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Estimation of intensity of tropical cyclone over Bay of Bengal using microwave imagery

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सार – बंगाल की खाड़ी में वर्ष 2008–2010 में एफ. डी. पी. अवधि (15 अक्तूबर से 30 नवम्बर) के दौरान आए पाँच चक्रवातों के सूक्ष्म तरंगीय मेघ बिम्बावलियों तथा 85 गिगाहट्‌र्ज आवृत्ति में प्राप्त किए गए उत्पादों की जाँच की गई है जिससे तापमान दीप्ति, तापमान दीप्ति में अनियमितता, केन्द्र का स्थान, सतह पर अनवरत बहने वाला अधिकतम पवन (एम. एस. डब्ल्यू.) तथा चक्रवातों के भिन्न–भिन्न स्थितियों में उनके तीव्रीकरण से संबंधित करकों जैसेः अवदाब (डी.), गहन अवदाब (डी. डी.), चक्रवातीय तूफान (सी. एस.), तीव्र चक्रवातीय तूफान (एस.सी. एस.), अति तीव्र चक्रवातीय तूफान (वी.एस.सी.एस.) आदि का आकलित केन्द्रीय दाब (ई. सी. पी.) का आकलन किया जा सके। प्रक्षित किए गए दीप्ति तापमान अनियमितताओं की तुलना सैद्धांतिक रूप से ई.सी.पी. के बेस्ट ट्रैक आकलन पर आधारित दीप्ति तापमान अनियमितता एवं इन चक्रवातों के बाहरी दाब के साथ भी की गई है। केन्द्र के स्थान, ई.सी.पी. एवं सूक्ष्मतरंगीय बिम्बावली के आधार पर आकलित एम. एस. डब्ल्यू. की तुलना बेस्ट ट्रैक एवं भारत मौसम विज्ञान विभाग के डी. वोरॉक के आकलन से की गई है और उसका विश्लेषण किया गया है।

चक्रवातीय विक्षोभ (सी. डी.) के केन्द्र के स्थान में अंर्त जैसाकि सूक्ष्मतरंगी बिम्बावलियों तथा बेस्ट ट्रैक आकलन के द्वारा आकलित किया गया है, विक्षोभों के तीव्रीकरण के साथ–साथ कम होता जाता है और अवदाब (डी.) की स्थिति में लगभग 25 कि.मी. से अति तीव्र चक्रवातीय तूफान (वी.एस.सी.एस.) की स्थिति में 18 कि. मी के बीच बदलता रहता है। जबकि यह अंतर डी वोरॉक के आकलन से काफी अधिक है। सूक्ष्मतरंगीय आकलनों पर आधारित एम. एस. डब्ल्यू. आकलन वी.एस. सी. एस. के दौरान बेस्ट ट्रैक आकलनों से लगभग 28 नॉट्स अधिक आकलित किया गया है और अवदाब (डी.)/चक्रवातीय तूफान (सी.एस.)/तीव्र चक्रवातीय तूफान (एस. सी. एस.) की स्थिति में यह 6–8 नॉट्स आकलित किया गया है। बेस्ट ट्रैक आकलनों से सापेक्षिक अंतर को देखने से पता चला है कि सी.एस. और एस.सी. की स्थिति में सूक्ष्म तंरग में एम.एस.डब्ल्यू. लगभग 12–15 प्रतिशत और वी.एस. सी.एस. की स्थिति में लगभग 30 प्रतिशत अधिक आकलित हुआ है जबकि डी. वोरॉक का एम. एस. डब्ल्यू. आकलन सी. एस., एस. सी. एस. और वी. एस. सी. एस. की स्थितियों में 15–18 प्रतिशत कम हो गया है। बंगाल की खाड़ी के ऊपर 230 केल्विन का दीप्ति तापमान अवदाब के बनने के लिए अनुकूल होता है, 250 केल्विन का तापमान इसको चक्रवाती तूफान में 260 केल्विन तीव्र चक्रवाती तूफान में और 270 केल्विन अति प्रचंड़ चक्रवाती तूफान में बदल देता है। दीप्ति तापमान के देहलीमान (थ्रेसोल्ड वेल्यू) के अभिज्ञान (डिटैक्शन) से इस प्रणाली के तीव्र होने का पूर्वानुमान देने के लिए प्रयाप्त अग्रिम समय मिल सकता है। इसी प्रकार दीप्ति तापमान विसंगति 3 केल्विन से अधिक होने पर चक्रवातीय तूफान तीव्र चक्रवातीय तूफान में बदल जाता है और 8 केल्विन का तापमान इसे बंगाल की खाड़ी में अति प्रचंड चक्रवातीय तूफान के रूप में बदल देता है।

