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Characterisation and asymmetry analysis of rainfall distribution associated with tropical cyclones over Bay of Bengal : NISHA (2008), LAILA (2010) and JAL (2010)

S. BALACHANDRAN and B. GEETHA

Regional Meteorological Centre, Chennai, India

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e mail : balaimd@gmail.com

सार – इस शोध पत्र में तमिलनाडु के तटीय क्षेत्र को प्रभावित करने वाले बंगाल की खाड़ी में निर्मित हुए तीन उष्णकटिबंधीय चक्रवातों जैसे - निशा (2008) लैला (2010) तथा जाल (2010) के समय हुई वर्षा के लक्षणों और स्थानिक वर्षा विषमता का अध्ययन टी आर एम एम के आधार पर तैयार वर्षा आँकड़ों का उपयोग करते हुए किया गया है। उष्णकटिबंधीय चक्रवातों के जीवन चक्र को उसके तीव्र होने और कमजोर होने की अवस्थाओं को विभिन्न अवस्थाओं में बाँटकर विश्लेषण किया गया है। प्रत्येक उष्णकटिबंधीय चक्रवात की बारंबारता वितरण का प्रतिशत, त्रिज्य रूपरेखा और वर्षा दरों के चतुर्थांश औसत का निर्धारण अलग-अलग चरणों में किया गया है। इसके अलावा फुरिए विश्लेषण पद्धति का उपयोग करते हुए उष्णकटिबंधीय चक्रवात केंद्र के चारों ओर की प्रथम श्रेणी के वेव नं.1 विषमता की गणना के द्वारा स्थानिक कालिक भिन्नताओं से वर्षा की विषमता का अध्ययन किया गया है। इस अध्ययन से प्राप्त हुए परिणामों से पता चला है कि उष्णकटिबंधीय चक्रवात के घनीभूत होने से लेकर कमजोर होने तक की अवस्थाओं में वर्षा की दरों की बारंबारता बढ़ने से अधिकतम वर्षा से कम वर्षा दर का बदलाव आया है। दिगंशीय औसत माध्य वर्षा दरें दर्शाती हैं कि उष्णकटिबंधीय चक्रवात केंद्र से 50-100 कि.मी. के आगे 4-5 मि.मि. प्रति घंटा की दर से अत्यधिक भारी वर्षा होती है और यह गति धीरे-धीरे कम होते हुए कमजोर पड़ने के अंतिम चरण तक घटकर 1 मि.मि. प्रति घंटा हो जाती है। समान प्रकार की तीव्रता श्रेणी के लिए औसत वर्षा दरों की त्रिज्यीय प्रोफाइलें घनीभूत होने और कमजोर पड़ने की स्थितियों में महत्वपूर्ण अंतर को दर्शाती हैं। चतुर्थांश औसत वर्षा दरें तीव्रीकरण की अवस्थाओं के दौरान वाताग्र चतुर्थांश में हुई सघन वर्षा के साथ त्रिज्य वर्षा वितरण में हुई बड़ी विषमता को दर्शाती है। इस प्रकार की उष्णकटिबंधीय चक्रवातीय वर्षा विषमताएँ पर्यावरणीय उदग्र पवन अपरूपण (विंड शियर) और उष्णकटिबंधीय चक्रवात से उत्पन्न गति से प्रभावित होती हैं। जब पवन अपरूपण (विंड शियर) और तूफान की गति की दिशा समान दिशा में होते हैं तो पाया गया है कि हावी होने वाला पवन अपरूपण (विंड शियर) विषमता को छोड़ देता है। वेव नं.1 विषमता की उत्पति दर्शाती है कि कुल मिलाकर विषमता आयाम केंद्र से बाहर की ओर बढ़ता है और उष्णकटिबंधीय चक्रवातों के घनीभूत होने (कमजोर पड़ने) की अवस्थाओं के दौरान एक चक्रवातीय (प्रति चक्रवाती) शिफ्ट होता है।

ABSTRACT. The precipitation characteristics and spatial rainfall asymmetry in respect of three tropical cyclones (TCs) of Bay of Bengal, *viz*., NISHA (2008), LAILA (2010) and JAL(2010) that affected coastal Tamil Nadu are studied using TRMM based rain rate data. The analysis is carried out by dividing the life cycle of the TC into various stages of intensification and weakening. Percentage frequency distribution, radial profile and quadrant-wise mean rain rates are determined stage-wise for each TC. Further, spatio-temporal variations in the rainfall asymmetry is studied using Fourier analysis by computing the first order wave number-1 asymmetry around the TC centre. The results indicate a shifting of higher frequency rain rates from higher to lower rain rate side when the TC passes from intensification to weakening stages. The azimuthally averaged mean rain rates indicate a peak rain rate of 4-5 mm/hr over 50-100 km from the TC centre during intensification stages which decreases to a very low rate of about 1 mm/hr during the final stages of weakening. For the same intensity category, the radial profiles of mean rain rates show marked difference between the intensification and weakening stages. The quadrant mean rain rates show large asymmetries in the radial rainfall distribution with more rainfall concentrated in front left quadrant during the stages of intensification. Such TC rainfall asymmetries are shown to be influenced by the environmental vertical wind shear and translational speed of the TC. When the wind shear and storm motion vectors are in the same direction, a dominant down shear left asymmetry is observed. Evolution of wave number-1 asymmetry indicates that, by and large, asymmetry amplitude increases from the centre outwards and a cyclonic (anti-cyclonic) shift during the intensification (weakening) stages of the TCs.

Key words – Tropical cyclone, TRMM, Precipitation, Rainfall, Asymmetry, Fourier analysis, Vertical wind shear, Translational speed.

1. Introduction

Tropical Cyclone (TC) rainfall distribution is determined by environmental factors such as wind shear, sea surface temperature (SST), moisture distribution etc. as well as TC specific factors such as intensity, location and translational speed. Rainfall measured at a particular location during the passage of a TC also depends on local effects such as topography and orientation of the coast (Rogers *et al*., 2003). Consequently, TC precipitation characteristics can vary greatly from one TC to another and even from time to time for a particular TC. A thorough knowledge of TC rainfall characteristics is a critical step towards understanding and improving Quantitative Precipitation Forecasts (QPFs) in respect of TCs. The early models developed for QPFs did not show good skill as they assumed a constant rain rate, while in reality, precipitation distribution displayed asymmetric nature. Rodgers and Adler (1981), Marks (1985), Burpee and Black (1989) have worked on radial profiles of rainfall associated with some Pacific typhoons and Atlantic Hurricanes using satellite passive microwave imager and airborne radar observations and have brought out the complex and asymmetric rainfall structures associated with TCs.

For the Indian region, studies on rainfall associated with land falling TCs of North Indian Ocean (NIO) basin which comprises of the Bay of Bengal (BOB) and the Arabian Sea (AS) have been undertaken by several earlier workers. The chief cyclone season for the NIO basin is the northeast monsoon season of October-December (OND) followed by the pre-monsoon months of April and May. While most of the pre-monsoon TCs recurve towards northeast, TCs of northeast monsoon season predominantly move northwestwards and affect the eastern coastal belt, especially, Coastal Andhra Pradesh (CAP) and coastal Tamil Nadu (CTN). Freshwater flooding during TC landfall have caused extensive damage to life and property over these coastal regions so much so that several studies related to rainfall distribution and associated asymmetric structures have been undertaken in the past. Boothalingam and Srinivasan (1950) have studied five storms of pre-monsoon season and found that heavy rainfall occurred mainly south of the cyclone track. Raghavan and Varadarajan (1981) discussed distribution of rainfall rates and latent heat release in three TCs of the BOB and noted asymmetric concentration of latent heat release in right rear sector well away from core of storm about 150 to 200 km. Jayanthi and Sen Sarma (1987) studied the rainfall patterns of cyclonic disturbances over NIO for the period 1877 to 1984 and observed that rainfall is more concentrated in the left forward sector followed by the right rear sector. These studies indicate asymmetric nature of rainfall distribution

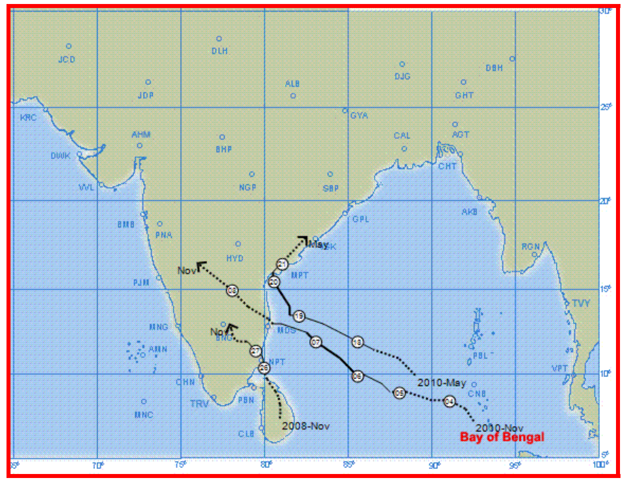

Fig. 1. Tracks of CS NISHA, SCS LAILA and SCS JAL that affected Tamil Nadu coast during 2008-2010

for landfalling TCs over the NIO. However, there are a few studies on the changing pattern of rainfall distribution during landfall and the physical features associated with it.

