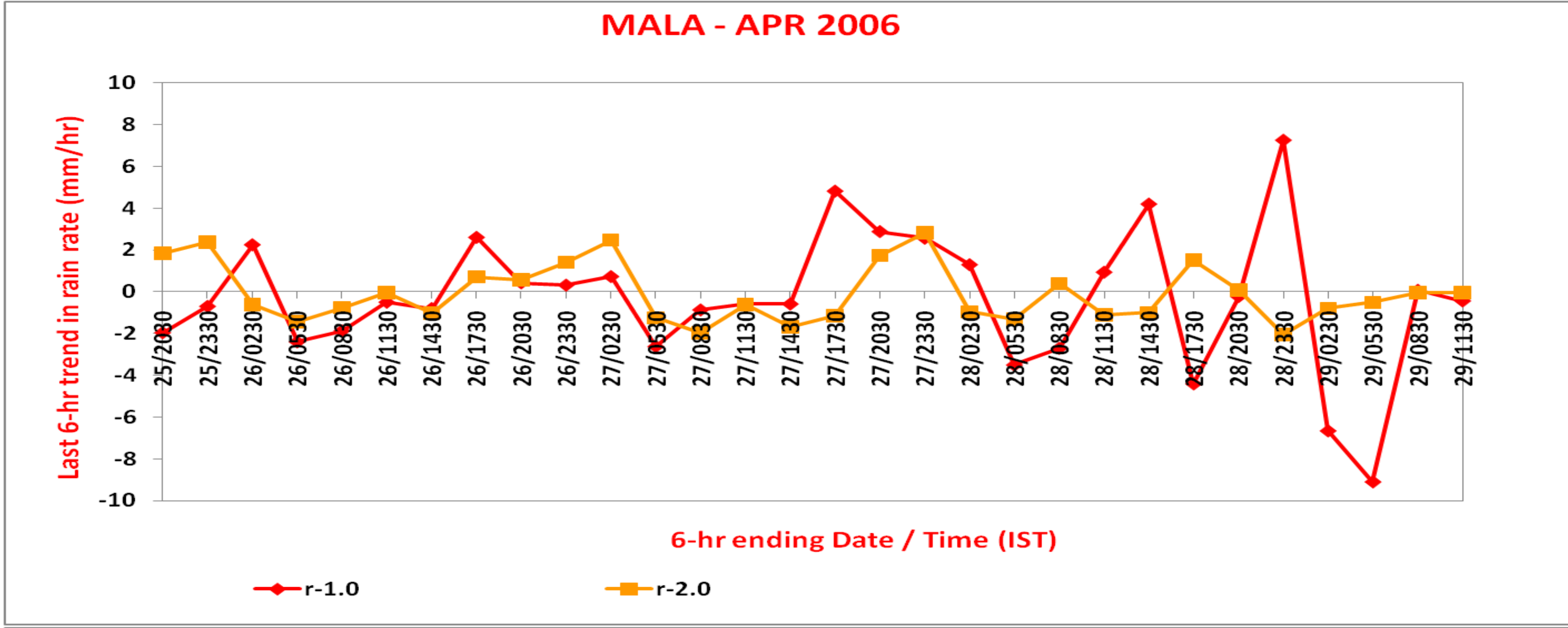
# Pre-monsoon: AS




- ✓No discernible diurnal cycle pattern in the outer region
- ✓Afternoon increase (1430-1730 IST) noticeable


