MAUSAM, **69**, 2 (April 2018), 209-218

551.515.2

Monitoring of tropical cyclone formation, growth and dissipation by using SAPHIR sensor

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(*Received 20 July 2017, Accepted 20 March 2018*)

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सार – इस शोध पत्र में उष्णकटिबंधीय चक्रवात के उद्गम एवं विकास तथा अरब सागर एवं बंगाल की खाड़ी में उसकी प्रचंडता का अध्ययन किया गया है। उष्णकटिबंधीय चक्रवात के विकसित होने और समाप्त होने के मूल्यांकन करने से धरती की सतह के उत्सर्जन और महासागर की सतह के तापमान जैसे धरती की सतह की भौतिक विशेषताओं को समझने में सहायता मिलती है। इस शोध पत्र में (*i*) उष्णकटिबंधीय चक्रवात की प्रचंडता के उत्सर्जन, इसके बनने और विकसित होने और (*ii*) SAPHIR मेघा ट्रॉपिक्स सैटेलाइट पर लगे सूक्ष्म तरंग संवेदी की विभिन्न तरंग दैर्घ्य से मापन में विभिन्नता का मुख्य रूप से विश्लेषण किया गया। जून 2015 में अरब सागर में एक चक्रवाती तूफान अशोबा चक्रवात आया और 183+/-110 GHZ पर SAPHIR ब्राइटनेस टेंपरेचर (TB) पैटर्न का प्रयोग करते हुए भारतीय उपमहाद्वीप पर उसके प्रभाव का अध्ययन किया गया। इसके अलावा उष्णकटिबंधीय चक्रवात के विकसित होने और उसकी प्रचंडता में परिवर्तनशीलता को मापने के लिए SAPHIR के सभी छह चैनलों की क्षमताओं का तुलनात्मक मूल्यांकन किया गया। आगे, हमारे इस अध्ययन में SAPHIR साउंडर से मापे गए TB की क्षमताओं के मूल्याकंन से इस बात की पुष्टि होती है कि मेघा ट्रॉपिक्स उपग्रह मिशन की कक्षीय स्थिति अपेक्षाकृत अधिक बार (4-6 बार) होगी और उष्णकटिबंधीय चक्रवात उत्सर्जन से लेकर समाप्त होने और धरती पर इसके प्रभाव को मॉनीटर करने में उपयोगी होंगे।

ABSTRACT. A critical study of origin and development of Tropical Cyclone (TC) and its intensity over the Arabian Sea and Bay of Bengal is carried out. Evaluation of TC growth and dissipation helps in understanding the physical properties of earth surface such as land surface emissivity and ocean surface temperature. In this paper a study of (*i*) Genesis, growth/development of TC intensity and (*ii*) Critical analysis of variations in measurement by different wavelengths of Sondeur Atmosphérique du Profil d'Humidité Intertropicale par Radiométrie (SAPHIR) microwave sounder sensors on-board Megha-Tropiques satellite. A cyclonic storm, Ashobaa cyclone observed in the Arabian Sea during June 2015 and its impact on Indian subcontinent is made by using the SAPHIR Brightness Temperature (TB) patterns at 183+/-11.0 GHz. In addition a comparative evaluation of the capabilities of all six channels of SAPHIR in measuring TC development and its intensity variations. Further evaluation of capabilities of TB measured by SAPHIR sounder made in our study confirms that orbit position of Megha-Tropiques satellite mission will enable to obtain comparatively more frequent sampling (4-6 times) that is useful for monitoring tropical cyclone genesis to dissipation and its effects on land.

Key words – Tropical cyclone, Brightness temperature, T-Number, SAPHIR, Ashobaa cyclone.

1. Introduction

Tropical cyclone is one of the major natural events which cause variation in monsoon and climatic condition, besides causing physical disasters. Similarly atmospheric humidity is chiefly responsible for variation in energy budget in the atmosphere. Forecasting TC genesis and intensity tracking is essential to understand the atmospheric changes to minimize the possible life and material losses. Tropical cyclones, has strong impact on atmospheric humidity, climate and vegetation. Hence the knowledge about variation of atmospheric humidity due to tropical cyclone is necessary. Observations of (*i*) TC genesis and intensities, (*ii*) Atmospheric humidity and (*iii*) Land surface emissivity using microwave and/or infrared images obtained by sounder onboard satellites enables us to obtain almost real time information relating to the said parameters (Suresh Raju *et al*., 2013). Among the various satellite missions useful to these activities, the Advance Microwave Sounding Unit (AMSU) sensors on NOAA satellite and SAPHIR sensor on Megha-Tropiques satellite missions have been considered for our studies. The primary data used for our analysis is in the form of brightness temperature measurement of microwave sounders.

The forecasts of cyclone indicating its accurate eye location and intensity at 24-hr and/or 48-hr time-steps are useful for all rehabilitation measures. Measurements of TC properties made by all the six channels of SAPHIR have been collected for comparative evaluation of their capability in measuring properties of cyclone genesis over Arabian Sea and Bay of Bengal of the Indian sub-continent. Our discussion will highlight the role of SAPHIR aboard Megha-Tropiques satellite mission in getting repetitivity and good sampling, *i.e*., 4-6 times in a day in the tropics followed by improved and accurate (best resolution 10 km) measurement in all atmospheric conditions when compared to AMSU. Facilitate a concise correlation on the information from the India Meteorological Department (IMD) which is cyclone eye technique in tracking TC intensity is applied by Rani and Prasad (2014).