Lonfat *et al*. (2004) determined the asymmetry pattern in rainfall distribution for TCs of global oceanic basins and attributed vertical wind shear and variations in the translational speeds of TCs of various basins as important factors amongst others for the evolution of different asymmetry patterns over various oceanic basins. Chen *et al*. (2006) have recently studied TC rainfall structure in relation to the environmental wind flow for all oceanic basins of the globe except the NIO.

In the present study, an analysis of precipitation characteristics and asymmetry in the rainfall distribution of three tropical cyclones of NIO, *viz*., NISHA (25-27 November, 2008), LAILA (17-21 May, 2010) and JAL (4-7 November, 2010) using a high resolution, research quality TRMM data that includes rainfall over oceanic region also, is carried out. Further, asymmetry in rainfall distribution is analysed in the context of environmental vertical wind shear and translational speed of the TC. This attempt would help in understanding the complexities of TC rainfall asymmetry over the NIO basin.

2. Data and methodology

2.1. *TCs chosen for the study*

According to India Meteorological Department (IMD) classifications, based on maximum sustained surface wind speeds, low pressure systems are categorised as low (<17 knots), Depression (D, 17-27 knots), Deep Depression (DD, 28-33 knots), Cyclonic

Storms (CS, 34-47 knots), Severe Cyclonic Storms (SCS, 48-63 knots), Very Severe Cyclonic Storm (VSCS, 64-119 knots) and Super Cyclonic Storm (SuCS, ≥ 120 knots) (IMD, 2003).

As mentioned earlier, three TCs, *viz*., LAILA, JAL and NISHA were selected for the present study. While LAILA and JAL were SCS, NSIHA attained a maximum intensity of CS. The tracks of these systems are shown in Fig. 1. The SCS LAILA (17-21 May, 2010), a pre-monsoon season cyclone, formed over the Bay of Bengal on 17th May, 2010, caused heavy rainfall over the north CTN and south CAP before landfalling over Bapatla in Andhra Pradesh on 20th May. Generally, pre-monsoon TCs move northwards or recurve towards northeast and affect Bangladesh or Myanmar coasts and seldom affect Tamil Nadu coast. But LAILA initially moved northwestwards, came close to north Tamil Nadu coast and caused heavy (7-12 cm/day) to very heavy (12-24 cm/day) rainfall over north CTN. The SCS JAL (4-7 Nov 2010), a typical cyclone of northeast monsoon season, weakened into DD over sea itself before crossing north Tamil Nadu – south Andhra Pradesh coast, north of Chennai on 7th November. Even though, the system crossed just north of Chennai, rainfall recorded at Chennai was only 5cm on 8th November. However, very heavy to heavy rainfall were recorded in the districts of Villupuram, Cuddalore, Kancheepuram, Thirvannamalai, Vellore, Dharmapuri and Krishnagiri of North Tamil Nadu and in case of Andhra Pradesh, extreme north (Srikakulam, and Visakhapatnam) and extreme south (Nellore) coastal districts and some interior districts (Cuddapah and Chittoor) recorded very heavy to heavy rainfall on 8th November. But, extremely heavy rainfall (>24 cm) of 27 cm was recorded at Palasa (Srikakulam district, extreme north CAP (IMD, 2011). As such, these two SCSs that made different distinct impacts over CTN with respect to the associated rainfall are considered for the study. Further, the cyclonic storm (CS) NISHA (25-27 November, 2008) which did not attain severe cyclone intensity, but crossed Tamil Nadu coast, North of Karaikal and made very distinct impact with reference to rainfall along the coastal districts is also considered for rainfall analysis. One salient feature of this TC was that it remained quasi-stationary close to the coast for about 24 hours and caused exceptionally heavy rainfall along the Cauvery delta areas which led to flooding over the coastal areas of Tamil Nadu and Puducherry. Rainfall of the order 25-33 cm/day were recorded consecutively for two days on 26th and 27th November, 2008 at Orathanadu, Vedaranniyam and Thanjavur of the Cauvery delta region (IMD, 2009). Several places in north Tamil Nadu and south Andhra Pradesh had received heavy to very heavy rainfall on 28th and 29th November, 2008. Hence, the above three cyclones, *viz*., SCS LAILA, SCS JAL and CS NISHA which showed a high degree of variation in spatial rainfall distribution and affected Tamil Nadu coast in three distinct ways with reference to the associated rainfall are chosen for the present analysis.

2.2. *Precipitation data*

The TRMM based precipitation data (3B42V6) is used for this study. The dataset has a spatial coverage of 50° S to 50° N at 0.25° × 0.25° resolution at 3 hourly intervals and has been generated using 3B42 algorithm (http://trmm.gsfc.nasa.gov/) The rainfall measuring instruments on the TRMM satellite include Precipitation Radar (PR), TRMM Microwave Imager (TMI) and Visible and Infrared Scanner (VIRS). The 3B42 algorithm produces TRMM-adjusted merged-infrared (IR) precipitation data which consists of GMS, GOES-E, GOES-W, Meteosat-7, Meteosat-5, and NOAA-12 data. The data processing has been designed to maximise data quality and has been recommended for research work (http://disc.sci.gsfc.nasa.gov/additional/faq/). The 3B42V6 product has been found to be in good agreement with gauge observed data over the Indian region [Durai *et al*. (2010) and Srivastava (2011)].

2.3. *Methodology of analysis*

The IMD's best track data of TCs containing information on instantaneous position, intensity and direction of motion of the TC and TRMM precipitation data available at regular three hourly intervals at 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 UTC are used for the present study.

For the purpose of analysis, the life cycle of a TC is stratified based on intensity and grouped into 5 stages as shown in the schematic diagram Fig. 2. As can be seen, the first three stages are associated with formation and growth (intensification stages 1, 2 and 3) of the TC and the fourth and fifth stages correspond to the decay (weakening stages 1 and 2) of the TC. For each TC, all three hourly TRMM rainfall data are grouped together for each stage as per the above stratification and the composited rainfall characteristics are studied by determining the following parameters of rainfall distribution, namely,

(*i*) Frequency distribution of rain rates within 500 km from the TC centre

(*ii*) Azimuthally averaged radial profiles of mean rain rates within 500 km from the TC centre and

(*iii*) Quadrant-wise mean rain rates within 200 km from the TC centre.

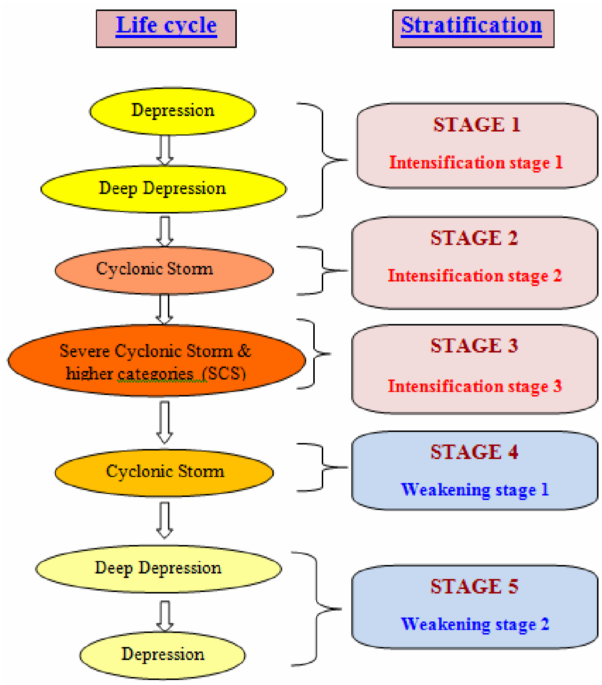

Fig. 2. Schematic representation of intensity based stratification of life cycle of a TC

In addition to above, time evolution of spatial rainfall asymmetry associated with these systems are examined through Fourier analysis by studying the first order asymmetry corresponding to wave number-1 at 12 hourly intervals as detailed in section 3.4.

The study of frequency distribution of rain rates gives valuable information on highly probable rain rates associated with different intensity stages of the TC. Azimuthally averaged radial profile of mean rain rates provides information on rainfall variability at different radial distances from the TC centre. For the present study, frequency distribution and azimuthally averaged radial profiles of mean rain rates are determined up to 500 km from the TC centre as the radial extent of the TCs, and hence its impact, normally extends up to 500 km. However, quadrant-wise mean rain rates, which provide information on the mean asymmetric characteristic of rainfall distribution, are computed up to 200 km only from the TC centre as generally, the most devastating torrential rains are realised within 200 km from the TC centre and beyond 200 km, the rain rates are generally not so alarmingly high [Lonfat *et al.* (2004), Chen *et al.* (2006), Singh *et al.* (2012)]. The asymmetry in rainfall distribution is also analysed with reference to vertical wind shear and TC translational speed to bring out the association between them.