MALA - APR 2006
Last 6-hr trend in rain rate (mm/hr)
10
8
6
4
2
0
-2
-4
-6
-8
-10
25/2030
25/2330
26/0230
26/0530
26/0830
26/1130
26/1430
26/1730
26/2030
26/2330
27/0230
27/0530
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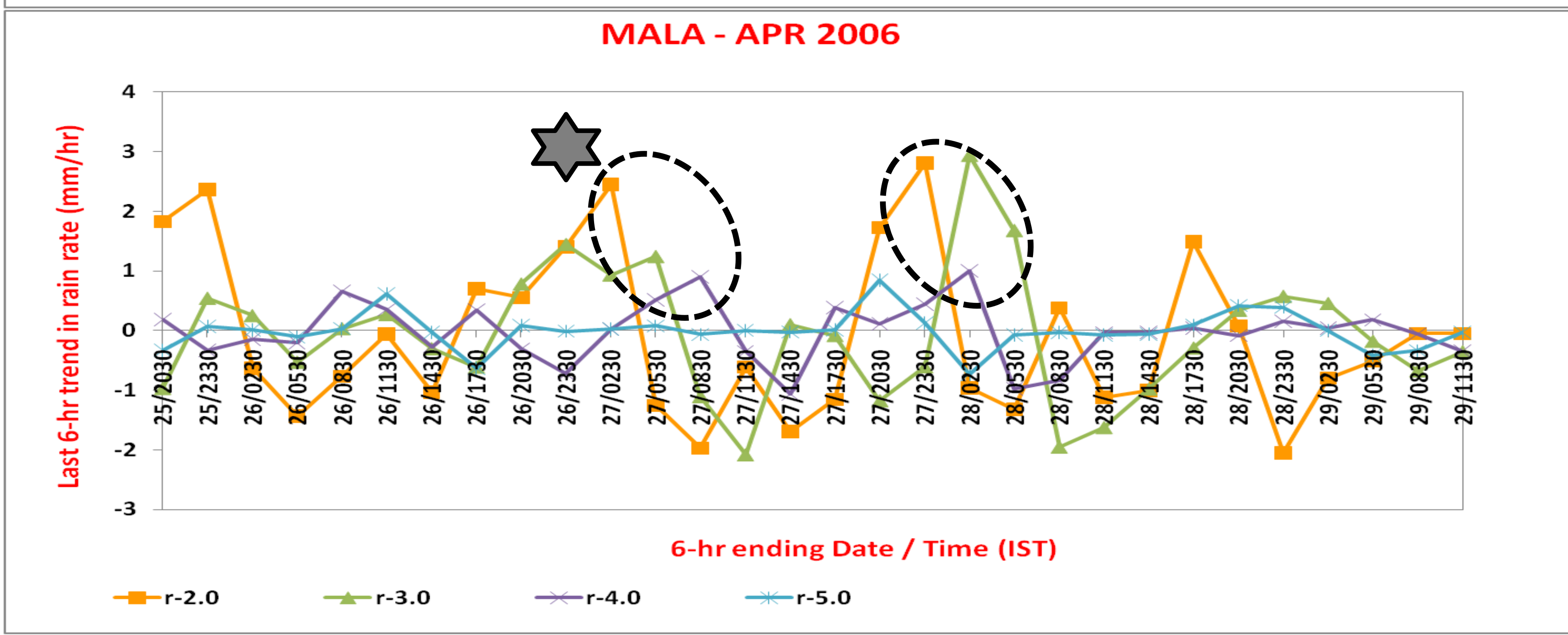
27/2030
27/2330
28/0230
28/0530
28/0830
28/1130
28/1430
28/1730
28/2030
28/2330
29/0230
29/0530
29/0830
29/1130
6-hr ending Date / Time (IST)
r-1.0
r-2.0


MALA - APR 2006
Last 6-hr trend in rain rate (mm/hr)
4
3
2
1
0
-1
-2
-3
25/2030
25/2330
26/0230
26/0530
26/0830
26/1130
26/1430
26/1730
26/2030
26/2330
27/0230
27/0530
27/0830
27/1130
27/1430
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28/0230
28/0530
28/0830
28/1130
28/1430
28/1730
28/2030
28/2330
29/0230
29/0530
29/0830
29/1130
6-hr ending Date / Time (IST)
r-2.0
r-3.0
r-4.0
r-5.0

# TC - Convection due to Diabatic heating :
## Vertical profiles of heat & moisture during Rapid Intensification & Rapid weakening

# Role of Vertical Non-Uniform Heating rate (Q1) in TC intensity change: Vorticity tendency eqn

Vorticity tendency

$$\frac{\partial \varsigma}{\partial t} = -\left(u\frac{\partial \varsigma}{\partial x} + v\frac{\partial \varsigma}{\partial y}\right) - \left(u\frac{\partial f}{\partial x} + v\frac{\partial f}{\partial y}\right) + (1-\kappa)(f+\varsigma)\frac{\omega}{p} - (f+\varsigma)\frac{Q}{\theta} + \frac{f+\varsigma}{\theta_z}\frac{\partial Q}{\partial z} - \frac{1}{\theta_z}\frac{\partial v}{\partial z}\frac{\partial Q}{\partial x} + \frac{1}{\theta_z}\frac{\partial u}{\partial z}\frac{\partial Q}{\partial y},$$

