MAUSAM, **63**, 2 (April 2012), 193-202

551.501.777 : 551.515.2

Rainfall estimation of landfalling tropical cyclones over Indian coasts through satellite imagery

CHARAN SINGH, SUNIT DAS*, R. B.VERMA, B. L. VERMA and B. K. BANDYOPADHYAY

India Meteorological Department, New Delhi – 110 003, India

**Regional Meteorological Centre, Guwahati, India*

(*Received 19 November 2009, Modified 27 January 2011*)

e mail : csingh1964@gmail.com

सार – उष्णकटिबंधीय चक्रवातों के तट से टकराने का सबसे महत्वपूर्ण प्रभाव यह होता है कि इससे बहुत अधिक वर्षा होती है। इस शोध पत्र का मुख्य उद्देश्य प्रचालनात्मक पूर्वानुमानकर्ताओं को इन चक्रवातों के तट से टकराने के बाद प्रभावित क्षेत्रों में होने वाली वर्षा की संभावनाओं को दर्शानें के लिए कुछ मार्ग–दर्शन देना है। चक्रवातों के तट से टकराने वाले पिछले 14 चक्रवातों के अध्ययन से यह पता चला है कि उष्णकटिबंधीय चक्रवात की गति के प्रथम वृत्तपाद में अधिकतम वर्षा हुई है, उसके द्वितीय वृत्तपाद में वर्षा हुई है और चक्रवातों के मार्ग के नजदीकी क्षेत्रों में वर्षा हुई है। प्रत्येक चक्रवातों के लिए 24 घंटों में हुई वर्षा का समवर्षा विश्लेषण करने से पता चला है कि तूफान केन्द्र से 150 कि. मी. की त्रिज्या में ही सामान्यतः भारी वर्षा होती है और करीब 300 कि. मी. तक वर्षा होती है तथा वर्षा की मात्रा धीरे–धीरे कम होती जाती है। वर्षा होने वाले क्षेत्र अक्सर संवहनीय मेघों से आच्छादित रहते है और इस सिस्टम के स्थल प्रवेश के पूर्व और बाद में बादल शीर्ष के तापमान -80 से -60 डिग्री सेल्सियस तक होते हैं। अध्ययन किए गए 14 घटनाओं में से 93 प्रतिशत उष्णकटिबंधीय चक्रवात है, इसमें से 70 प्रतिशत का संवहन मार्ग के दाएँ तरफ हुआ है। संवहन वितरण में विषमता के कारण हुई वर्षा की विषमता की जाँच करने के लिए उपग्रह अवरक्त चित्र आँकड़ों से मेघ शीर्ष के तापमान प्राप्त किए गए है जिसे प्रौक्सी ऑफ स्ट्राँग कनवेक्शन के रूप में लिया गया है। इस अध्ययन से यह पता भी पता चला है कि तीव्र गति से बढ़ने वाले उष्णकटिबंधीय चक्रवातों की तुलना में धीमी गति से बढ़ने वाले उष्णकटिबंधीय चक्रवातों से भारी वर्षा होती है। बंगाल की खाड़ी में निर्मित चक्रवात जो समुद्र तट को चक्रवाती तूफान तथा प्रचंड चक्रवाती तूफान के रूप में पार किए उनसे 0–10 से. मी. तक की सीमा में 71.4 प्रतिशत वर्षा, 11–20 से. मी. की सीमा में 22.8 प्रतिशत वर्षा और 21–30 से. मी. की सीमा में 4.3 प्रतिशत वर्षा चक्रवाती तूफानों के केन्द्र से 300 कि. मी. की त्रिज्या वाले क्षेत्रों में हुई। अरब सागर में निर्मित उष्णकटिबंधीय चक्रवातों से सामान्यतः 24 घंटों में 16–25 से. मी. की सीमा में लगभग 70 प्रतिशत वर्षा हुई है।

ABSTRACT. One of the most significant impacts of landfalling tropical cyclones is caused by the copious rainfall associated with it. The main emphasis of present study is to provide some guidance to the operational forecasters for indicating the possible rainfall over the areas likely to be affected by the cyclones after landfall. Study of 14 past landfalling cyclones reveals that the maximum rainfall occurred in the first forward quadrant of tropical cyclone movement, followed by the second quadrant and the areas near the track of the cyclones. Isohyetal analysis of 24 hours rainfall for each cyclone reveals that occurrence of heavy rainfall is generally confined up to 150 kms radius from the storm centre and rainfall is found to generally extend up to 300 kms with gradual decrease in amount. The rainfall receiving areas are mostly covered with convective clouds with cloud top temperatures of -80 to -60 ºC, prior to and after the landfall of the systems. In 93% of tropical cyclones out of the 14 cases studied, 70 % convection lay to the right of the track. To examine the rainfall asymmetry due to asymmetry in distribution of convection, cloud top temperatures derived from satellite infrared imagery data have been taken as the proxy of strong convection. It is also revealed in the study that the slow moving tropical cyclones cause heavy rain rather than fast moving tropical cyclones. The Bay of Bengal cyclones which crossed coast as cyclonic storm and very severe cyclonic storm caused 71.4% rainfall within the range 0-10 cm, 22.8% rainfall in the range 11-20 cm and 4.3% rainfall within the range 21-30 cm in the area of radius of 300 kms from the centre of the cyclonic storms. For the Arabian Sea tropical cyclones, in general, about 70% rainfall occurred within the range 16-25 cm in 24 hours.

Key words – Convection, Cloud top temperature, Land falling tropical cyclone, Rainfall asymmetry, Sectors.

1. Introduction

Indicating the likely rainfall after landfall of tropical cyclones is most vital for real-time weather forecasters to provide useful guidance to the agencies that are engaged in taking safety measures or rehabilitation works. Apart from forecasting of tracks, intensity and storm surges, the likely rainfall expected is also an important component of