For the purpose of computations, a moving coordinate system with the TC centre as the origin and direction of motion of the TC as the reference direction is considered. For each instant of time, the centre of the coordinate system is first shifted to the centre of the TC at that instant and then the coordinate system is rotated such that the direction of motion of the TC at that specific instant of time coincides with the 0° azimuth which is taken as the positive Y-direction for the purpose of plotting. All 0.25° × 0.25° rainfall data points are then represented in terms of radial distance from the TC centre and with reference to the direction of motion of the TC.

3. Results and discussion

Quantitative description of rainfall around SCSs LAILA and JAL are presented through frequency distribution of rain rates, azimuthally averaged radial profile of mean rain rates, quadrant mean rain rates in Section 3.1-3.3. The associated physical processes and evolution of asymmetry in rainfall are presented and analysed in Section 3.4-3.6. The Precipitation characteristics and asymmetry in rainfall associated with the CS NISHA are discussed in Section 3.6.

3.1. *Frequency distribution of rain rates*

The frequency distribution of rain rates is determined by considering all data at 0.25° × 0.25° grids within 5° (approx. 500 km) radial distance from the TC centre. For this purpose, the rain rates are divided into nine classes (including no rain category) as 0.0, 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 and >10.0 mm/hr. This classification is based on the data range and also is in tune with earlier works (Lonfat *et al.*, 2004). The frequency distribution of rain rates for different stages of intensification and weakening of the SCSs LAILA and JAL are presented in Fig. 3.

In the case of LAILA, as the system passes from intensification to weakening stages, higher frequencies of rain rates shift from higher to lower rain rates (Fig. 3). During the stages 1, 2 and 3 corresponding to intensification of the TC, the modal value of rain rate is about 1-2.5 mm/hr, while during the stages 4 and 5 corresponding to weakening of the TC, the distribution is somewhat flat up to 1-2.5 mm/hr even though the peak rain rate is 0.2–0.5 mm/hr. In the case of JAL, for the stage-1 (intensification), the highest frequency of rain rates (20%) corresponds to the rain rate range of 1.0–2.5 mm/hr and for the second stage of intensification it corresponds to a higher rain rate class of 2.5 -5.0 mm/hr. In the stage-3 (SCS), still higher class of rain rate, *viz.*, 5.0-10.0 mm/hr is also becoming prominent in addition to the other two frequent classes (1.0–2.5 mm/hr and

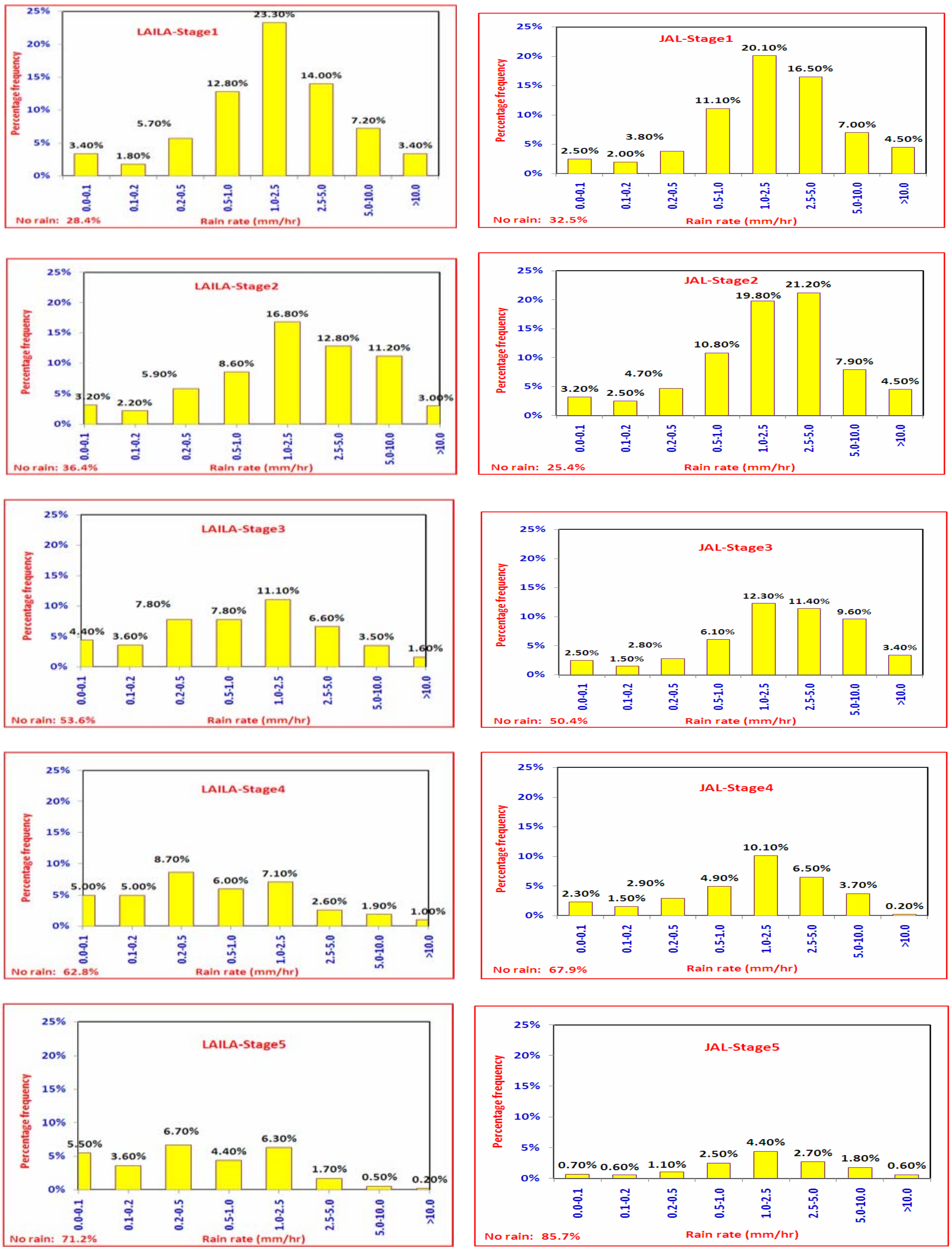

Fig. 3. Frequency distribution of rain rates within 5 degree radial distance from the cyclone centre during different stages of SCS LAILA and SCS JAL

2.5 - 5.0 mm/hr) and the distribution is highly concentrated on the higher rain rate side. During the weakening stages also, the rain rate distribution is greater towards the higher rain rates side, of course, with drastically reduced percentage of frequency. Thus, though both JAL and LAILA attained SCS intensity, rainfall distribution in LAILA is different from that of JAL during weakening stages.

In both the cases, percentage of non-raining areas (percentage of grid points with rain rate = 0 mm/hr) progressively increases as the system passes through various stages of its life cycle. The percentage frequency of no rain ranges between 25-54% (64-86%) during the intensification (weakening) stages. For the same intensity category of CS, in the case of LAILA (JAL), frequency of no rain during the intensification stage is 36.4% (25.4%) and that during the weakening stage is 62.8% (67.9%). This increase in the presence of non-raining areas in the vicinity of the TC (*i.e*., within 500 km from the TC centre) is likely to reflect in the asymmetric structure with greater asymmetry in the rain rate distribution during the weakening stages. Thus, analysis of the percentage frequency of rain rates depicts likely rates of rainfall during different intensity stages of the TC.

3.2. *Radial profile of azimuthally averaged mean rain rates*

To obtain the radial rainfall profile, the rain rates at various radial distances from the TC centre to 500 km radius are azimuthally averaged for each observation and grouped as per the five stratified intensity stages. The composite radial profile of the azimuthally averaged mean rain rates for each stage is analysed for both the SCSs.

For azimuthal averaging of mean rain rates, the area within 5° radial distance from the TC centre is divided into 50 annuli of thickness 0.1° (approx 10 km) from the TC centre and all data within each annulus are considered for determining the mean rain rate within the specific annulus. The profiles of smoothened (three point running mean) mean rain rates determined for all the 50 annuli of thickness 0.1° from the centre of the TC up to 5° radius for different stages of intensification and weakening of the two TCs LAILA and JAL are shown in Fig. 4.