Vorticity advection ($10^{-10}$)

β-effect ($10^{-10}$)

Upward motion ($10^{-9}$–$10^{-10}$)

heating source ($10^{-10}$–$10^{-11}$)

Contribution of vertical non-uniform heating to the vorticity development ($10^{-8}$–$10^{-9}$)

Contribution of horizontal non-uniform heating to the vorticity development ($10^{-10}$–$10^{-11}$)

(Wu and Liu, 1999; Liu et al., 1999)

# Precipitation profiles during RI & RW – Heat and Moisture budget

- ✓ **dQ/dz→Vertical profiles of heat & moisture → provide information on vertical precipitation profiles associated with TC intensity changes**

$$Q_1 = C_P\left[\frac{\partial T}{\partial t} + V.\nabla T + \left(\frac{p}{p_0}\right)^k \omega \frac{\partial \theta}{\partial p}\right]$$

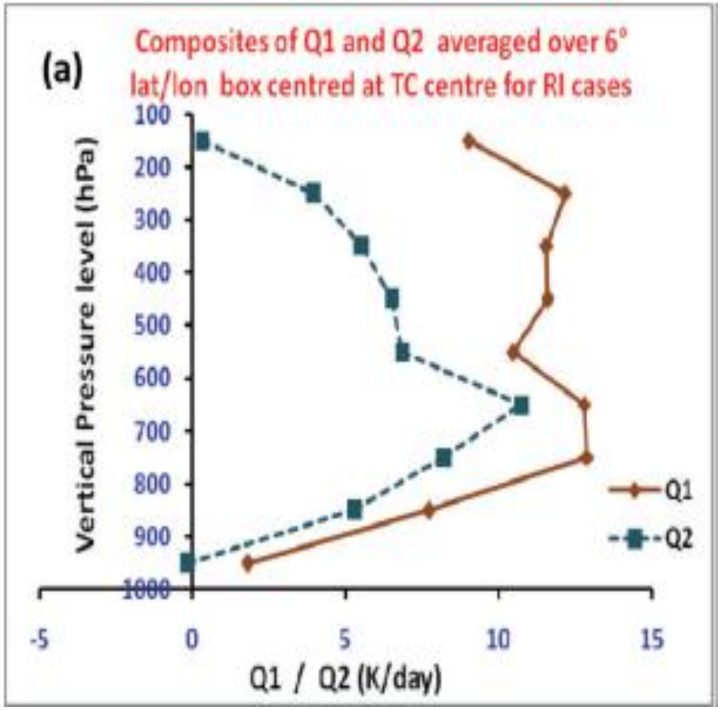
$$Q_2 = -L\left[\frac{\partial q}{\partial t} + V.\nabla q + \omega \frac{\partial q}{\partial p}\right]$$

**$C_p$: Sp heat capacity of air at const pr;**
**T: Temperature; V: Hor wind velocity,**
**P: Pressure; ω: Ver Vel (Pascal/sec);**
**ϴ: Potl. Temp & k=R/Cp**
**L: Latent heat of condensation,**
**q: mixing ratio of water vapour)**
**✓TC positions & MSW → from IMD's best track data**