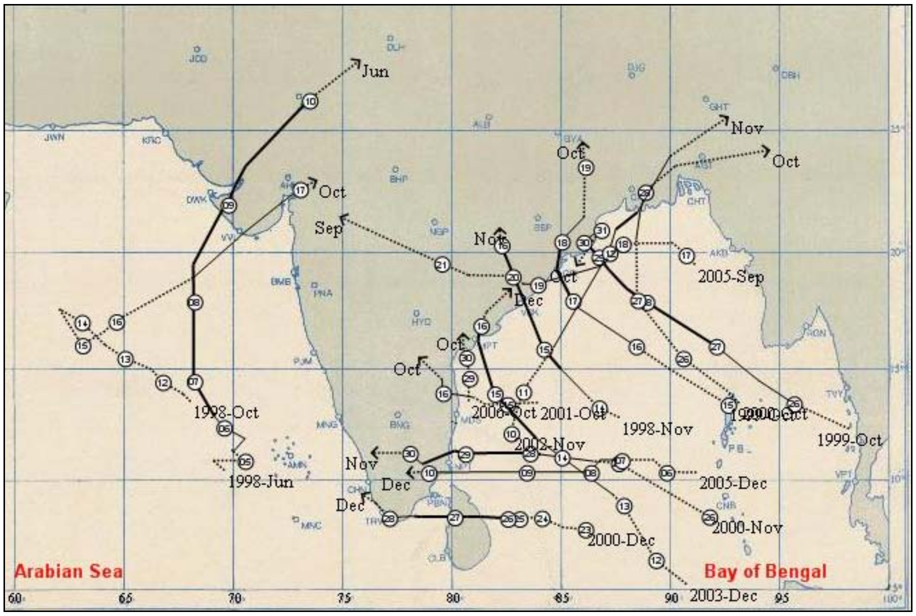

Fig. 1. Tracks of all 14 land falling cyclonic storms over east and west coasts of India during 1998-2008

tropical cyclone (TC) forecasting/warning. The expected rainfall distribution is one of the most important issues for TC landfall area. The impacts due to extreme weather caused by the cyclone are closely related with the rainfall, winds and storm surge associated with land falling tropical cyclones. While storm surge associated with TC is one of the major causes of damage and destruction, whenever rainfall merges with storm surges and coincide with high tide it becomes more dangerous. Obtaining accurate rainfall estimation for land falling TC is of great significance for the disaster management agencies to enable taking appropriate precautionary measures.

While over the years there have been significant improvements in TC track predictions, (Aberson, 2001; Franklin, *et. al*., 2003) and intensity forecasting to a certain extent (DeMaria and Gross 2003; DeMaria *et al*., 2005), less attention has been paid towards the improvement of rainfall forecasting associated with tropical cyclones.

Precise rainfall prediction associated with land falling TC is an operational challenge. The distribution of rainfall associated with land falling TC significantly depends on season, basin, convection patterns, movement of tropical cyclone and other environmental factors. The heaviest rainfall occurs in a narrow band close to the track of the cyclone (Lonfat *et al*., 2004), whereas the transitional speed of the cyclone plays an important role in determining the distribution of rainfall (Shapiro 1983). The vertical wind shear is also a determining factor for the spatial distribution of rainfall (Frank and Ritchie 2001; Corbosiero and Molinari 2002; Rogers *et al*., 2003). Topographic features such as coastal boundaries and mountains also determine the distribution of rainfall associated with land falling TC (Wu *et al*., 2002). In addition, intensity of the cyclone, the moisture supply and the properties of the underlying surface have significant effect on the rainfall distribution for land falling TC (Ying *et al*., 2005). The moisture supply is not only helpful in sustaining the land falling tropical cyclones; it is also the essential condition for causing torrential rain. A regression relation between cloud top temperature (CTT) and radar derived rain rate has also been established by (Gilberto *et al*., 1998). The relation with rain rate and cloud top temperature is Rain rate = 1.118×10^{11}. exp $(-3.6382 \times 10^{-2} \times T^{1.2})$, where rain rate is in mm/hour, and T is the CTT in degree K.

Past studies show that most of the TCs over North Indian Ocean (NIO) gain intensity of a tropical cyclone or more 24-36 hours prior to their landfall (Singh and Bandyopadhyay, 2004). Thus, 24 hours forecast of expected rainfall is of vital importance for TCs warning and forecasting over north Indian Ocean.

The objective of the present study is to generate some useful guidance for operational forecasters by finding out the spatial distribution of rainfall and amounts of rainfall due to asymmetries in convection and movement during next 24 hours in cases of past 14 land falling TCs. In addition, study also looks into the possibility of predictions of extreme rainfall associated with land falling TCs. Present criteria of defining the

TABLE 1

Date of cyclone, intensity of cyclone, basin of occurrence (BOB or ARB) of the cyclone, rainfall ranges, sector wise, within 150 kms and 300 kms radius, CTT and area of maximum convection

S. No.	Date & Year	Intensity	Basin	Observed Rainfall (cm)								Cloud top temperature	Sector of maximum convection
				150 km radius				300 km radius					
				I_i	II_i	III_i	IV_i	I_o	II_o	III_o	IV_o		
1	25-27 Nov 2008	CS	BOB	16-20	11-15	6-10	-	16-20	11-15	0-5	-	-60°C to -50°C	Left of the track 65%
2	25-27 Oct 2008	CS	BOB	-	6-10	11-15	-	-	6-10	0-5	-	-80°C to -70°C	Right of the track 60%
3	11-16 Nov 2007	VSCS	BOB	6-10	6-10	-	-	11-15	6-15	-	-	-70°C to -60°C	Right of the track 60%
4	29-30 Oct 2006	CS	BOB	26-30	6-15	-	-	6-10	0-5	0-5	-	-40°C to -20°C	Right of the track 60%
5	17-21 Sep 2005	SCS	BOB	16-20	11-15	6-10	-	6-10	6-10	0-5	-	-80°C to -40°C	Right of the track 70%
6	05-10 May 2004	SCS	ARB	0-5	0-5	16-20	-	0-5	6-10	-	-	-90°C to -40°C	Right of the track 70%
7	11-16 Dec 2003	SCS	BOB	0-5	-	0-5	-	0-5	-	0-5	-	-70°C to -40°C	Right of the track 70%
8	10-12 Nov 2002	SCS	BOB	11-15	-	6-10	6-10	6-10	-	0-5	0-5	-70°C to -40°C	Right of the track 70%
9	14-17 Oct 2001	CS	BOB	21-25	-	-	11-15	0-5	0-5	-	6-10	-90°C to -40°C	Right of the track 70%
10	26-30 Nov 2000	VSCS	BOB	0-5	-	-	6-10	6-10	6-10	-	0-5	-80°C to -40°C	Right of the track 70%
11	16-22 May 1999	VSCS	ARB	36-40	0-5	-	0-5	6-10	0-5	-	0-5	-80°C to -40°C	Right of the track 70%
12	15-19 Oct 1999	VSCS	BOB	26-30	-	0-5	16-20	11-15	-	0-5	6-10	-80°C to -40°C	Right of the track 70%
13	04-10 Jun 1998	VSCS	ARB	5-10	6-10	-	6-10	11-15	6-10	-	11-15	-80°C to -40°C	Right of the track 70%
14	13-16 Nov 1998	VSCS	BOB	5-10	-	-	6-10	6-10	-	-	0-5	-80°C to -40°C	Right of the track 70%

categories of rainfall is if the 24 hours rainfall is between 64.5-124.4 mm it is categorized as heavy, 124.5-244.4 mm as very heavy and >244.5 mm as extremely heavy. When the amounts is a value near about the highest recorded rainfall at or near the station for the month or season known as exceptionally heavy rainfall. However, the term exceptionally heavy rainfall will be used only when the actual rainfall amount exceeds 120 mm. These items are discussed in detail under Paras 3.1 to 3.3.