During the stage 1 of intensification, in the case of both LAILA and JAL, the peak rain rate of the order of 4 to 5 mm/hr occurred over a broad zone of 50 to 100 km from the TC centre. As the systems enter into the stage 2 of intensification, peak rain rate increases to 7-8 mm/hr, and shifts towards the centre (about 40 km from the centre) with a sharply defined peak. However, as the systems intensify further (stage 3), there are significant differences in the peak rain rates. In the case of LAILA, the peak rain rate decreases to 5-6 mm/hr and shifts to 80 km away from the TC centre while JAL displays a flat rain rate of 3 mm/hr over wide range between 120 km to180 km from the centre. Thus, in both the cases, for the stage 3, the radius of maximum rain rate is greater than that during the stage 2. Generally, the radius of maximum rainfall is expected to shift inwards, towards the TC centre, with increase in intensity. However, at times, opposite to this general relationship, higher rain rates occur in the outer storm region than in the inner regions as observed by Jinhua *et al*. (2010) in case of West North Pacific storm ‘Bilis’. This may be due to complex interactions amongst the factors that determine the asymmetry of TC rainfall.

During the weakening from SCS to CS (stage 4), LAILA displays a rain rate of 5 mm/hr at 50-80 km from centre while a very low rain rate of 1 mm /hr is observed in the case of JAL. During the final stage of weakening, stage 5, the rain rates are mostly very low at 1 mm/hr or even lesser in both the systems.

It may be noted that higher radial rain rates are seen within 50-250 km from the TC centre and beyond 250 km, the rain rates are of the order of 0-2 mm/hr for all the five stages of both the SCSs. Also, it may be pointed out that since the percentage of non-raining areas increases as the intensity of the TC passes from one stage to another (Section 3.1), increase in azimuthally averaged rain rates during the intensification of the system might imply a strong asymmetric component in the azimuth.

Further, it may be noted that the radial profiles of mean rain rates show marked difference between the intensification and weakening stages for the same intensity category. For *e.g*., in the case of JAL, for the intensity category CS, the peak rain rate is 8 mm/hr during intensification (stage 2) but just about 1 mm/hr during the weakening (stage 4) of the TC.

The above radial rainfall profile analysis depicts the mean rain rate at different radial distances from the TC centre. But, the precipitation structure in TCs is quite complicated and in general, rainfall around a TC can be considered as the sum of azimuthally averaged axi-symmetric component (radial distribution) and axially asymmetric component [Frank (1977) and Burpee and Black (1989)]. The asymmetric features of the rainfall distribution are brought out in the forthcoming sections.

3.3. *Quadrant mean rain rates*

The quadrant-wise mean rain rates for the various stages of intensification and weakening of the systems up

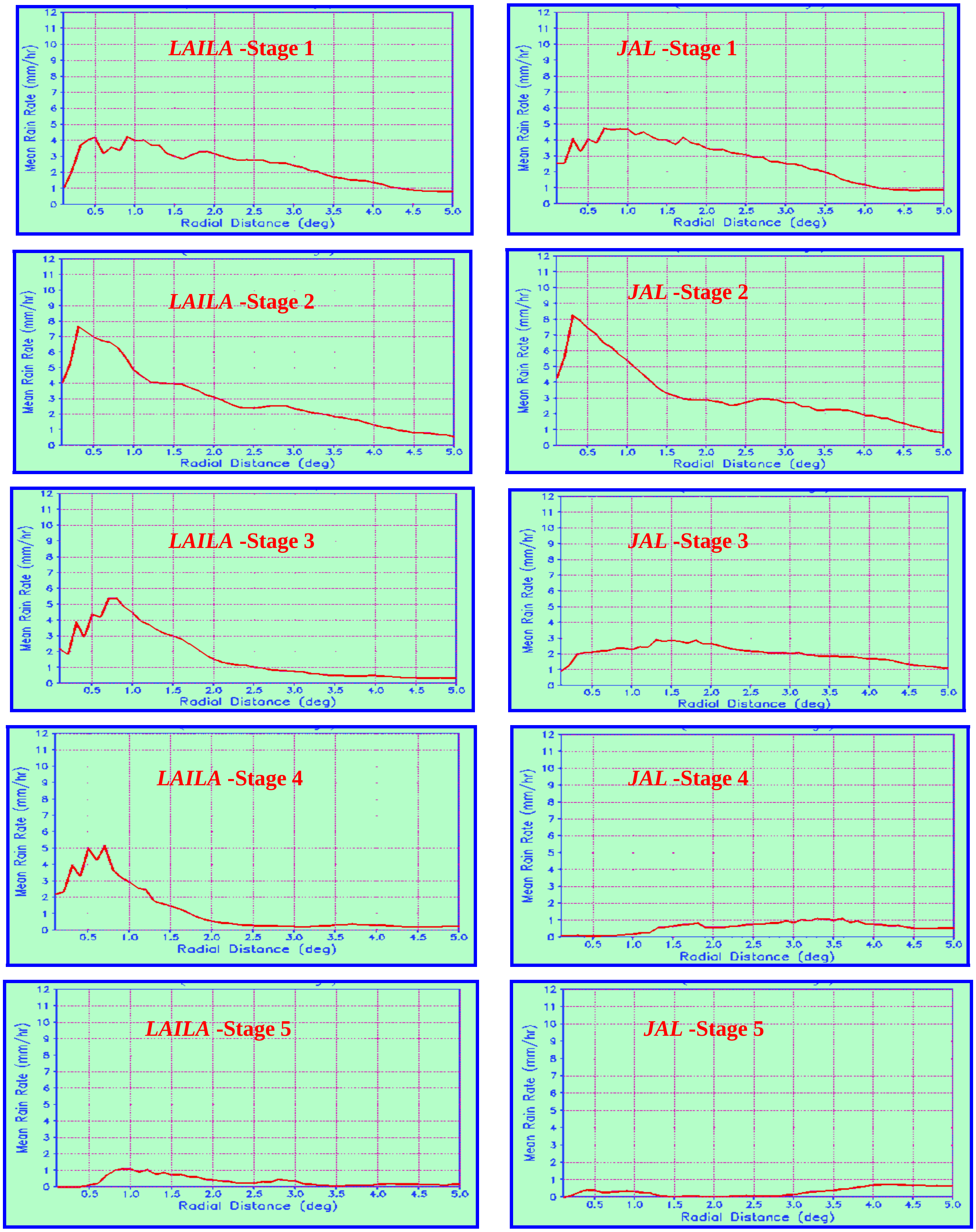

Fig. 4. Radial profile of mean rain rates within 500 km (0°-5° radial distance) from the TC centre for the various stages of intensification and weakening of SCS *LAILA* and SCS *JAL*

to 200 km from the TC centre (where higher rain rates than the outer region beyond 200 km are observed), are studied. This is done by considering all 0.1° (≈10 km) annuli up to 200 km from the TC centre for all instances of observation for each stage of intensification and weakening and averaging for each quadrant with respect