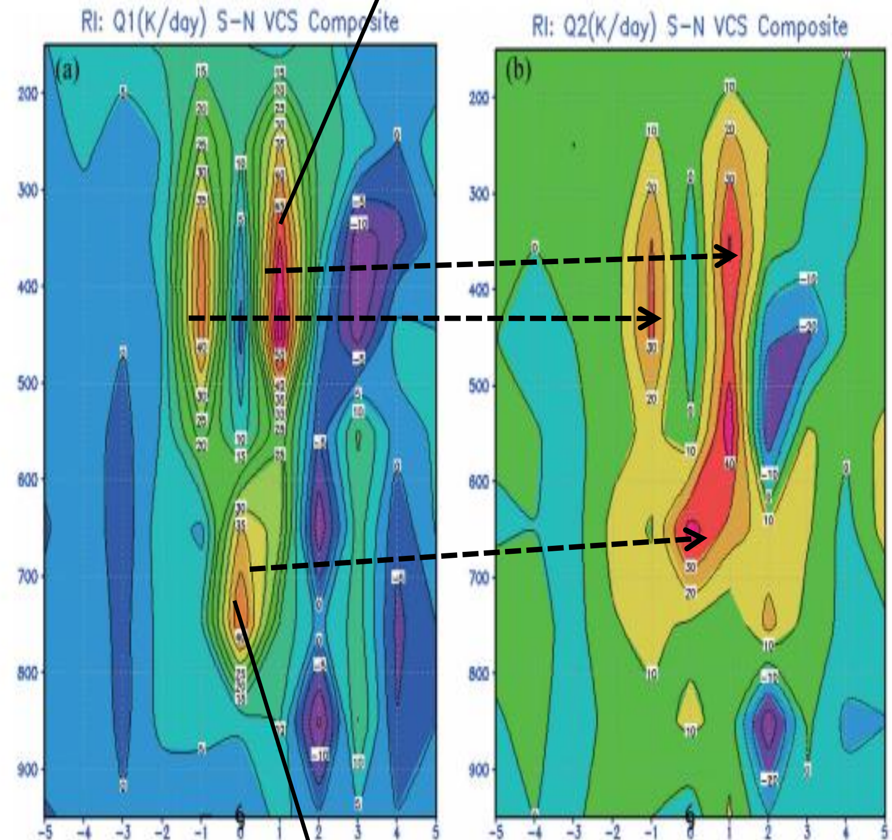
# Heat and Moisture budget …

## Vertical precipitation profiles for RI composite

✓NCEP-FNL 6-hrly, $1^{o}X1^{o}$ dataset




**Upper lev max→ latent heat release due to stratiform Anvil**




**RI→ Q1 & Q2→**
**Double maxima**
**(one in lower levels and another in the upper levels)**

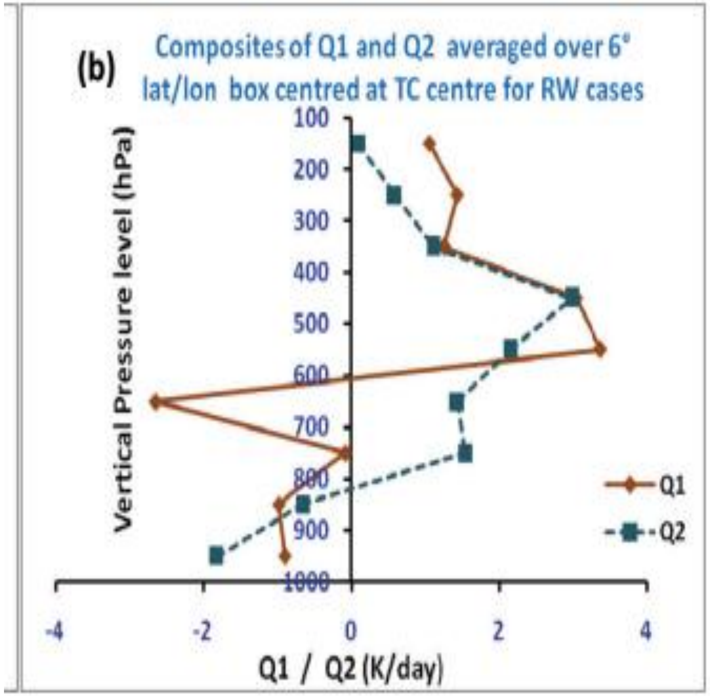
**Lower lev max→ latent heat release due to cumulus convection**

In a word, near the TC center between 500 and 200 hPa, $\frac{\partial Q}{\partial z} > 0$ corresponds to RI of the TC, and $\frac{\partial Q}{\partial Z} < 0$ corresponds to RW of the TC. In the lower troposphere near the TC center, with the increasing of $\frac{f+\varsigma}{\theta_z}\frac{\partial Q}{\partial z}$, the value of vorticity increases. This favors RI of the TC, and vice versa.