2. Background

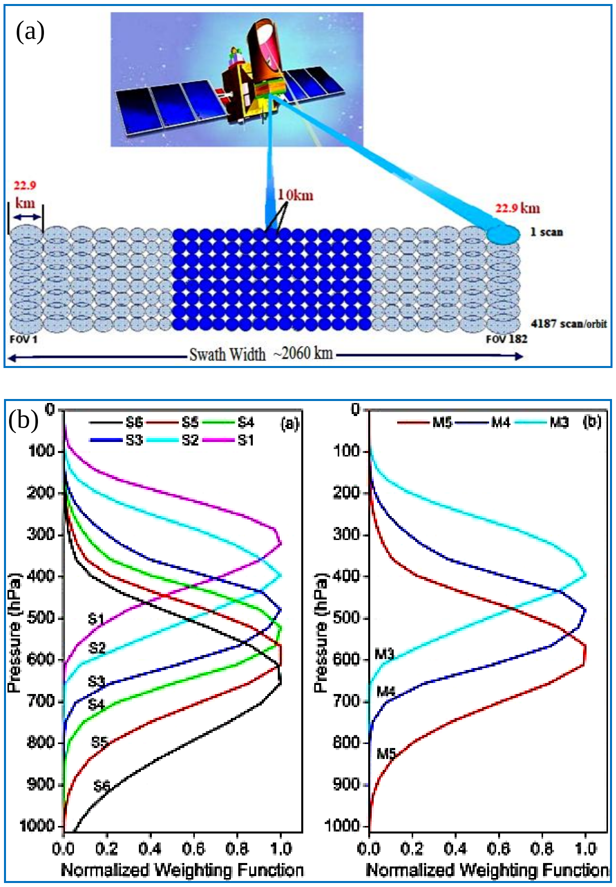
For the past four decades passive microwave sensor missions such as SEASAT, Special Sensor Microwave Imager (SSMI), Microwave Humidity Sounder (MHS), Humidity Sounder for Brazil (HSB), AMSU- A & B and SAPHIR have been used for oceanographic applications. SAPHIR aboard Indian satellite mission is mainly for profiling the atmospheric humidity and to understand tropical weather events and the climate. Here we have additionally endeavored to briefly study on ocean surface roughness and its variations. SAPHIR onboard Megha-Tropiques (MT) satellite has a good spatial resolution of 10 to 20 km and a swath of ~2060 km. Megha-Tropiques was launched in near-circular inclined orbit of 20 degrees on 12 October 2011 (Raju, 2012 and 2013) and providing high-quality data related to ocean surface (Aguttes *et al*., 2000), atmospheric humidity profile (Gohil *et al*., 2013 and Balaji *et al*., 2014) and land-related application (Suresh Raju *et al*., 2013). By using brightness temperature, SAPHIR measures the vertical distribution of atmospheric water-vapor (from surface to 12 km height).

Although SAPHIR is primarily implied for atmospheric humidity profile studies, it has shown interesting results exhibiting the possibilities of detection, tracking and movement of the cyclonic features over the ocean. A number of such tropical cyclones have been studied ever since Megha-Tropiques launch till 2015 (Keila, Thane, Nilam, Phailin, Hudhud, Nilofar and Ashobaa). This paper brings out a vivid picture of cyclonic features as observed over a period from (from: 0300 UTC 8 June, 2015 up to - 1200 UTC 12 June, 2015). The paper also highlights the capability of SAPHIR in studying satellite images of cyclone eye encircled by the eye wall and spiral bands of convection. Dvorak (1975) and later in Velden *et al.*, (2006) developed a method to observe the central and banding features of TC's and cloud-top temperatures near the eye by using visible and IR satellite imagery and the same was popularly adopted as Dvorak Technique. Kidder *et al*., (1980) demonstrated that the microwave sounder care capable of detecting the warm core was the aftereffect of upper-level warming over tropical storms. Roy Bhowmik (2003) used genesis parameter to study the developing and non-developing systems over north Indian ocean and observed parameter values around 20 × 10^{-12} Sec^{-2} against T-No:1.5. Julie *et al*. (2004) by using AMSU sounder data, (*i*) azimuthally averaged radii of 34, 50 and 64 knots winds, (*ii*) estimated tropical cyclone intensity and (*iii*) proposed algorithms for wind radii estimation by using AMSU data. Olander and Velden (2007) based on rigorous statistical and empirical analysis developed an algorithm to improve pattern recognition which introduced three major changes in automated storm center determination methodology. Shuuji Nishimura *et al.* (2008) an improved version of dvorak technique for analyzing center positions of tropical cyclones using this microwave imagery (from the AMSR-E system on board the Aqua) analysis is

TABLE 1

Comparison of SAPHIR, AMSU-B, INSAT-3D and MHS specifications

Features	SAPHIR	AMSU-B
Orbital inclination	20°	98°
No. of sounding channels	6	3
Swath width	~2060 km	~2300 km
Max incidence angle	50.4°	58.5°
Pixel size across track	10-22.7 km	20-64 km
Pixel size along track	10-14.5 km	16-27 km
No. of pixel/scan line1	182	90
Polarization	Horizontal	Horizontal
Central frequency / Central wavelength (GHz)	183.31 ± 0.2 ;183.31 ± 1.1 183.31 ± 2.8; 183.31 ± 4.2 183.31 ± 6.8; 183.31 ± 11.0	183.299 183.299 183.299
NEΔT (K)	2.35; 1.45; 1.36; 1.38; 1.03; 1.10	1.06; 0.7; 0.6



Figs. 1(a&b). (a) SAPHIR scanning geometry and (b) Weighting function of SAPHIR & AMSU-B