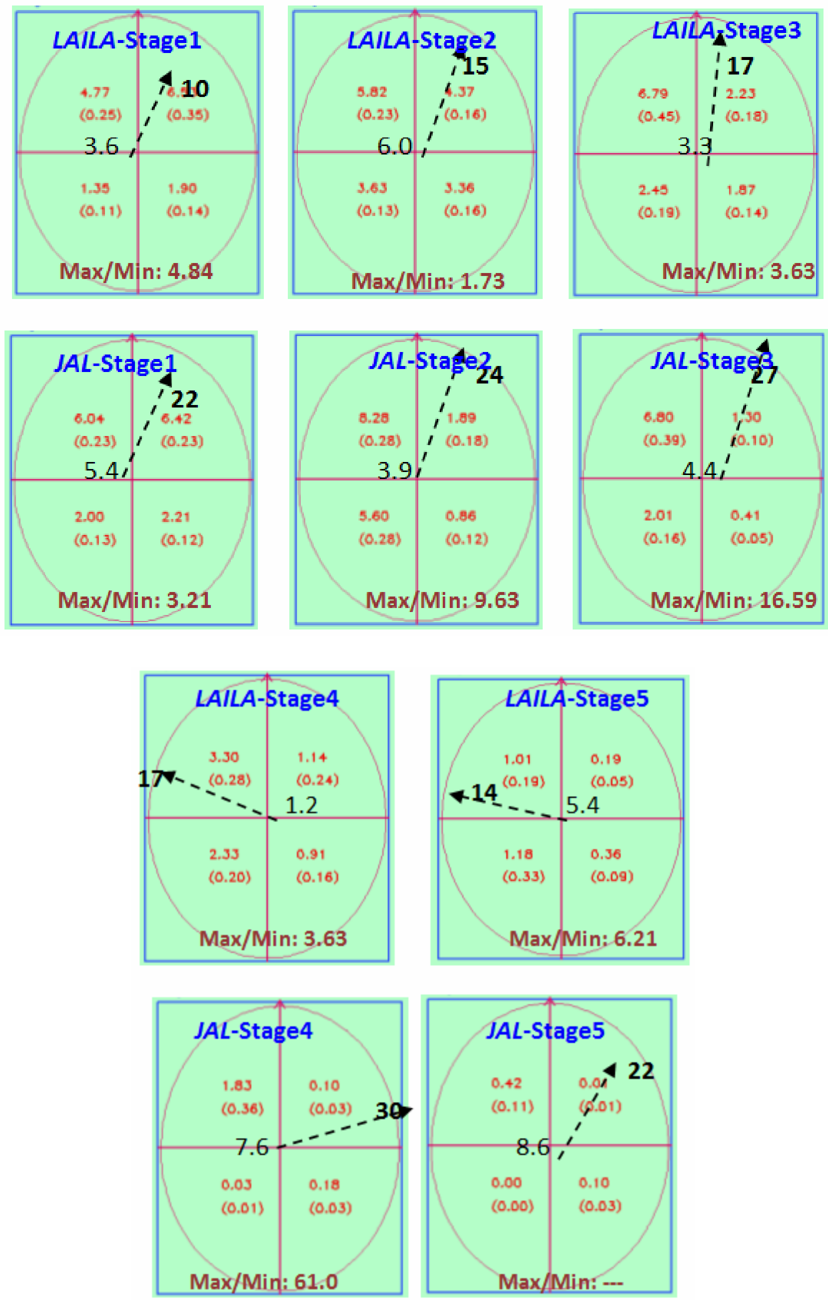

Fig. 5. Quadrant mean rain rate in mm/hr within 2 degree radial distance from the centre of the TC during different stages of SCS *LAILA* and SCS *JAL*. Figures in brackets indicate the standard deviation in mm/hr. TC motion is aligned with positive Y-direction (shown by arrow head at the top). TC translational speed (in m/s) is indicated in bold figure near the centre. 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

to the direction of motion of the TC at each instant. The quadrant mean rain rate and standard deviation for all the five stages of both the SCSs LAILA and JAL are shown in Fig. 5.

In the case of LAILA, the maximum and minimum rain rates during the first stage of intensification, stage 1, are in the front right quadrant and rear left quadrant respectively. However during intensification stages 2 and

TABLE 1

Difference in mean rain rates (in mm/hr) between front and back quadrants and that between left and right quadrants for various intensity stages of SCS LAILA and SCS JAL

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
			F-B		
LAILA	4.025	1.6	2.35	0.6	0.17
JAL	4.125	1.855	2.84	0.86	0.165
			L-R		
LAILA	1.155	0.86	2.57	1.79	0.82
JAL	0.42	0.11	0.21	0.055	0.155

F-B: front to back; L-R: left to right

3 as well as during the stage 4 (weakening), these maximum and minimum rain rates are shifted to front left and rear right quadrants respectively. During the last stage of weakening, stage 5, the maximum rain rate is shifted to rear left and minimum rain rate is shifted to front right quadrant.

In the case of JAL, the maximum rain rate is observed to shift from front right quadrant during the intensification stage 1 to the front left quadrant during the other two stages of intensification as well as during the two weakening stages. However, the minimum rain rate which shifted from rear left to rear right during the intensification stages shifts back to rear left during both the stages of weakening.

The above features are consistent with the earlier results shown by Singh *et al*. (2012) wherein an analysis based on 14 landfalling cyclones indicated that maximum rainfall is observed first in right forward quadrant and then in the left forward sector. Also, Raj *et al*. (2007) using Outgoing Longwave Radiation (OLR) data have shown the most intense clouding is found in the front / front left sector for severe cyclones of the BOB.

Highest rain rates of 7-8 mm/hr are observed during the growth of the TCs, stage 3 (2) in the case of LAILA (JAL). Also, during the intensification stages, the ratio of maximum to minimum rain rates is of the order of 2-5 mm/hr in the case LAILA but it is in the range 3-17 mm/hr in the case of JAL indicating much greater asymmetry in the rainfall distribution in the case of JAL. During the weakening stages, the rain rates are quite low but the asymmetry in the rainfall distribution is very large.

Difference in the mean rain rates between the front and the rear quadrants (within 200 km from the TC centre) as well as that between the left and right quadrants for both the SCSs LAILA and JAL for all the five stages are presented in Table 1. It may be noted that front to back asymmetry is greater than the left to right asymmetry except during the stages of 3-5 in the case of LAILA.

To understand the physical factors associated with asymmetric structure of rainfall distribution, we next examine the rainfall asymmetry in the context of environmental vertical wind shear (VWS) and TC translation speed as carried out by many earlier workers [(Chen *et al*. (2006), Corbosiero and Molinari (2003), Jinhua *et al*. (2010)].

3.4. *Role of vertical wind shear and translation speed in TC rainfall distribution*

The VWS vector is determined at 6-hrly intervals for the entire life period of the TC using 6-hrly NCEP reanalysis dataset (0000, 0600, 1200 and 1800 UTC). It is calculated as the difference between 200 hPa and 850 hPa wind averaged over a 4° square in a Lagrangian frame of reference centered at the TC centre and its direction is determined relative to the direction of motion of the TC. This 6-hrly VWS data is then classified as per the intensity stratification adopted for the study (stages 1 to 5) and the mean values of magnitude and direction (relative to the direction of motion of the TC) are determined for each stage of the TC. The storm relative VWS during various stages of intensification/weakening of the SCSs LAILA and JAL is indicated in the respective quadrant-wise mean rain rate plots in the form of dotted arrows (direction of the storm relative shear vector) and the magnitudes indicated near the end of the arrow-head (Fig. 5). The TC translational speeds corresponding to each intensity stage of these cyclones are also determined using the IMD's best track data and indicated in the same plots near the centre. Analysis of rain rate distribution relative to VWS indicates that, during intensification stages 2 & 3, the shear and storm motion vectors are in the same direction and a dominant down shear left asymmetry is observed which is consistent with results of earlier studies [Chen *et al*. (2006)]. But during first stage of intensification, down shear right asymmetry is observed in both the cases. During the stage 4 (weakening), while down shear right asymmetry is displayed in the case of JAL, up shear left asymmetry is displayed in case of LAILA. It may be noted that SCS JAL was mostly in strong environmental shear region (22-30 m/s) compared to SCS LAILA (10-17 m/s). Moreover the translational speed of JAL (4-9 m/s) (except during intensification stage 2) was significantly higher than that of LAILA (1-6 m/s). These factors also could have contributed to greater asymmetry in rainfall distribution in the case of JAL.

It is interesting to note that when SCS JAL entered into the weakening stages (stage 4), its translational speed

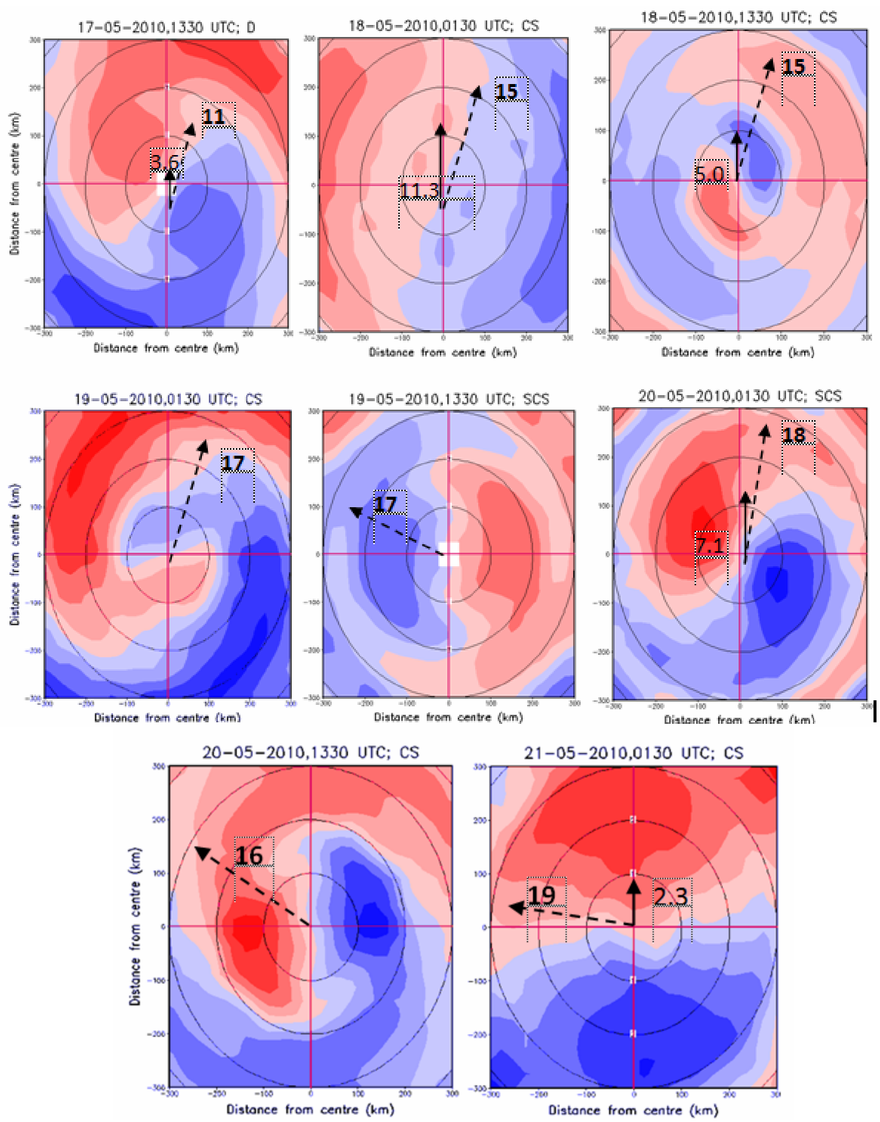

Fig. 6(a). Wave number–1 rainfall asymmetry normalied by the azimuthal mean (wave number - 0) in the case of SCS LAILA at 12 hourly intervals from 17/1330 UTC to 21/0130 UTC, May 2010. TC motion is aligned with positive Y-direction (shown by arrow head at the top). TC translational speed (m/s) is indicated 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

almost doubled (from 4.4 m/s to 7.6 m/s, Fig. 5), which, along with strong VWS of 30 m/s, might have caused the weakening when it was still over the sea (Fig. 1). Under the influence of strong VWS and greater translational speed, moisture could have been advected out resulting in very little rainfall in the vicinity of the TC centre but greater rainfall farther away (as mentioned in Section 2.1).