2. Data and methodology

In the present study, 14 cases of land falling TCs of intensity cyclone and above, which formed over the Bay of Bengal & the Arabian Sea during the period 1998-2008 have been considered. The rainfall data for 24 hours recorded at 0830 hours IST of next day of TC landfall on the coast is utilized. These data have been taken from Weekly Weather Reports (WWR) of India Meteorological Department (IMD) and from concerned Area Cyclone Warning Centres (ACWC)/Cyclone Warning Centres (CWC) of IMD. The tracks of these cyclones and other synoptic features used in the study are based on the Annual Reports of the Regional Specialised Meteorological Centre (RSMC) - Tropical Cyclone, New Delhi. The tracks of the 14 cyclones are given in Fig. 1. To calculate the speed of movement of TCs prior to landfall, 3 hourly positions were taken from RSMC-New

TABLE 2

Frequency of occurrence of rainfall in different ranges *i.e.*, 0-10, 5-15, 10-20, 15-25, 20-30 etc. within 150 kms radius and between radius 150-300 kms

150 km radius	0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	>41	Total Sectors	% of sector wise rainfall
I_i	3	2	1	2	1	2	-	1	-	12	35.3
II_i	2	3	3	-	-	-	-	-	-	8	23.5
III_i	2	3	1	1	-	-	-	-	-	7	20.6
IV_i	1	4	1	1	-	-	-	-	-	7	20.6
150-300 km radius											
I_o	3	6	3	1	-	-	-	-	-	13	36.1
II_o	3	5	1	-	-	-	-	-	-	9	25.0
III_o	7	-	-	-	-	-	-	-	-	7	19.4
IV_o	4	2	1	-	-	-	-	-	-	7	19.4
Total	25	25	11	5	1	2		1		70	100
% of category wise rainfall	35.7	35.7	15.7	7.1	1.4	2.9	00	1.4	00		

Note : Sector wise rainfall %, $I_{(i+o)}$ =35.7%, $II_{(i+o)}$ =24.3%, $III_{(i+o)}$ =20.0%, $IV_{(i+o)}$ =20.0%

Delhi. Satellite imageries along with isotherms and CTT data are taken from the Satellite Division of IMD for the day when the system made a landfall over the coasts. In these satellite imageries the areas of maximum convection are considered according to CTT, *i.e*., -80° C or less and -80° C to -40° C which shows the intense to very intense convection. Full details of observed rainfall range in different sectors, their CTTs and area of maximum convection are shown in Table 1 for all 14 cyclones. While preparing this table the rainfall data has been taken into consideration in four forward and rearward sectors located within radii of 150 and 300 kms from the centre of tropical cyclones.

Tropical cyclones over NIO basin are generally smaller in size in comparison to the similar systems over other basins. 300 kms distance from the centre is believed to be adequate to cover majority of the rainfall associated with TCs. Table 2 has been prepared considering the rainfall amount and sectors of radius 150 and 300 kms and it shows the intensity and distribution of the rainfall category in individual sectors for each cyclone. This table also used in preparing the ranges, *i.e*., 0-10, 11-20, 21-30 and 31-40 and greater than 41cms. The sectors are decided on the basis of the direction of movement of TCs and the landfall point. The I^{st} quadrant is right forward sector (I_i for 150 kms and I_o 300 kms radius respectively), II^{nd}, III^{rd} & IV^{th} quadrants are located in anticlockwise direction from I^{st} quadrants as shown in Fig. 2. Figs. 3 (a), 4(a), 5(a) and 6(a) show the track of the cyclones and the isohyetal analyses for the full period. Maximum area of convective cloud along with the isotherms are shown in

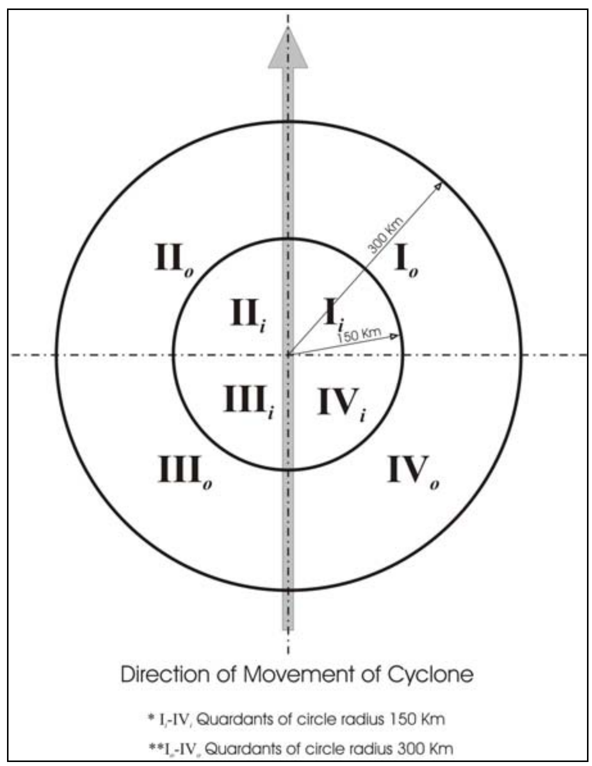

Fig. 2. Direction of movement of cyclonic storms, sectors within 150 kms and 300 kms are (I_i, II_i, III_i & IV_i) and (I_o, II_o, III_o & IV_o) respectively

Figs. 3(b-c), 4(b-c), 5(b-c) and 6(b-c) for a few selected dates and times. Fig. 7 shows maximum rainfall (cms) in 24 hours *versus* speed of 9 land falling cyclones over east and west coasts of India during 1998-2005.