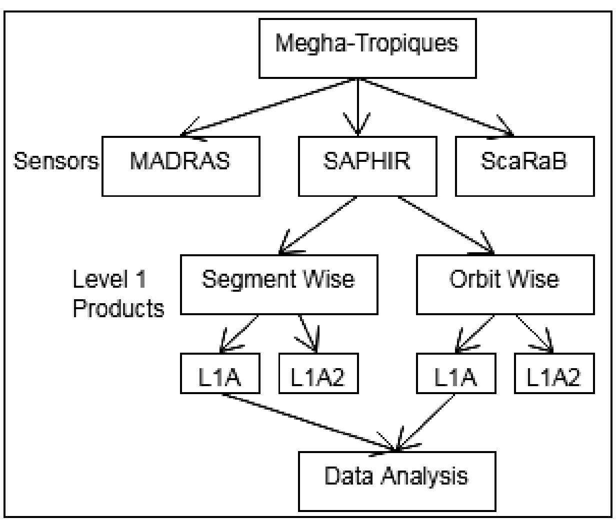
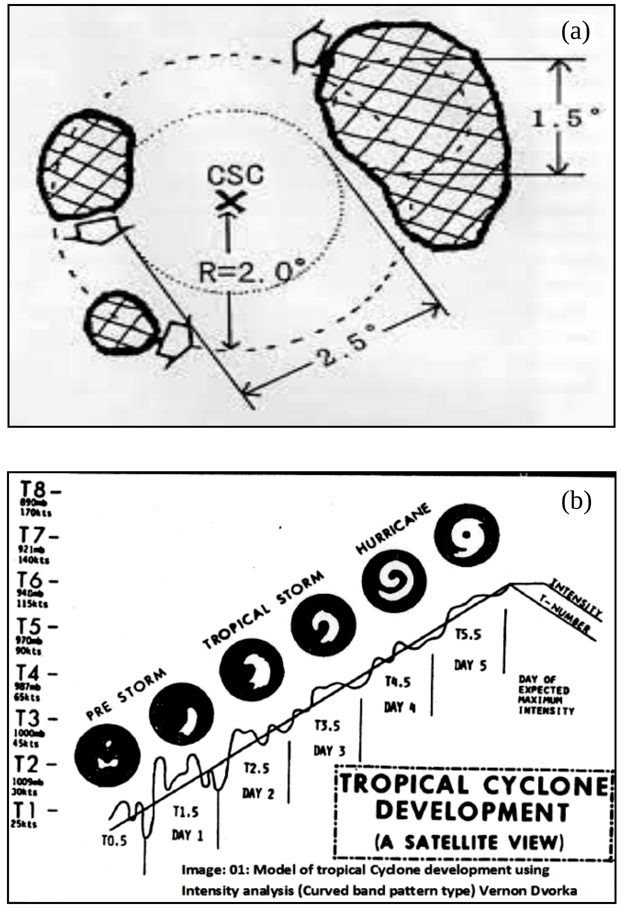


Fig. 2. Data flow structure

developed. Kotal and Bhattacharya (2013) applying genesis potential parameter model for tracking cyclone over the North Indian Sea and explained the early stages



Figs. 3(a&b). (a) Cyclone intensity number determination and (b) TC development model [Dvorak (1975)]

development for determining intensification of low pressure systems.

3. Sensor details

The SAPHIR sounder which provides atmospheric humidity profile utilizing six channels with high temporal receptivity. It is ranging from surface 1000 hpa to the stratosphere 86 hpa (layer 1: 1000 - 850 hpa; layer 2: 850 - 700 hpa; layer 3: 700 - 550 hpa; layer 4: 550 - 400 hpa; layer 5: 400 - 250 hpa; layer 6: 250 - 100 hpa), is similar to 3 layers of AMSU-B. Comparison of technical specifications of SAPHIR sounder (Singh *et al*., 2013) and AMSU-B (Julie *et al*., 2004) sounder tabulated in Table 1.

SAPHIR sounder performing cross track scanning when satellite is moving ahead offers 10 km at nadir resolution and 22.9 km at edge spatial resolution, number of pixels per each scan is 182 per scan (130 per scan without overlap) and for one complete orbit 4187 scans as shown in Fig. 1(a) (Michel Capderou *et al*., 2013).

TABLE 2

Major cyclones occurred during 2011 to 2015

Year	Cyclone name	Duration	Ocean
2011	Keila	29 Oct 2011 to 4 Nov 2011	Arabian Sea
2011	Thane	25 Dec 2011 to 31 Dec 2011	Bay of Bengal
2012	Nilam	28 Oct 2012 to 3 Nov 2012	Bay of Bengal
2013	Phailin	4 Oct 2013 to 14 Oct 2013	Bay of Bengal
2014	Hudhud	7 Oct 2014 to 14 Oct 2014	Bay of Bengal
2014	Nilofar	25 Oct 2014 to 31 Oct 2014	Arabian Sea
2015	Ashobhaa	7 June 2015 to 12 June 2015	Arabian Sea

TABLE 3

Comparison of observed and estimated parameters for Ashobaa cyclone tracking

Date	Time (UTC)	Estimated surface wind speed (kmph)	Category	Observed surface wind speed (kmph)	Category
8 June, 2015	0600	50-60 kmph; Gust: 70 kmph	DD	60-70 kmph; Gust: 80 kmph	CS
9 June, 2015	1200	90-100 kmph Gust: 120 kmph	CS	80-90 kmph ; Gust: 100 kmph	CS
10 June, 2015	1200	95-105 kmph; Gust: 120 Kmph	SCS	80-90 kmph ; Gust: 100 kmph	CS
11 June, 2015	1200	65-75 kmph ; Gust: 85 kmph	CS	60-70 kmph ; Gust: 80 kmph	CS
12 June, 2015	1200	25-35 kmph; Gust 45 kmph	L	35-45 kmph ; Gust 55 kmph	D

SAPHIR provides the vertical distribution of atmospheric water-vapour 6 channels provide relatively narrow weighting functions from the surface to about 12 km as shown in Fig. 1(b) which shows the normalized weighting function of SAPHIR (S3, S4 and S5) that are similar to AMSU-B (M3, M4 and M5) channels (Singh *et al*., 2013).