SCS LAILA, on the other hand, started weakening only after landfall and hence, when it entered the stage 4, it was under the influence of land and was changing its direction of movement and recurving. Its translational speed was very low at 1.2 m/s during this stage. It may be pointed out here that LAILA was a pre-monsoon cyclone which occurred during the peak summer month of May, and hence at the time of coastal crossing the land would have been warmer than the sea leading to warming of the low level air by the underlying warmer surface resulting in greater upward motion and convection. This, along with the slower movement of the TC could have been associated with greater rainfall associated with SCS LAILA during the stage 4.

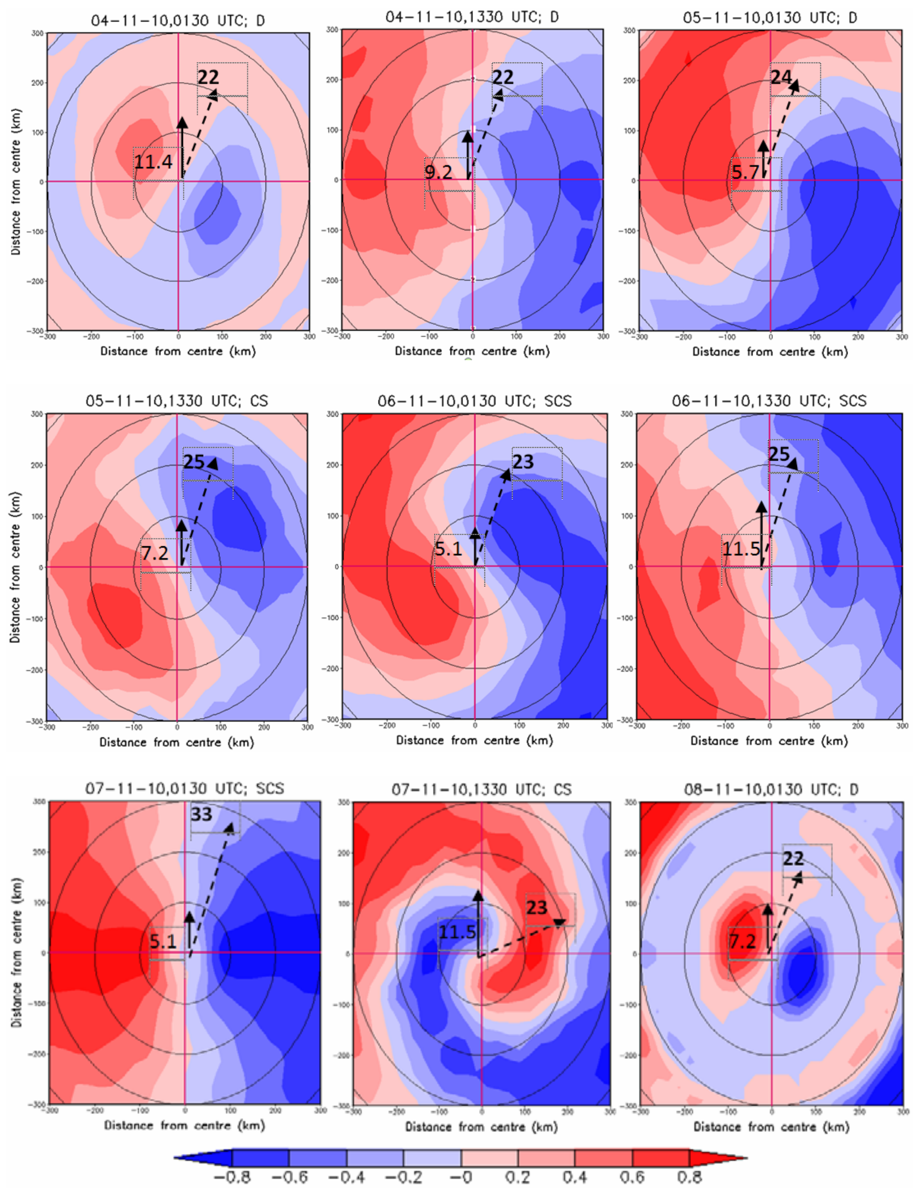

Fig. 6(b). Wave number–1 rainfall asymmetry normalised by the azimuthal mean (wave number-0) in the case of SCS JAL at 12 hourly intervals from 4/0130 UTC to 08/0130 UTC, November 2010. TC translational speed and storm relative vertical wind shear are indicated as in Fig. 6(a)

3.5. *Time evolution of spatial pattern of rainfall asymmetry*

In the earlier sections, composited rainfall distributions around SCS LAILA and SCS JAL were analysed by grouping of observations into five stages based on intensity stratification. In this section, time evolution of the first order asymmetry patterns corresponding to wave number-1 are analysed for instantaneous observations at 12 hourly intervals for the above TCs by following the methodology adapted by Lonfat *et al*. (2004).

Here, the asymmetry is defined relative to the direction of motion of the system at the respective time of observation. The mean rain rate is first computed for 10 km wide annuli around the TC centre as described earlier (Section 3.2). For each annulus, the first order