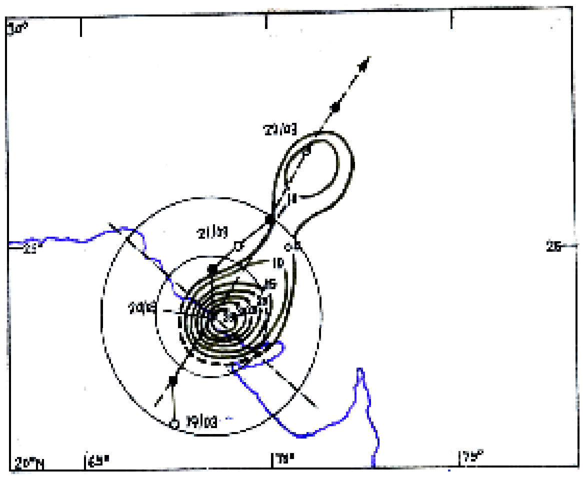

Fig. 3(a). Track of VSCS over Arabian Sea during 16-22 May 1999 and Isohyetal analysis

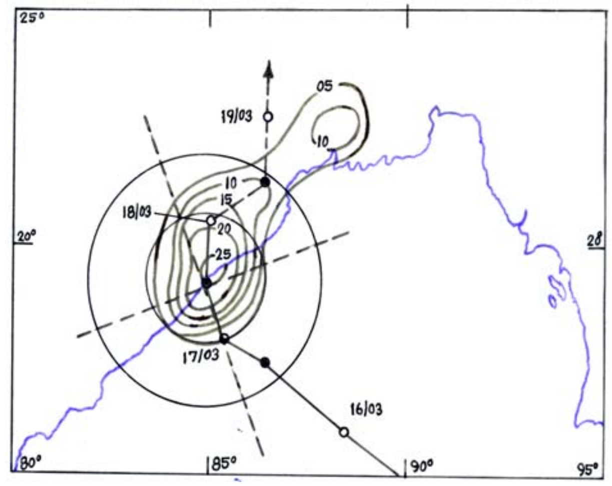

Fig. 4(a). Track of VSCS over Bay of Bengal during 15-19 October1999 and Isohyetal analysis

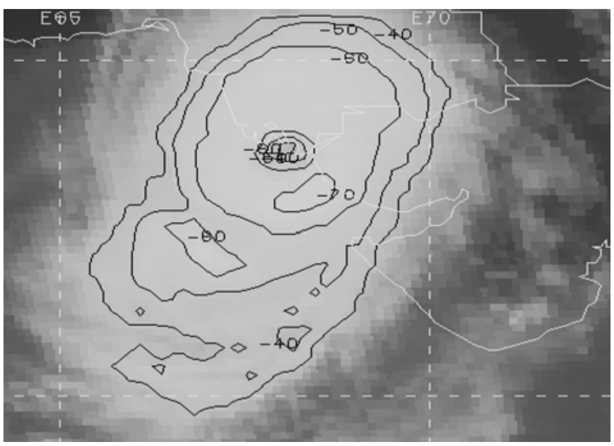

Fig. 3(b). Convective cloud along with Isotherm at 0600 UTC on 20 May, 1999

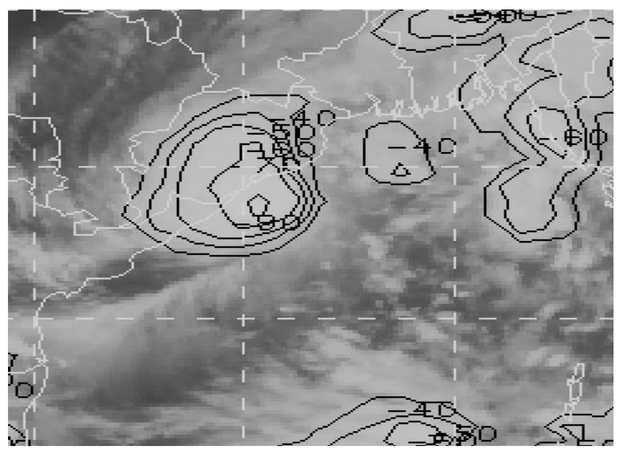

Fig. 4(b). Convective cloud along with Isotherm at 1500 UTC on 17 October, 1999

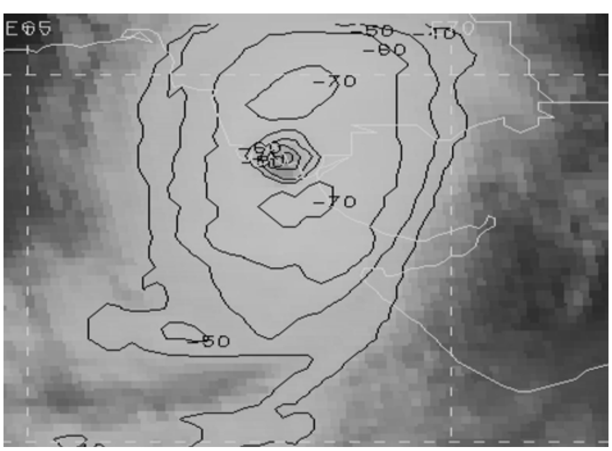

Fig. 3(c). Convective cloud along with Isotherm at 0900 UTC on 20 May, 1999

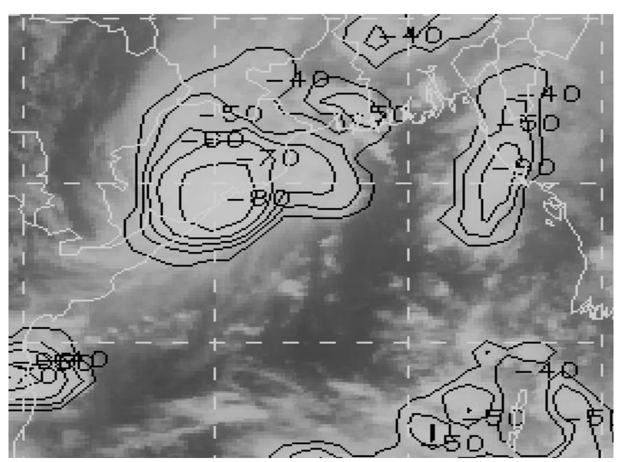

Fig. 4(c). Convective cloud along with Isotherm at 2100 UTC on 17 October, 1999

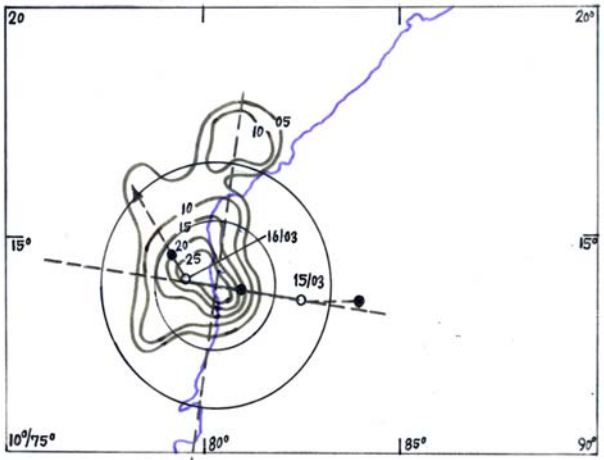

Fig. 5(a). Track of CS over Bay of Bengal during 14-17 October 2001 and Isohyetal analysis