4. Methodology

4.1. *Data source*

Megha-Tropiques SAPHIR metadata products named as "MT1SAPSL1A" contains all channels the scientific parameters of brightness temperature temporal samples, latitude and longitude samples, incident angles samples of all 6 channels available from 2011 to 2015 from MOSDAC (ISRO Ahmedabad) (www.mosdac.gov.in.) and ICARE (France) (www.icare.fr.).

Fig. 2 shows the selection processes of data product type orbit-wise or segment-wise of respective level will be archived in HDF5 format. Level-1(L1) products generate two types of files are segment-wise (possibly exceeding one revolution, variable in size) and orbit-wise (*i.e*., one revolution). The L1 products that are available to the users are L1A and L1A2. Level 1A (L1A) is the brightness temperature geo-tagged product and along the scan line, samples of all the 6 channels are collocated and have exactly the same footprint dimensions projected on ground as well the same geo-location (Karouche and Raju, 2013). Level 1A2 (L1A2) is the re-sampling of L1A (180 pixels) data brightness temperature to produce de-correlated non-overlapping 130 pixels for all channels.

4.2. *Tropical cyclone tracking by intensity estimation*

(*i*) Dvorak technique (TC eye detection and tracking method) has been adopted to detect and track cyclone from brightness temperature data as derived/obtained from all the six channels of SAPHIR. Fig. 3(a) illustrates the organized Cloud System Center (CSC) formation to determine the cyclone intensity are, The cloud system has a CSC within the diameter 2.5° latitude or less and CSC lasts for 6 hours or more; The cloud system has an area of dense, cold that appears less then 2° latitude from center and 1.5° latitude in diameter. If CSC satisfied above features, it is determined as T-number (Tropical-number) T1.0, otherwise consider the T-number of less than T1.0. Fig. 3(b) shows the dvorak model of tropical cyclone

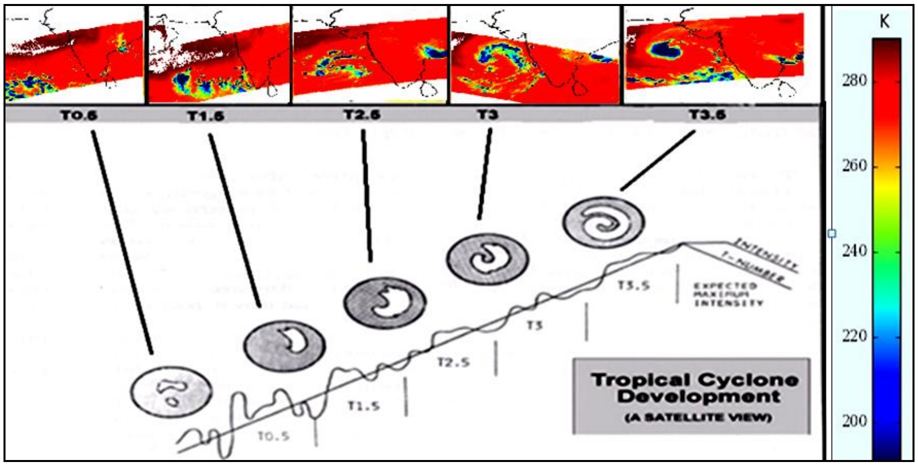


Fig.4. Ashobaa cyclone development

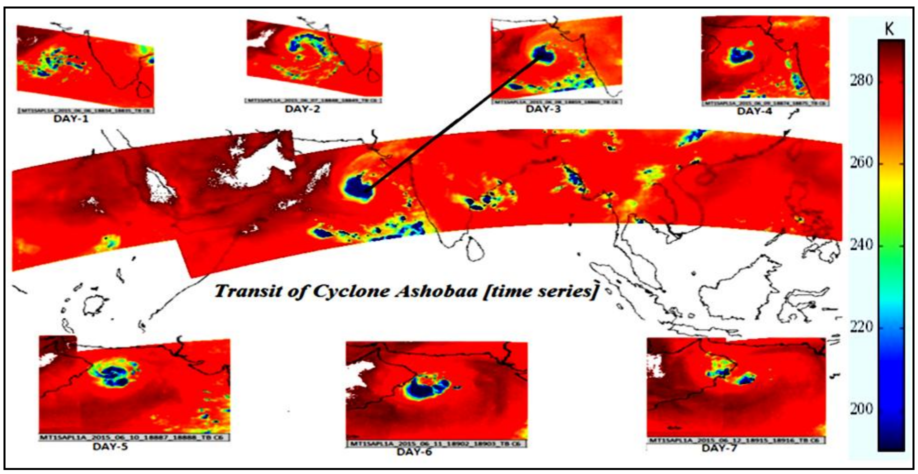


Fig. 5. Development and movement of Ashobaa cyclone over Arabian Sea from Day1 to Day7 where Day3 shown in enlarged image [source ICARE france SAPHIR data]

development using curved band type intensity analysis, (*ii*) The results so obtained are compared with the actual/observed data obtained from Indian Meteorological Department (IMD) at an interval of 3 hours prediction to predict the accuracy in the application of sounder data, (*iii*) TC detection and tracking from Dvorak technique using brightness temperature data obtained from all six channels of SAPHIR is compared with AMSU-B sounder images with an intention to identify the genesis and tracking of TC more clear cloud structure formation.