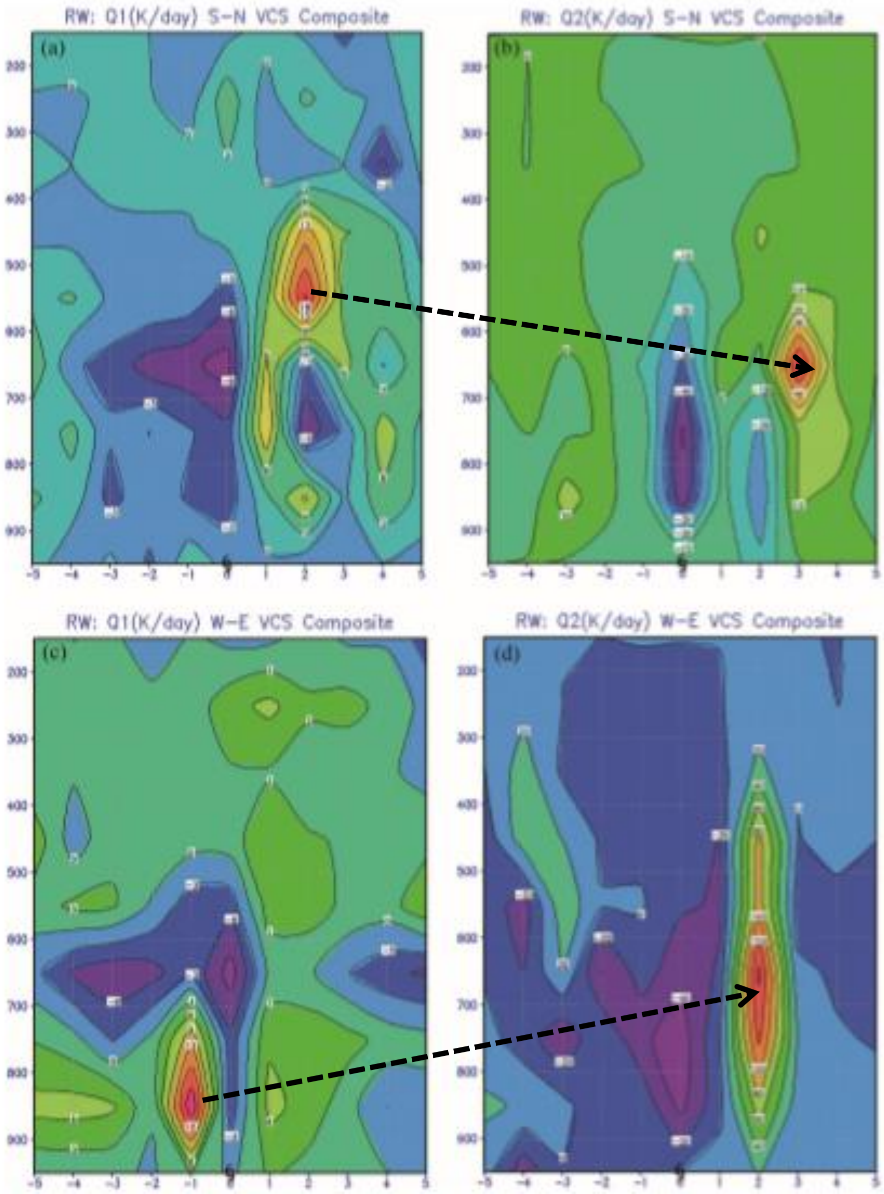
Geetha & Balachandran, TCRR, 2016

# Heat and Moisture budget …

## Vertical precipitation profiles for RW composite

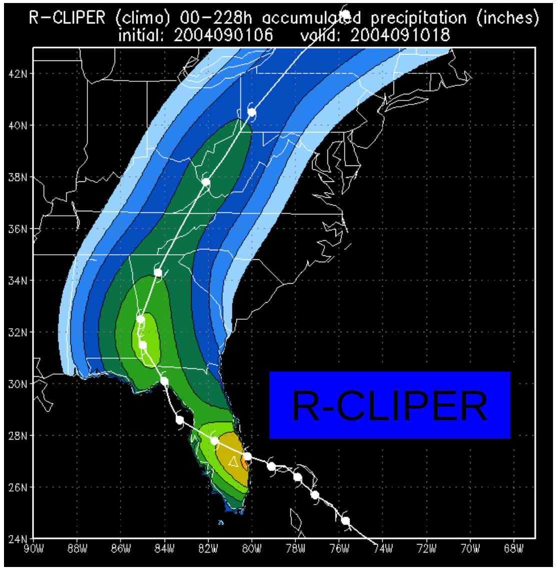


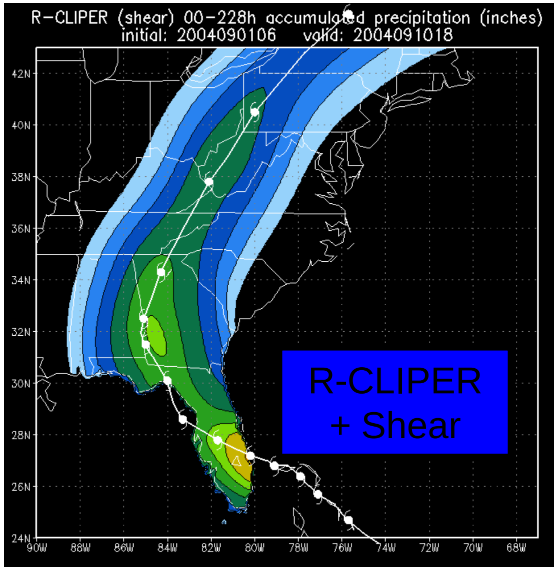

RW→ Q1 & Q2→ single max in the mid levels

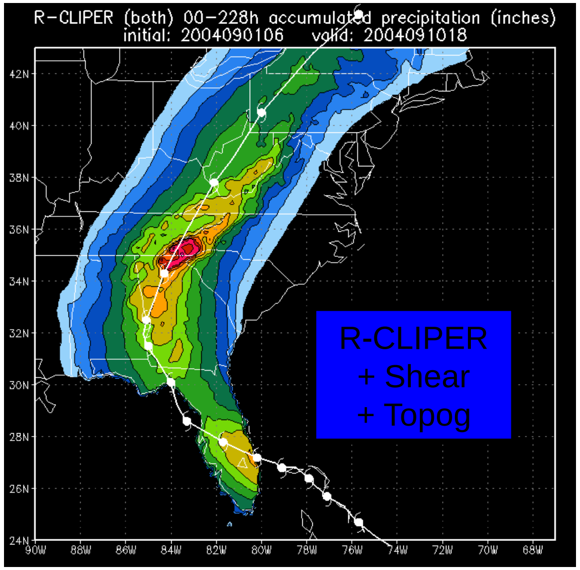


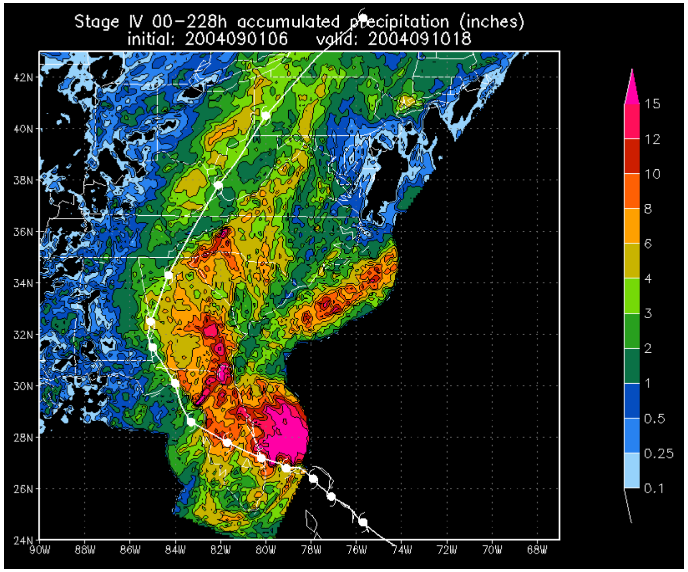
# Modelling the TC Rainfall

## R-CLIPER Improvements for Atlantic Hurricanes - 2007




- **Includes shear and topographic effects**

# Summary

Forecasting heavy rainfall associated with passage of TCs → one of the greatest challenges in TC forecasting.
Several observational studies have brought out the rainfall characteristics of TCs over various oceanic basins.
Major feature brought out by these studies – asymmetry in radial rainfall distribution.
Rainfall covers only about 25% of the total area within 500 km of the storm center.
Eyewall is very well defined in the radial profile of rain rates (6-14 mm/hr in the eye wall region).
Inner spiral bands→ 4-6 mm/hr; Outer bands → 1-4 mm/hr upto about 250 km.
Asymmetries in radial rainfall distribution → caused by TC motion, VWS, low level frictional convergence within the boundary layer
TC Motion→ Front / FL asymmetry
VWS→ Downshear left asymmetry
Asymmetry maxima shits cyclonically outwards during intensification stages (inward spiralling bands)
Diurnal variation → afternoon minimum, late night / early morning maximum
Diurnal pulse → emitted during convective bursts during late night; it propogates to outer radii slowly and may be seen in the next afternoon at some out radial distance.

Complexities of precipitation processes associated with TCs and lack of microphysical data to support parameterizations in numerical models has limited the QPF

# Thank You