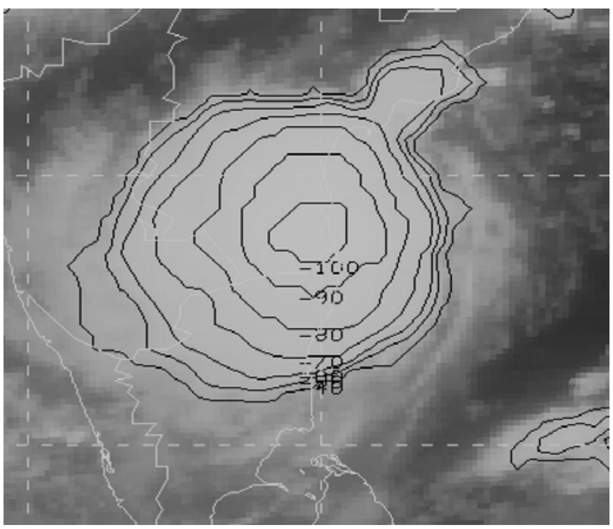

Fig. 5(b). Convective cloud along with Isotherm at 2100 UTC on 15 October, 2001

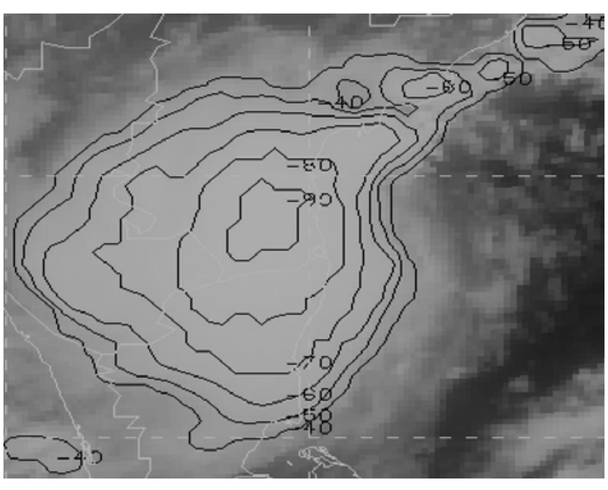

Fig. 5(c). Convective cloud along with Isotherm at 0000 UTC on 16 October, 2001

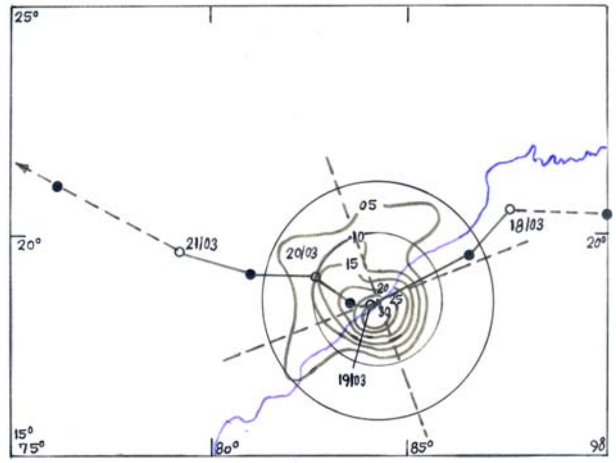

Fig. 6(a). Track of CS over Bay of Bengal during 17-22 September 2005 and Isohyetal analysis

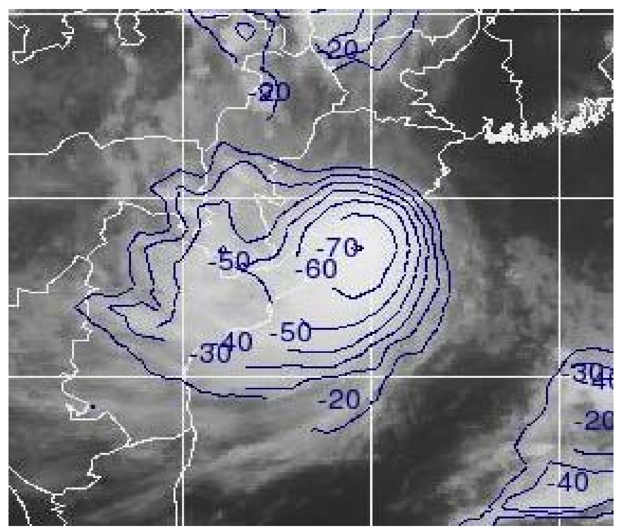

Fig. 6(b). Convective cloud along with Isotherm at 1500 UTC on 18 September, 2005

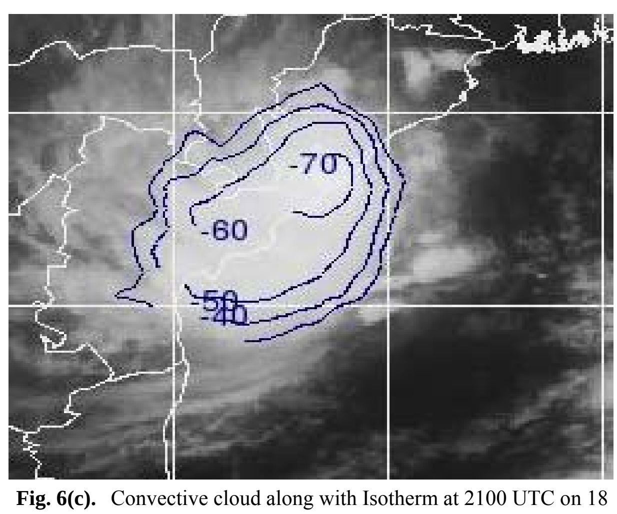

Fig. 6(c). Convective cloud along with Isotherm at 2100 UTC on 18 September, 2005