5. Observation and analysis

A number of cyclone observations have been considered to study the impact of ocean surface features and atmospheric humidity. Apart from several cyclones a few severe cyclones that occurred in the Indian geographical region have been listed in Table 2. As a preliminary study qualitative analysis of tropical cyclone features over Arabian Sea and Bay of Bengal surrounding the Indian sub-continent from 2011 to 2015 are observed during October to December of every year.

As an example the dvorak technique has been implemented on Ashobaa cyclone to determine the T-number in every stage occurred from 7 June to 12 June, 2015 as highlighted in Fig. 4. As observed when the cyclone eye (deep depression area) has been surrounded by cloud band at least halfway around the eye, the cyclone intensity T-number is assigned as T1.0. If the cloud area is more organized than at the previous analysis, 0.5 is added to the previous T-number and CSC increase along with their T-number.

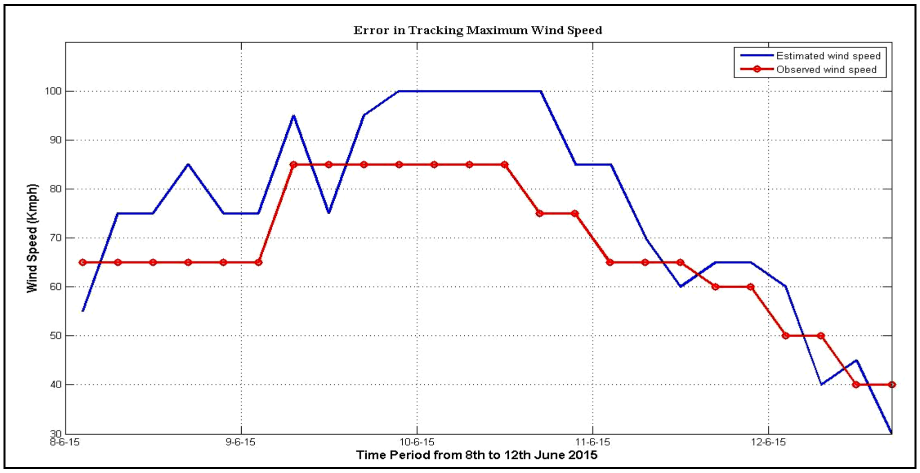
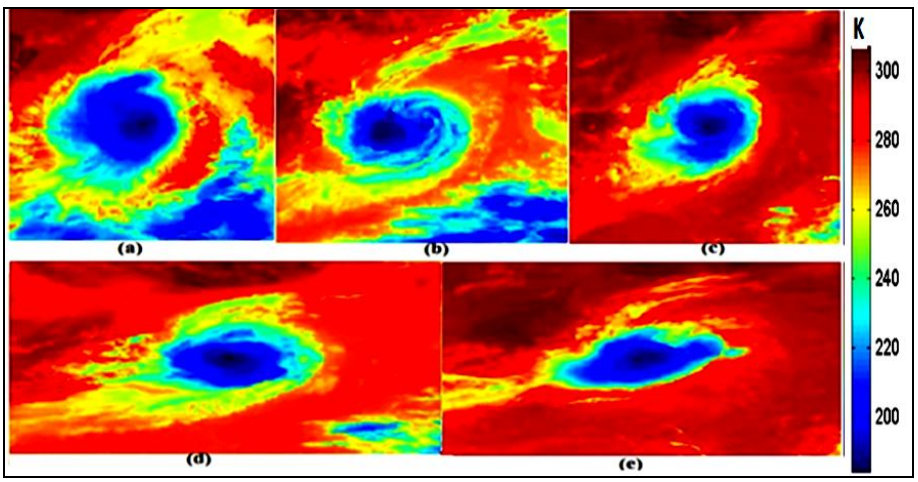