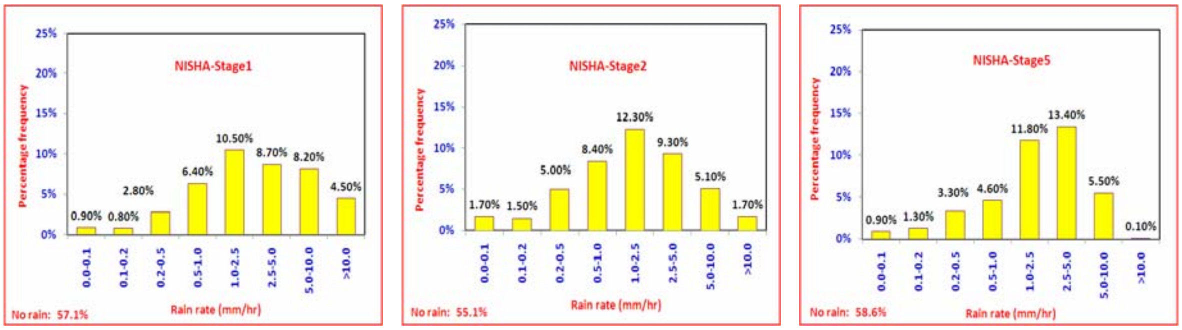

Fig. 7(a). Same as Fig.3 but for CS NISHA

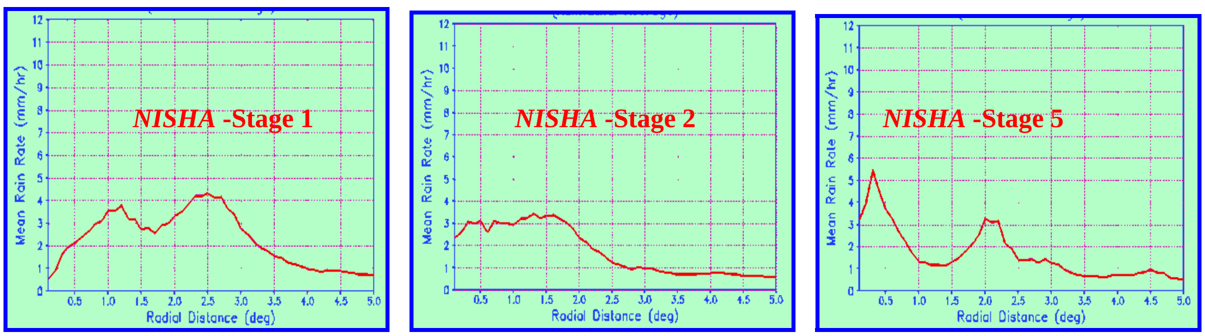

Fig. 7(b). Same as Fig.4 but for CS NISHA

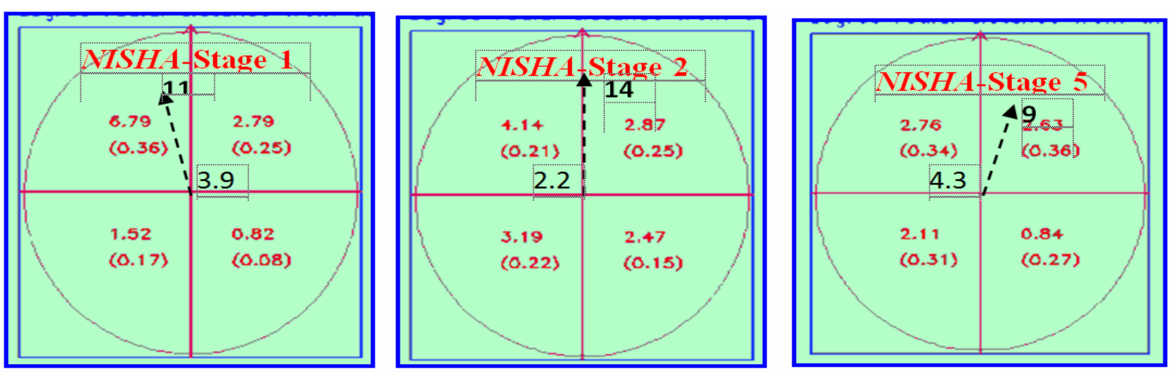

Fig. 7(c). Same as Fig. 5 but for CS NISHA

Fourier coefficients are computed using all individual rain rates as

$$a_i = \sum_i [R_i \cos\theta_i] \quad \text{and} \quad b_i = \sum_i [R_i \sin\theta_i]$$

where R_i represents individual rain rates and θ_i, the phase angle of the corresponding grid point relative to the direction of motion of the TC. The spatial structure of the first order asymmetry can then be represented by

$$M_1 = \frac{(a_1 \cos\theta + b_1 \sin\theta)}{R}$$

where R is the mean rain rate calculated over the entire annulus. M_1 is calculated for all data points within 3° radius at a specific instant of time. The asymmetry amplitudes are then normalised to the ambient mean rain rate of each annulus so that amplitude near unity implies that the wave number signal at that point is as strong as the axi-symmetric average. The asymmetric structures evolving at 12-hourly intervals are presented for each TC in Figs. 6(a&b).

It is observed that, by and large, the first order asymmetry amplitude increases from centre outwards. Also, during intensification stages from depression to severe cyclonic storm intensity, M_1 maximum shifts

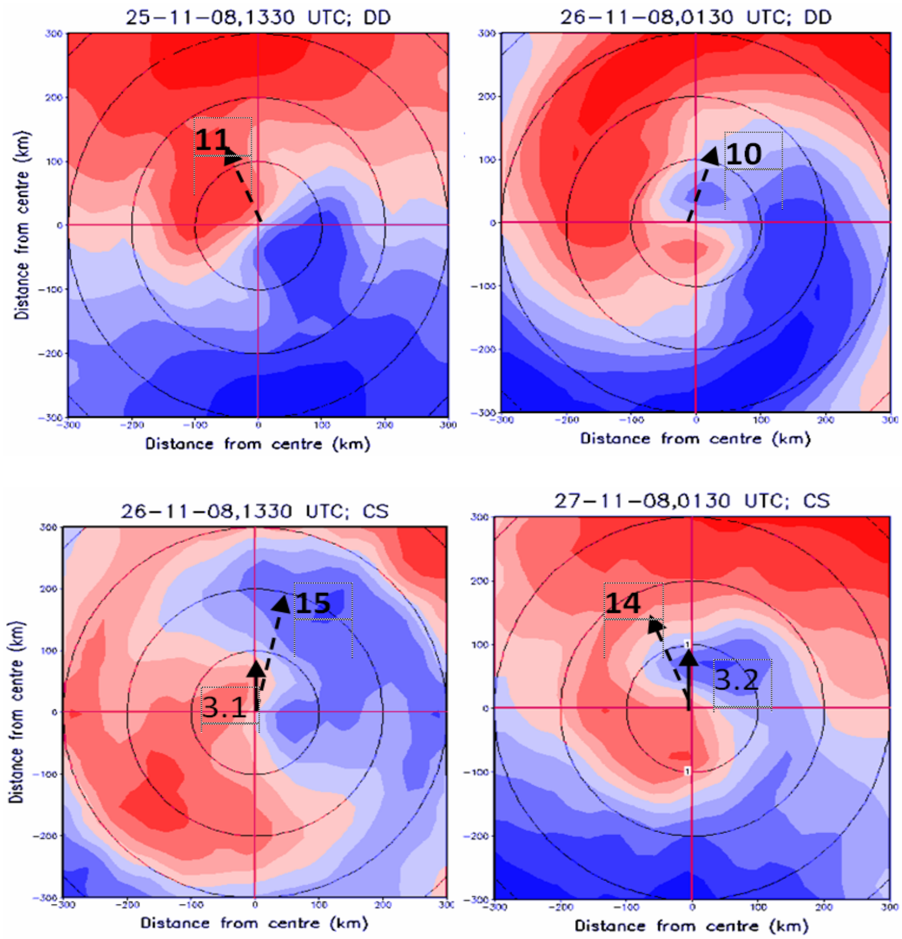

Fig. 7(d). Wave number–1 rainfall asymmetry normalised by the azimuthal mean (wave number-0) in the case of CS *NISHA* at 12 hourly intervals from 25/1330 UTC to 27/0130 UTC, November 2008. TC translational speed and storm relative vertical wind shear are indicted as in Fig. 6(a)

cyclonically while it shifts anti-cyclonically during weakening stages from severe cyclonic storm intensity to depression. These features are consistent with earlier studies for TCs over other oceanic basins [Marks (1985), Burpee and Black (1989)]. It may be noted that in the case of LAILA, which was in an environment of moderate VWS (11-19 m/s) and moving at a lower speed (less than 7 m/s), rainfall was more concentrated in the down shear left quadrant of the TC under the condition of VWS along the direction of motion of the TC [Fig. 6(a)]. But, in the case of JAL, which was in a strong shear environment (22-33 m/s) and was having greater translational speed (5-12 m/s), rainfall was somewhat evenly distributed in the both down shear and upshear quadrants under the condition of VWS along the direction of motion of the TC [Fig. 6(b)]. When the wind shear direction was oriented across and to the right of movement of JAL (07-11-2010, 1330 UTC; CS), asymmetry pattern in rainfall distribution was different in the outer region compared to the inner region. Rainfall was concentrated in down shear left quadrant in the region up to 200 km; however, it was concentrated in the up shear left quadrant beyond 200 km from the TC centre.

3.6. *Precipitation characteristics and asymmetry in rainfall associated with the CS NISHA*

In the earlier sections, rainfall characteristics and asymmetry in spatial rainfall distribution were analysed for two cyclones of NIO that attained severe cyclone intensity. In this section, the same type of analysis is carried for a cyclone that did not reach the stage of severe cyclone category, *viz*., CS NISHA (25-28 Nov, 2008, Fig. 1). The results obtained in this case are presented in Figs. 7(a-d). It may be noted from Fig. 1 that CS NISHA passed through three stages of intensity only, namely, the stages 1, 2 (D and CS during intensification) and 5 (D during weakening). It did not enter into stages 3 (SCS during intensification) and 4(CS during weakening). It has been under the influence of land throughout its life (Fig. 1).

As in the other two cases, the most frequent rain rate in the case of CS NISHA is 1-2.5 mm/hr; however, rain rates of 2.5-5 mm/hr are also highly frequent even during the weakening stage [Fig. 7(a)]. Another striking feature in the frequency distribution of rain rates is that the percentage of non-raining areas has been consistent at 55-58% throughout the life cycle of CS NISHA in contrast to the two SCSs LAILA and JAL where the percentage of non-raining areas progressively increased from stage1 to stage 5 (28-71% and 36-86% respectively). The radial profile of azimuthally averaged mean rain rates indicate 3-4 mm/hr (7-10 cm/day) rain between 50-200 km from the TC centre during the intensification stages [Fig. 7(b)]. However, during the stages 1 and 5 (depression), two peak values of rain rates (4-5 mm/hr) are observed at about 120 km and 250 km from the TC centre during intensification and 30 km and 200 km during weakening. Also, Fig. 7(c) indicates strong asymmetry in radial rainfall distribution up to 200 km from the TC centre with most of the rainfall concentrated in the front left quadrant of the TC during the intensification stages where the Cauvery delta region is located. Quadrant mean rain rate of 8mm/hr (19cm/day) is consistent with the actual rainfall of the order 25-33 cm/day realised in some locations of Cauvery delta region situated in that quadrant. The ratio of maximum to minimum quadrant rain rate during the first intensification stage is 8.3 which decreased drastically to 1.7 during the second intensification stage with the spreading of intense convection to other quadrants too.