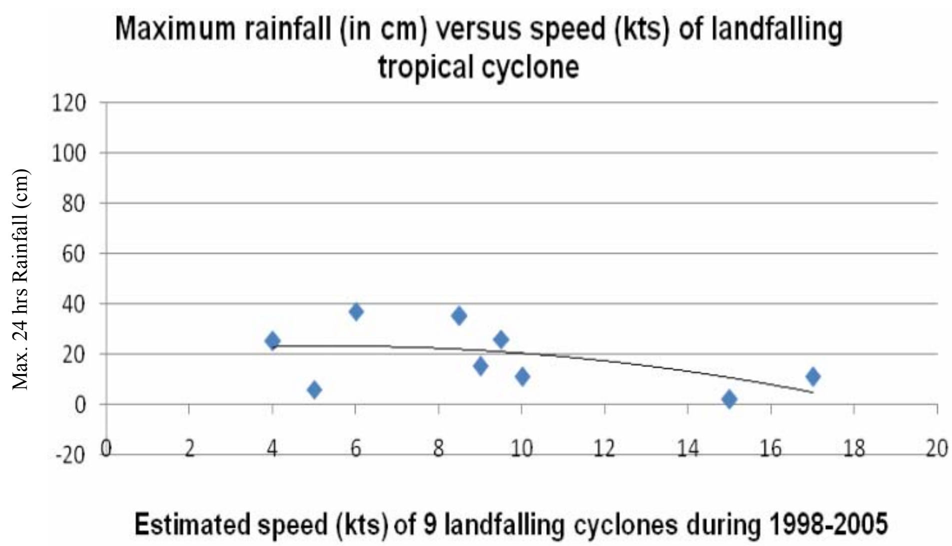

Fig. 7. Maximum rainfall (in cm) recorded in 24 hours *versus* speed (kts) of 9 landfalling tropical cyclones over east and west coasts of India during 1998-2005

3. Result and discussions

3.1. *Asymmetries in rainfall distribution*

Table 2 reveals that the observed rainfall distribution mainly exhibits two distinct patterns. In the area from 00-150 kms radius from the TCs centre, rainfall intensity is more on first right forward quadrant followed by second quadrant and on some occasions rainfall in the range 21-40 cm is also observed within these quadrants. Same feature is also observed for the outer radius from 150-300 kms, but the amounts of rainfall are less. In this case rainfall in the range 11-15 cm is observed in both first and second quadrants with respect to the track of the TC, *i.e*., occurrence of rainfall is more in first and second quadrants with gradual decrease in amount from the inner core to the outer core. Isohyetal analysis suggests that the occurrence of high rainfall is confined mainly within 150 kms radius from centre on both sides of the track with maximum amount and intensity distributed towards the right of the track.

On the west coast, systems mostly cross from the southwest or west-southwesterly direction and cause major rainfall in the right and forward sector of the track, with area of rainfall generally limited upto 150-200 kms radius from the centre of landfall point on both sides. The 24 hours rainfall ranges between 16-25 cm and maximum convective clouds area lay to the right of the track. In all three land falling cyclones over west coast, maximum CTT area also lay to the right of the track.

On the east coast, systems generally cross the coast from southeasterly or east-southeasterly direction causing fairly widespread heavy to very heavy rainfall to the right of the track that extends 150-200 kms from the centre. It occasionally extends beyond 200 kms. The 24 hours maximum rainfall has been recorded within the radius of 300 km with ranges between 0-10 cm over the quadrants I^{st}, II^{nd}, III^{rd} and IV^{th} respectively, 11-20 cm over the quadrants I^{st}, II^{nd}, IV^{th} and III^{rd} respectively. Rainfall in the range of 21-30 cm has been recorded only over the I^{st} quadrant within the radius of 150 km only. Sometimes rainfall has been recorded up to 50 cm depending upon the characteristics of TCs. In 2005 a cyclone crossed Orissa coast from northeast direction which caused heavy to very heavy rainfall to the left of track; ranging between 11-25 cm in 150 kms radius from the landfall point of cyclone. Detail of rainfall sectors and ranges are shown in the foot note of Table 2. It is seen that 35.7% rainfall occurred in I^{st} quadrant ($I_i + I_o$) and 24.3% in II^{nd} quadrant ($II_i + II_o$) followed by 20% each in III^{rd} ($III_i + III_o$) and IV^{th} ($IV_i + IV_o$) quadrants within the area covered by 300 kms radius.

3.2. *Distribution of convection zone*

In tropical cyclones, maximum rainfall occurred in the area of maximum convection zone (Corbosiero and Molinari, 2002). According to (Raghavan, 1990) the maximum low level convergence appears to occur in the right sector, which contributes to this maximum in the right rear sector and the formation of convective ‘streamer’ bands in the rear. This represents an area of high rainfall. To assess the strength of convection, CTT from infra-red satellite imagery is used as the proxy. Colder cloud top temperature of convective clouds suggests that the vertical extent of the cloud is more.

Therefore, CTT is used as a measure of convection strength. Isotherm analysis of CTT reveals that for most of the cases, convection generally tends to be enhanced over the region to the right of the track. About 70% convection is to the right of track, which is well in agreement with the distribution of rainfall. In most of the cases, intense to very intense convection is observed in the inner core of the TCs just prior to landfall, at the time of landfall and soon after landfall. The asymmetries in convection are due to unequal wind shear in vertical levels (Corbosiero and Molinari, 2002). In most of the cases the vertical wind shear prior to landfall is lower on the right of the systems track except in one case where, for the TC over Arabian Sea (5-10 May 2004), the stronger convection is observed towards the left of the track.

3.3. *Rainfall in relation with the speed of the storm*

The precipitation forecasts associated with land falling TC, in practice, are based on the simple algorithm known as Kraft's rule of thumb (Pfost, 2000), where the heaviest rainfall (inches) in 24 hours over a given location is C/*v*, where C is a constant (generally taken as 100) and *v* (in knots) is the transitional speed of the TC. This algorithm, however, provides little insight in to the precipitation distribution and intensity that can be expected in land falling TCs. To investigate the heaviest rainfall reported in association with land falling cyclones including Orissa super cyclone. Fig. 7 is prepared by plotting estimated speed of 9 tropical cyclones which have the minimum speed of movement 4 knots. The cyclonic storm during 5-10 May 2004 over Arabian Sea is not considered here, as this cyclone has the speed of movement of 2 knots and it caused 117 cm rainfall over Aminidevi in 24 hours.