Fig. 6. Error in wind speed (kmph) of Ashobaa cyclone tracking

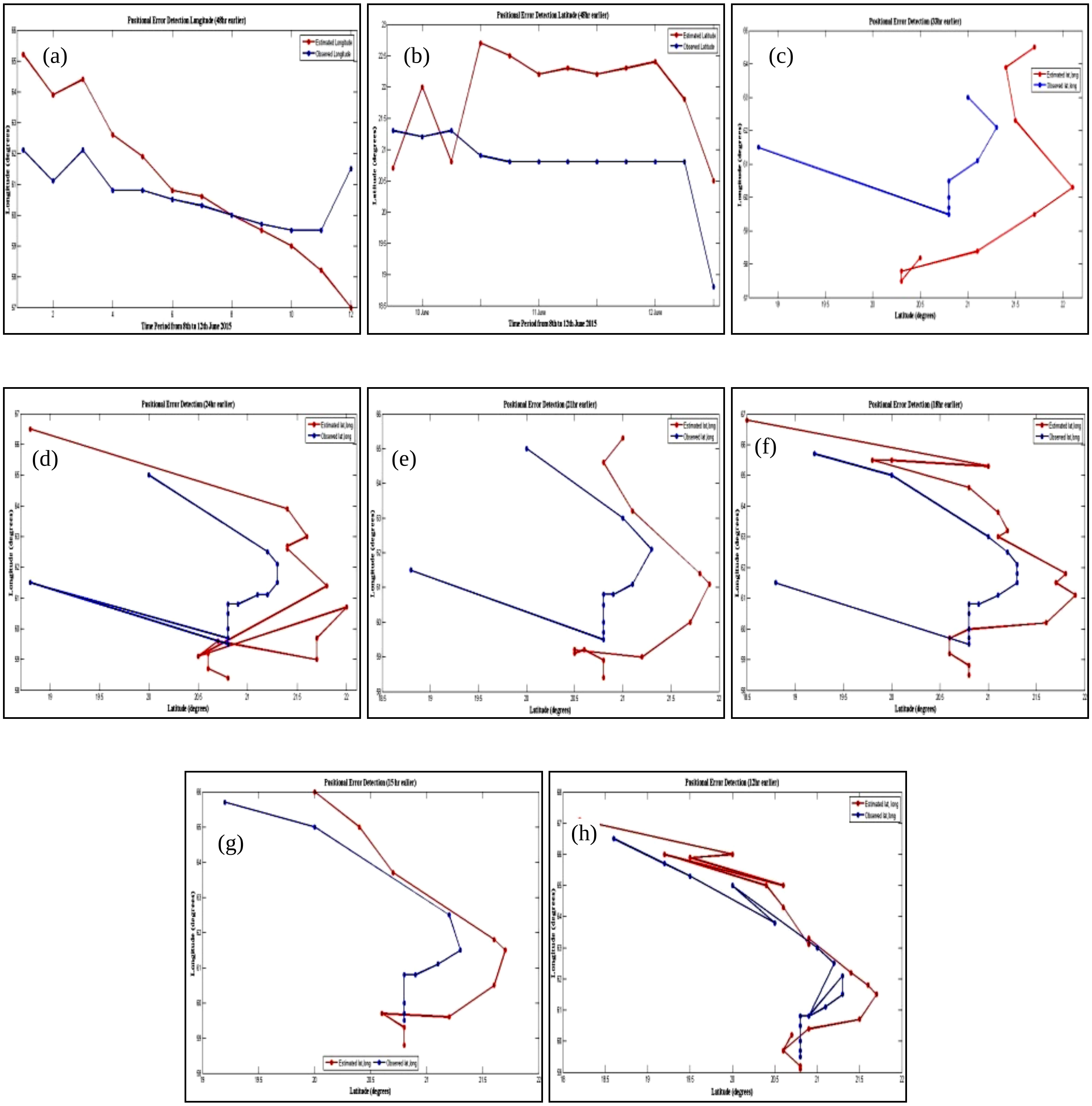


Figs. 7(a-e). Ashobaa cyclone eye center detected from TB measurement made by SAPHIR on same day at lead time, (a) 1:40 to 3:33 UTC; (b) 3:28 to 5:22 UTC; (c) 5:17 to 7:12 UTC; (d) 7:17 to 9:02 UTC and (e) 23:37 to 1:31 UTC.

Fig. 5 shows the progressive development of Ashobaa cyclone (7 June to 12 June, 2015) based on cyclone eye pattern method of Dvorak technique for the lead time of 24 hrs observation based on cyclonic rotation of cloud area. A CSC is observed with respect to time variation from Day-1 to Day-7 as the curvature and length of cloud bands rotation area increased. The mean error (variation/difference) between actual observations and estimation of surface wind speed (MSSLP) reported by IMD is shown in Table 3. Further, the graphical representation of variation between observed and estimated wind speed is shown in Fig. 6.

On 8 June, 2015 at different time intervals cyclone eye center intensity has been calculated using brightness temperature parameter and same shown in Figs. 7 (a-e) of Ashobhaa cyclone. A verification of the forecast TC positions, Maximum Sustained Surface Wind Speed (MSSWS) and Gust made by the IMD (using NWP models) with the observed positions reported by the Regional Specialized Meteorological Centre (RSMC) (RSMC Bulletin, 2015) New Delhi has been carried out. Verification of forecast and observed positions of TC Ashobaa is performed by using 121 samples for the lead time 12 hr, 15 hr, 18 hr, 21 hr, 24 hr, 33 hr, 36 hr, 45 hr and 48 hr, which includes verification of increase and decrease between average track forecast and observed positions.