It can be noted from Fig. 7(c), that NISHA was in a low shear environment (9-14 m/s) and was also slow moving (translational speed was less than 5 m/s). These factors, along with interaction with land, could have caused, along with other factors, exceptionally good rainfall.

Time evolution of asymmetry depicted in Fig. 7(d) indicates shifting of asymmetry maximum cyclonically up to 26/1330 UTC when the TC centre was in the sea. Thereafter, the system crossed coast on 27th between 0000 and 0100 UTC and entered into land. The rainfall asymmetric structure changes on 27/0130 UTC, especially beyond 150 km from the TC centre wherein high rainfall belt shifts from up shear left to down shear right which might have been associated with heavy to very heavy rainfall at many places over north Tamil Nadu and south Andhra Pradesh (Section 2.1).

4. Conclusions

Based on TRMM and NCEP data, the precipitation characteristics and asymmetry in spatial rainfall distribution in respect of three TCs, *viz*, SCS LAILA, SCS JAL and CS NISHA are examined in the frames of reference of two dominant dynamical settings, *viz*., environmental wind shear and TC translational speed. The main results of the present study are, *viz*:

(*i*) The most frequent rain rate is of the order of 1-2.5 mm/hr, followed by 2.5-5 mm/hr. Generally, higher frequencies of rain rate distribution are observed at higher (lower) rain rate side during intensification (weakening) stages except during weakening stages of JAL, when more frequent rain rates distribution is on the higher rain rate side only.

(*ii*) The percentage of non-raining areas increases progressively during the life cycle of the TCs and this would weigh heavily on the mean rain rates and also contribute significantly to greater asymmetry in the spatial rainfall distribution.

(*iii*) The radial profile of azimuthally averaged mean rain rates indicate that the peak rain rate of the order of 4 to 5 mm/hr occurs over a broad zone of 50 to 100 km during the intensification stages. During higher stages of intensification the peak rain rates increases to 7-8 mm/hr which occurs at about 40 km from the TC centre. As the TC enters into weakening stages, the radial rain rates decrease drastically and during the final stage of weakening, the rain rates are mostly very low at 1mm/hr or even less. As such, radial profiles of mean rain rates show marked difference between the intensification and weakening stages for the same intensity category.

(*iv*) Quadrant-wise mean rain rates indicate strong asymmetry in radial rainfall distribution with more rainfall concentrated in front left quadrant during the stages of intensification. During the weakening stages, the mean rain rates are quite low, but the asymmetry amplitude (ratio of maximum to minimum quadrant rain rate) is very high. Front to back asymmetry is greater than the left to right asymmetry.

(*v*) Analysis of rain rate distribution relative to environmental wind shear and TC movement indicates that, during intensification stages, wind shear and storm motion vectors are in the same direction and a dominant down shear left asymmetry is observed. Further, this down shear left asymmetry is noted to shift from down shear right asymmetry during the initial stages of intensification from the stage of depression to cyclonic storm.

(*vi*) Whereas, SCS LAILA was in moderate shear environment and moving at a low translational speed, SCS JAL was in an environment of strong vertical wind shear and was moving at a higher speed, which contributed to greater rainfall asymmetry in the case of JAL.

(*vii*) Time evolution of spatial rainfall asymmetry indicates that, by and large, asymmetry amplitude increases from the centre outwards. Further, a cyclonic (anti-cyclonic) shift of the asymmetry maximum during the intensification (weakening) stages is also observed.

(*viii*) The CS NISHA, which was under the influence of land throughout its life cycle and did not intensify into a severe cyclone, showed different rainfall characteristics when compared to the SCS LAILA and SCS JAL. Percentage of non-raining areas has been consistent throughout the life cycle of CS NISHA in contrast to the two SCSs where the percentage of non-raining areas progressively increased from stage1 to stage 5. The mean radial profile of rain rates for CS NISHA displayed dual peak values of 4-5 mm/hr at about 120 km and 250 km (30 km and 200 km) from the TC centre during stage 1 (stage 5). Further, strong asymmetry in radial rainfall distribution up to 200 km from the TC centre was observed with most of the rainfall concentrated in the front left quadrant of the TC during the intensification stages. NISHA was in a low shear environment (9-14 m/s) and was also slow moving (translational speed was less than 5 m/s), combination of which, along with the coastal influence resulted in good rainfall activity.

The above results are limited by interpolation of TC positions to TRMM observation time, grouping of observations into stages, limitations associated with statistical methods used for analysis as well as accuracy of TRMM data. Further extension of the present study with more TCs, including those over the Arabian Sea, by a comprehensive analysis involving factors such as the sea surface temperature, boundary layer convergence, beta effect etc. would help in generalisation as well as in bringing out deviations of TC rainfall patterns for the NIO basin under different physical and dynamical conditions. Such knowledge would help in development of QPF and validation of TC rainfall forecasts from numerical weather predication models.

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References

Boothalingam, P. N. and Srinivasan, V., 1950, India Met. Deptt., Sci. Notes, **XI**, 132.

Burpee, R. W. and Black, M. L., 1989, "Temporal and spatial variations of rainfall near the centres of two tropical cyclones", *Mon. Wea. Rev*., **117**, 2204-2218.

Chen, S. S., Knaff, J. A. and Marks, F. D. Jr., 2006, "Effects of vertical wind shear and storm motion on tropical cyclone rainfall asymmetries deduced from TRMM", *Mon. Wea. Rev*., **134**, 3190-3208.

Corbosiero, K. L. and Molinari, J., 2003, "The relationship between storm motion, vertical wind shear and convective asymmetries in tropical cyclones" *J. Atmos. Sci*., **60**, 366-376.

Durai, V. R., Bhowmik, S. K. R. and Mukhopadhyay, B., 2010, "Evaluation of Indian summer monsoon rainfall features using TRMM and KALPANA-1 satellite derived precipitation and rain gauge observation", *Mausam*, **61**, 3, 317-336.

Frank, W. M., 1977, "The structure and energetics of the tropical cyclone. Part-I: Storm structure" *Mon. Wea. Rev*., **105**, 1119-1135.

India Met. Deptt., 2003, "Cyclone Manual".

India Met. Deptt., 2009, "Cyclones and depressions over the north Indian Ocean during 2008", *Mausam*, **60**, 3, 267-288.

India Met. Deptt., 2011, "Cyclones and depressions over north Indian Ocean during 2010", *Mausam*, **62**, 3, 287-304.

Jayanthi, N. and Sen Sarma, A. K., 1987, "Rainfall associated with cyclonic disturbances from Indian seas during pre and post monsoon seasons" India Met. Deptt., PPSR No. 87/2.

Jinhua, Yu., Zhemin, Tan and Yuqing, Wang, 2010, "Effects of vertical wind shear on intensity and rainfall asymmetries of strong tropical storm Bilis (2006)", *Adv. Atm. Sci*., **27**, 3, 552-561.

Lonfat, M., Marks, F. D. Jr. and Chen, S. S., 2004, "Precipitation distribution in tropical cyclones using the Tropical Rainfall Measuring Mission (TRMM) microwave imager: A global perspective", *Mon. Wea. Rev*., **132**, 1645-1660.

Marks, F. D. Jr., 1985, "Evolution of the structure of precipitation in Hurricane Allen (1980)", *Mon. Wea. Rev*., **113**, 909-930.

Raghavan, S. and Varadarajan, V. M., 1981, "Radar estimate of rainfall and latent heat release in tropical cyclones of the Bay of Bengal", *Mausam*, **32**, 3, 247-252.

Raj, Y. E. A., Muthuchami, A. and Ramanathan, RM. A. N., 2007, "Asymmetric structure of a severe cyclonic storm of North Indian Ocean as derived through INSAT OLR data", *Mausam*, **58**, 4, 481-500.

Rodgers, E. B. and Adler, R. F., 1981, "Tropical cyclone rainfall characteristics as determined from a satellite passive microwave radiometer", *Mon. Wea. Rev*., **109**, 506-521.

Rogers, R., Chen, S., Tenerelli, J. and Willoughby, H., 2003, "A numerical study of the impact of vertical shear on the distribution of rainfall in Hurricane Bonnie (1998)", *Mon. Wea. Rev.*, **131**, 1577-1599.

Singh, C., Das, S., Verma, R. B., Verma, B. L. and Bandyopadhyay, B. K., 2012, "Rainfall estimation of landfalling tropical cyclones over Indian coasts through satellite imagery", *Mausam*, **63**, 2, 193-202.

Srivastava, T. P., 2011, "Rainfall climatology over India using TRMM 3B42 V6 and GPCP V2.2" , *Vatavaran*, **35**, 2, 14-32.