In Fig. 7, along the *x*-axis is the movement speed of the cyclones and 24 hours accumulated heaviest rainfall recorded is plotted along *y*-axis. The movement of Orissa super cyclone after landfall was not unidirectional; it moved in a triangular path till its weakening into a depression. Fig. 7 shows that the 24 hours accumulated rainfall is, to a certain extent inversely proportional to the speed of movement of cyclonic storm with the best fit for speed range 4-10 knots. The maximum rainfall from a landfalling TCs moving with speed in the range 4-10 knots can be estimated by [R (extreme = -5.3429 × (Speed) + 64.905], with a standard deviation of 8.9 mm which is quite large. Large standard deviation arises due to smaller data set used in the study. Thus, assessing extreme rainfall amount in ranges will give a better result rather than quantifying it with a single number. Studies by (Singh and Bandyopadhyay, 2007) suggest that most of the TCs over NIO basins move with a transitional speed between 4-12 knots. Therefore, the above emperical relation could be used as a first guess by the operational forecasters to assess the extreme rainfall that could occur in association with land falling TCs. Due to severe cyclonic storm over southeast Arabian Sea from 05-10 May 2004, Aminidevi received 117 cm rainfall in 24 hours on 6 May 2004 and slow movement of the system also contributed to enhance the rainfall. The estimated speed of movement of this system in a day was 2 knots.

The TCs which moved with the speed less than 20 kmph some time caused heavy to very heavy rainfall amounts. These are CS 25-27 November 2008, 29-30 October 2006, SCS 17-21 September 2005, 5-10 May 2004 and 14-17 October 1999. All 14 cyclones (except 3) moved with speed 20 kmph or more. These three cases are SCS 10-12 November 2002, 11-16 December 2003 and CS 25-27 October 2008. Detailed characteristics of a few important cases are given below.

Case I : *Very severe cyclonic storm over Arabian Sea during May 16-22, 1999*

The system moved with an average speed of about 18 kmph in a northeasterly direction before crossing the Pakistan coast close to international border in the afternoon of 20 May, 1999. At the time of crossing the coast on 20 May, 1999 between 0900-2000 hours IST winds of the order of 85 kts have been reported at Naliya which was close to the landfall point. Satellite imageries received at 1130 and 1430 hours IST of 20 May showed CDO pattern with CTT -80 to -40° C. It indicates that the convective cloud spread over about 400 kms diameter in which severe convective cloud mass was located over a diameter of 150 kms [Figs. 3 (b&c)]. Tables 1&2 show that the extremely heavy rainfall (35-40 cm) occurred near the landfall point. Fig. 3(a) also shows that the area of maximum rainfall was to the right of the track of cyclone and was confined up to 150 kms radius of the landfall point except along the forward sectors, where it was up to 300 kms radius or more than that. This is also supported by satellite imageries derived convective cloud area associated with the cyclone. As per earlier studies, cyclone/depressions which passed over the Bhagirathi catchment area caused about 16.9 cm rainfall in 24 hrs (Gupta *et al*., 1972), except near the centre.

Case II : *Very severe cyclonic storm over Bay of Bengal during October 15-19, 1999*

This cyclone moved in a north-northeasterly direction before crossing the coast near Gopalpur (Orissa) in the early morning of 18 October. From 17 October the cyclone was tracked by Cyclone Detection Radars (CDRs) at Paradip and Visakhapatnam. CDR Visakhapatnam reported 'eye' at 2300 hours IST on 17 October with eyewall width of 10 kms, diameter of 16 kms and radius of maximum reflectivity of 13 kms. When the radar observed eye and the dynamic centre were not co-located, the dynamic centre was displaced towards the area of most intense eyewall convection. Willoughby and Chelnow (1982) study also supports shift of the precipitation area. Maximum surface sustained winds were estimated to be 90 kts at the time of crossing the coast. Satellite imageries received at 2030 hours (IST) of 17 October and 0230 hours IST of 18 October show dense cloud mass with CTT -80° to -40° C, spread over about 350 kms diameter elongated along the track of the cyclones [Figs. 4 (b&c)]. Tables 1&2 show that the maximum rainfall has occurred within 150 kms radius from the landfall point and it was located on both sides along the track. It is clear in this case that the maximum rainfall occurred over the area which lay under the most convective cloud cover area. The right first quadrant in this case also got good amount of rainfall that ranged between 25-30 cm followed by again fourth quadrant Fig. 4(a) and it further extends beyond 300 kms diameter along the cyclone.

Case III : *Cyclonic storm "NISHA" over the Bay of Bengal (25-27 November, 2008)*

On 23 November, an embedded cyclonic circulation extending up to lower tropospheric levels developed over the southwest Bay of Bengal. Under its influence, a low pressure area formed over north Sri Lanka and neighbourhood on 24 November, 2008. A trough from this system extended to west central Bay of Bengal off Tamilnadu and south coastal Andhra Pradesh. The convective cloud mass over southwest Bay of Bengal and neighbourhood organized into a vortex around 1130 hours IST on 25 November and its intensity was estimated to be T1.0. Associated intense to very intense convection was observed over southwest Bay of Bengal and adjoining Indian Ocean and Sri Lanka. It concentrated into a depression over north Sri Lanka on 25 November. It moved northwestwards and intensified into a cyclonic storm 'NISHA' over the southwest Bay of Bengal and lay centred close to Vedaranniyam (Tamilnadu). The lowest CTT was around -75 °C at 0830 hrs (IST) of 26 November, 2008. The system moved northwards with a very slow speed. As the system lay close to the coast in the evening of 26th, the system did not intensify further. Rather, the CTT was decreased to -70 ºC. However, as the vertical wind shear continued to be low (about -05 to -10 knots) at 1730 hours (IST) of 26 November, the system could maintain its intensity of cyclonic storm. It continued to move further northwards and lay centred at 0530 hrs (IST) of 27th over the southwest Bay of Bengal, close to north of Karaikal. At this time the CTT rose to -60° C and vertical wind shear increased to 10-20 knots. It crossed Tamilnadu & Puducherry coasts north of Karaikal

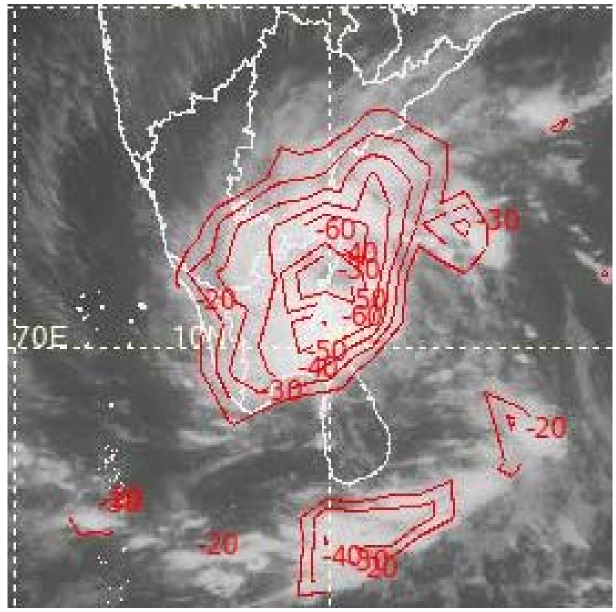

Fig. 8. Kalpana-I imagery at 0830 hours (IST) of 27 November, 2008 showing CTT contours over south peninsular India in association with cyclonic storm 'NISHA' during 25-27 November, 2008

between 0630 and 0730 hours (IST) of 27th and lay centred over coastal Tamil Nadu and Puducherry, about 50 km northwest of Karaikal in the morning of 27th. Due to land interaction, the system, while moving northwestwards, weakened gradually over north interior Tamilnadu. The system remained under influence of trough in easterlies and most of the convection was observed to the left of the track. Satellite imagery at 0830 hours (IST) of 27 November. Fig. 8 provides evidence that the convection was lying to the left of the track after crossing the coast.