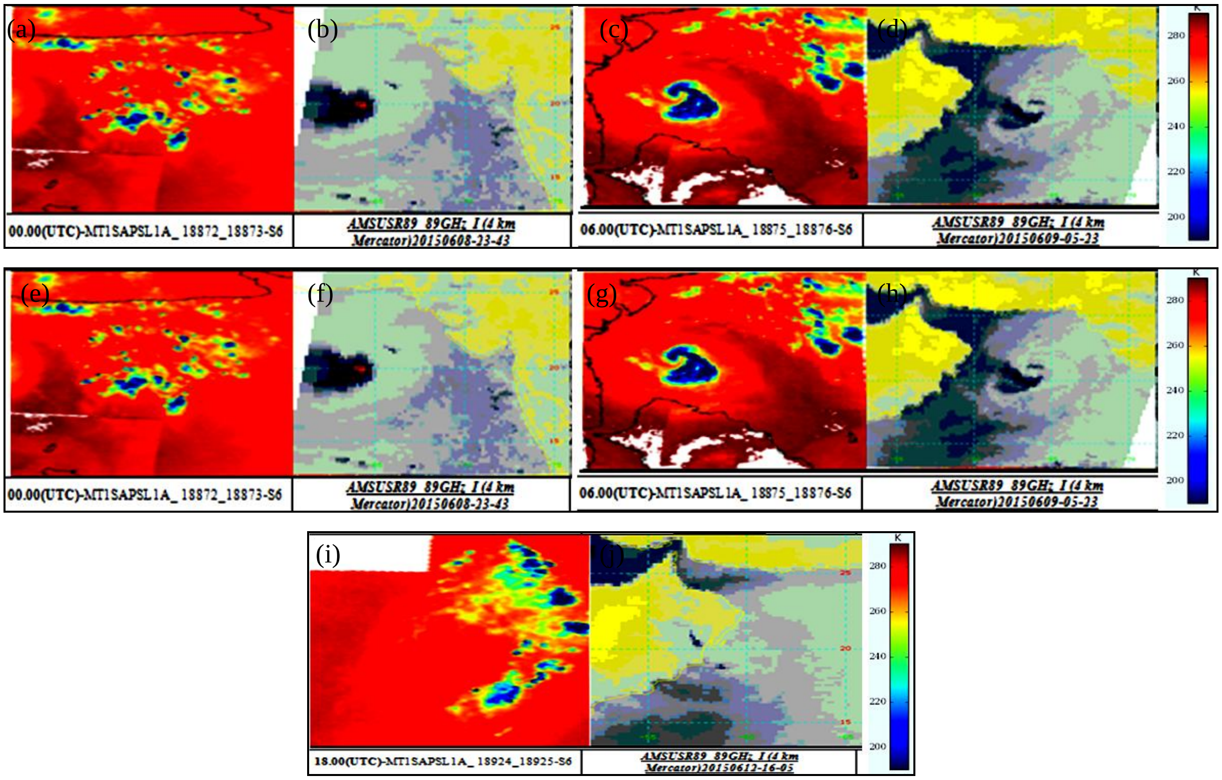
The average mean error detected after verification is summarized as: (*i*) 0.75° N - 1.16° E average forecast errors in TC positions; (*ii*) 4.59 knots average forecast error of MSSWS during cyclone period and (*iii*) average forecast error of 4.81 knots gust during cyclone period.



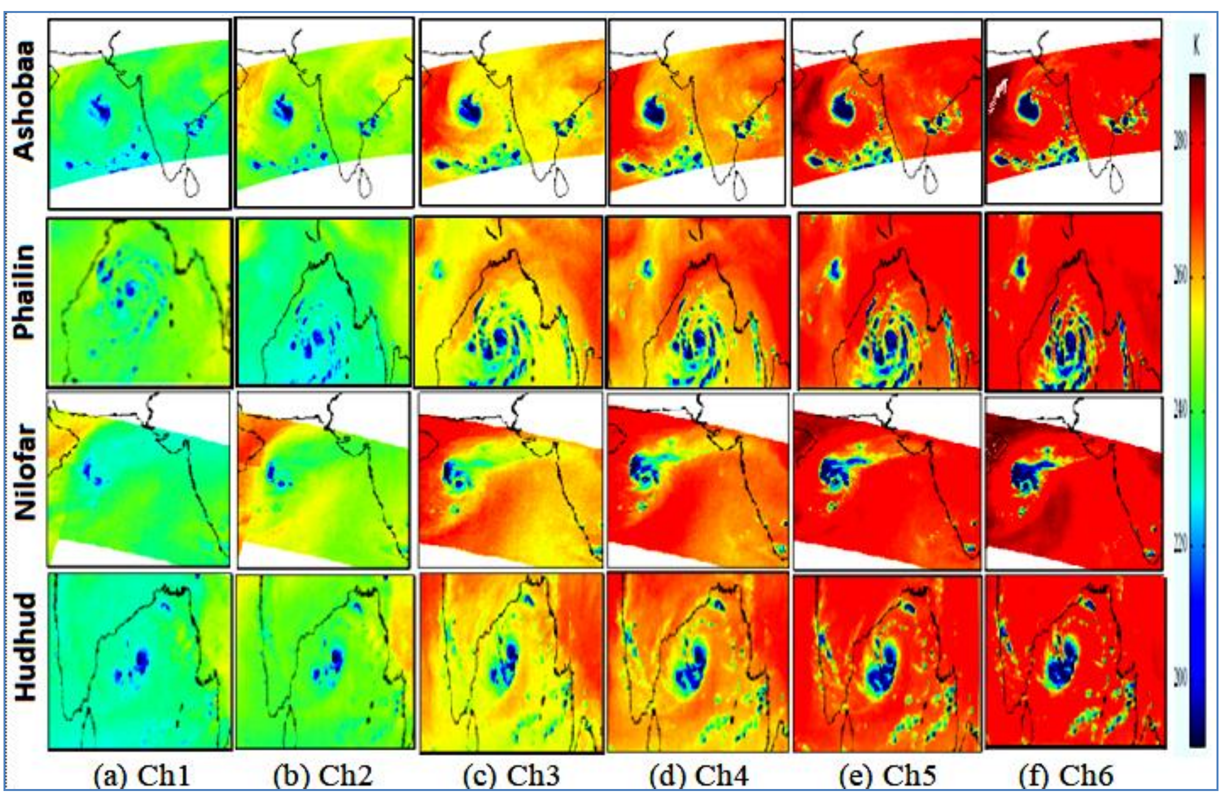
Figs. 8(a-h). Positional error detection of Ashobaa cyclone (a) 48 hr earlier Long. (b) 48 hr earlier Lat. (c) 33 hr earlier (d) 24 hr earlier (e) 21 hr earlier (f) 18 hr earlier (g) 15 hr earlier (h) 12 hr earlier

We have made graphical representation shown in Figs. 8(a-h) estimated and observed positional error (latitude and longitude) detection of Ashobaa cyclone from 7 to 12 June 2015 as well as statistical representation in Table 4 of mean track forecast error corresponding to lead time 12 hr, 15 hr, 18 hr, 21 hr, 24 hr, 33 hr, 36 hr, 45 hr and 48 hr respectively and the abstract of the same is shown graphically in Figs. 8(a-h).

A comparison of brightness temperature profiles of select images of SAPHIR and AMSU sounder is shown in Figs. 9(a-j), which represents the day to day variation of Ashobaa cyclone from genesis on 7 June to dissipation 12 June, 2015. It also shows that images of SAPHIR are more prominent and clear cloud structure visible when compared to AMSU images.



Figs. 9(a-j). Comparison of two different sensor SAPHIR sounder and AMSU sounder observed on Ashobaa cyclone from 7 to 12 June 2015 occurred in Arabian Sea (a) 7 June SAPHIR (b) 7 June AMSU (c) 8 June SAPHIR (d) 8 June AMSU (e) 10 June SAPHIR (f) 10 June AMSU (g) 11 June SAPHIR (h) 11 June AMSU (i) 12 June SAPHIR and (j) 12 June AMSU



Figs. 10(a-f). Comparison of SAPHIR sounder 6 channels (Ch1 to Ch6) of selected TC

TABLE 4

Mean track forecast error corresponding to lead time of Ashobaa cyclone

Lead time UTC	Verified Samples	Lat. (°North)			Long. (°East)			MSSWS (knots)			Gust (knots)		
		Increase	Decrease	Average	Increase	Decrease	Average	Increase	Decrease	Average	Increase	Decrease	Average
12 hr - 48hr	121	0.41	0.99	0.75	1.05	1.17	1.16	1.77	7.05	4.59	2.78	8.95	4.81

TABLE 5

Mean error detection estimation of tropical cyclone position and intensity

TC Names	Lead time UTC	verified Samples	Lat. (°North)			Long. (°East)			MSSWS (Kts)		
			Increase	Decrease	Average	Increase	Decrease	Average	Increase	Decrease	Average
KEILA	1245	19	0.64	0.00	0.64	2.1	0.00	2.1	0.3	7.33	3.81
THANE	1248	89	1.46	0.64	1.05	0.95	0.62	0.78	13.24	10.71	11.97
NILAM	1248	28	045	0.32	0.38	0.71	1.67	1.19	1.66	6.69	4.17
PHAILIN	1248	70	0.3	0.52	0.41	0.56	0.17	0.36	19.62	23.53	21.57
NILOFAR	1248	136	0.24	0.68	0.46	0.54	1.08	0.81	12.85	25.28	19.06
HUDHUD	1248	114	0.23	0.44	0.33	0.31	0.60	0.45	9.48	5.96	7.72
ASHOBAA	1248	121	0.41	0.99	0.75	1.05	1.17	1.16	1.77	7.05	4.59

Figs. 10(a-f) shows the comparison of SAPHIR sounder all 6 channels (Ch1 to Ch6) from left to right and from top to bottom of selected cyclone are Ashobaa cyclone 2015 (Arabian Sea), Phailin cyclone 2013 (Bay of Bengal), Nilofar cyclone 2014 (Arabian Sea) and Hudhud cyclone 2014 (Bay of Bengal). Study considers 2 cyclones from Arabian Sea and 2 cyclones from Bay of Bengal observed that based on the weighting function of Ch 6 of SAPHIR sounder is more accurate in showing the cloud formation area and cloud cyclonic region compared to other channels.

Comparative study of observed cyclone tabulated in Table 5, observed that 579 samples related to 7 cyclones from 2011 to 2015 near Indian sub-continent were chosen and the average increase or decrease variation in TC position and MSSWS speed (Kts).

6. Conclusions

This paper shows the comparative results studied by the SAPHIR sounder sensor on-board Megha-Tropiques at various altitudes (0-12 km). The present describes the monitoring of tropical cyclones occurred in Arabian Sea and Bay of Bengal basin in north Indian Ocean. A comparison of brightness temperature profile of selected cyclone (from 2011 to 2015) images of SAPHIR sounder obtained from all six channels shows (*i*) the images of SAPHIR are also capable of providing information relating to TC genesis and development and (*ii*) since SAPHIR has relatively higher spatial resolution, it is observed that it has more clear contrast near real-time image. Data obtained from SAPHIR microwave sounders is used to estimate (*i*) cyclone eye (*ii*) cyclone intensity T-no estimation by organizational/structure characteristics at each stage. A comparison of temperature profile of select images of tropical cyclone from SAPHIR and AMSU shows that images of SAPHIR is more prominent and clear when compared to AMSU images as the spatial resolution of SAPHIR relatively higher.

Among all the six channels channel of SAPHIR sounder, more distinct features can be observed based on the vertical distribution of weighting function of different channels and Ch6 is suitable for detection of TC and its intensity variations. Since there is no exactly coincident observation with IMD, there is some variation in estimation and actual observations of TC properties, *i.e.*, averaged variation between observed measurement and estimate made by IMD is (a) Lat. 0.75° N and Long. 1.16° E (b) MSSWS:4.59 knots (c) gust: 4.81 knots. It can be improved with more coincident measurements.

Acknowledgements

The authors would like to express their sincere gratitude to Indian Space Research Organization (ISRO) MOSDAC and ICARE France for providing SAPHIR sensor dataset. The authors also thank Dr. Keshavan.H.R and Dr. N. Thangadurai, Jain Univeristy, for their valuable suggestions which led to the improvement of the manuscript.

The contents and views expressed in this research paper/article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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