Throughout the life cycle of the system over the sea, the features as seen by DWR Chennai were not sufficient to attempt centre fixing. However, after crossing the coast the system came closer to DWR Chennai, features grew prominent and based on a few spiral bands and in some cases with partial eye-wall, centre was fixed during 1030 to 1830 hours (IST) of 27 November. Maximum velocity observed in the cyclone field was not associated with the eye-wall region, but mostly associated with strong echoes in spiral bands, which were mainly over land area. The spiral band was reported by CDR Karaikal during 0830 of 26 to 0830 hours (IST) of 27 November. Karaikal, CDR imagery taken at 2121 UTC on 25 November showed the maximum convection lying over land area along the Tamilnadu and south Andhra Pradesh in association with cyclonic storm. Figures for imageries taken from CDRs are not reproduced for sake of brevity.

4. Conclusions

Based on the study of specific 14 tropical cyclones that formed during the period 1998-2008, the following conclusions can be drawn :

(*i*) In severe and very severe cyclonic storms the rainfall is generally more confined to the right of the track rather than the other side of the track giving asymmetric distribution. The maximum rainfall generally occurs within a radius of 150 km from the centre of the tropical cyclone. Beyond 150 km, rainfall is gradually decreased and significant rainfall is generally found to occur only up to the radius of 300 km from the centre.

(*ii*) Maximum rainfall amounts occurred in the first right quadrant of tropical cyclones followed by second quadrant and then third and fourth.

(*iii*) The Bay of Bengal cyclones which crossed coast as cyclonic storm and very severe cyclonic storm caused 71.4% rainfall within the range 0-10 cm, 22.8% rainfall in the range 11-20 cm and 4.3% rainfall within the range 21-30 cm in the area of radius of 300 km from the centre of the cyclonic storms. For the Arabian Sea tropical cyclones, in general, about 70 % rainfall occurred within the range 16-25 cm in 24 hrs.

(*iv*) Rainfall appears to be directly related with the cloud top temperature, *i.e*., if cloud top temperature is less than -80° C rainfall is more. In case when the cloud top temperature is -90 to -80° C the 24 hour rainfall amounts may be between the ranges 30-40 cm.

(*v*) The transitional speed of movement of a tropical cyclone and the associated convective asymmetries determine the distribution and intensity of rainfall in landfalling tropical cyclones. For cyclonic storms moving in the speed range from 4-16 knots, 24 hours accumulated rainfall is inversely proportional, to a certain extent, to the speed of cyclone. More studies are required in future for further fine tuning of this relationship and its better understanding.

References

Aberson, S. D., 2001, "Five-day tropical cyclone track forecasts in the North Atlantic basin", *Wea. Forecasting*, **13**, 1005-1015.

Corbosiero, K. L. and Molinari, J., 2002, "The effects of vertical wind shear on the distribution of convection in tropical cyclones", *Mon. Wea. Rev*., **130**, 2110-2123.

DeMaria, M. and Gross, J. M., 2003, "Evolution of tropical cyclone forecast models. Hurricane! Coping with Disaster", R. Simpson, Ed., *Amer. Geophys. Union*, 103-126.

DeMaria, M., Mainelli, M., Shay, L. K., Knaff, J. A. and Kaplan, J., 2005, "Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS)", *Wea. Forecasting*, **20**, 531-543.

Frank, W. M. and Ritchie, E. A., 2001, "Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes", *Mon. Wea. Rev*., **129**, 2249-2269.

Franklin, J. L., McAdie, C. J. and Lawrence, M. B., 2003, "Trends in track forecasting for tropical cyclones threatening the United States, 1970–2001", *Bull. Amer. Meteor. Soc*., **84**, 1197-1203.

Gupta, G. R., Srivastava, K. K., Mehra, H. C. and Jasra, T. C., 1972, "Forecasting storm rainfall over Bhagirathi catchment due to depression/cyclonic storms", *Mausam*, **30**, 1, 139-156.

Gilberto A. Vicente, Roderick Scofield, A. and Paul Menzel, W., 1998, "The operational GOES Infrared Rainfall Estimation Technique", *American Meteorological Society*, **79**, 9, September 1998, 1883-1898.

Lonfat, M., Marks Jr., F. D. 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.

Pfost, R. L., 2000, "Operational tropical cyclone quantitative precipitation forecasting", *Natl. Wea. Dig*., **24** (1–2), 61-66.

Rogers, R. F., Chen, S. S., Tenerelli, J. E. and Willoughby, H. E., 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.

Raghavan, S., 1990, "Structure of tropical cyclones in the Bay of Bengal", *Mausam*, **41**, 2, 325-328.

Shapiro, L. J., 1983, "The asymmetric boundary layer flow under a translating hurricane", *J. Atmos. Sci*., **40**, 1984-1998.

Singh, C. and Bandopadhyay, B., 2004, "Behaviour of tropical cyclones along the east coast of India prior to landfall", *Mausam*, **58**, 2, 273-279.

Willoughby, H. F. and Chelnow, M. B., 1982, "Objective determination of hurricane tracks from aircraft observation", *Mon. Wea. Rev*., **110**, 1298-1305.

Wu, C. C., Yen, T. H., Kuo, Y. H. and Wang, W., 2002, "Rainfall simulation associated with Typhoon Herb (1996) near Taiwan, Part I: The topographic effect", *Wea. Forecasting*, **17**, 1001-1015.

Ying, Li. *et al*., 2005, "Numerical study on impacts of boundary layer fluxes over wetland on sustention and rainfall of landfalling tropical cyclone", *Acta Meteorologica Sinica*, **63**(5), 683-693.