ABSTRACT. Microwave cloud imageries and derived products in the frequency of 85 GHz have been examined for five cyclones that occurred during FDP period (15 October- 30 November) of 2008-2010 over the Bay of Bengal to estimate the brightness temperature, brightness temperature anomaly, location of centre, maximum sustained wind (MSW) at surface level and estimated central pressure (ECP) associated with cyclones in their different stages of intensification like depression (D), deep depression (DD), cyclonic storm (CS), severe cyclonic storm (SCS), very severe cyclonic storm (VSCS), etc. Also the observed brightness temperature anomalies are compared with theoretically derived brightness temperature anomalies based on the best track estimates of ECP and outermost pressure for these cyclones. The location of centre, ECP and MSW based on microwave imagery estimates have been compared with those available from the best track and Dvorak's estimates of India Meteorological Department and analyzed.

The difference in location of the centre of cyclonic disturbance (CD) as estimated by microwave imageries and best track estimates decreases with intensification of the disturbances and varies from about 25 km in depression (D) stage to 18 km in VSCS stage whereas the difference is significantly higher in case of Dvorak estimate compared to best track estimate. The MSW based on microwave estimates is higher than that of best track estimates by about 28 knots during VSCS and 6-8 knots during D, CS, SCS stage. Considering relative difference with respect to best track estimates, the MSW is overestimated in microwave by about 12-15% in case of CS and SCS stage and by about 30% in VSCS stage while Dvorak's MSW overestimation reduced to 15-18% during CS, SCS and VSCS stages. Brightness temperature of the order of 230 K is favourable for genesis (formation of D), 250K for its intensification into CS, 260 K for intensification into SCS and 270K for its further intensification into VSCS stage over the Bay of Bengal. Detection of threshold value of brightness temperature may provide adequate lead time to forecast intensification of the system. Similarly, when brightness temperature anomaly exceeds 3K, CS intensify into SCS and 8K, it intensifies into a VSCS over Bay of Bengal.

Key words - Cyclone, Microwave, Satellite, Bay of Bengal, Track, Intensity

1. Introduction

Early warning system of cyclonic disturbances (Depressions and cyclones) involves various aspects including monitoring and prediction of their genesis, intensity and movement. Forecasters essentially require maximum surface wind and central pressure to estimate the intensity of cyclonic disturbances (CDs). Presently genesis and intensity of CDs over north Indian ocean (NIO) are mainly monitored by Infrared (IR) and visible cloud imageries from geostationary satellites as surface observations over ocean are scanty [India Meteorological Department (IMD), 2003]. There is scarcity of direct observations from the surface and upper air over the NIO due to limited number of buoys and ships and absence of aircraft reconnaissance unlike over the North Atlantic Ocean and northwest Pacific Ocean. Dvorak's technique (Dvorak, 1975) is used to determine intensity of CDs using IR and visible cloud pattern taken by the satellites. The technique is subjective and imprecise as high degree of skill is required to recognize cloud patterns and secondly convection is also not well related with storm intensity (Arnold, 1977). During night, intensity of the disturbance is not available for want of visible cloud imagery limiting operational requirement of the technique.

Microwave is powerful electromagnetic radiation for atmospheric sounding which is transparent to dense cloud due to high weighting function in middle atmospheric region (Meeks and Lilley, 1963; Veldon and Smith, 1983). Several studies have been made to convert microwave-based brightness temperature of the cloud into rain rate and surface wind associated with tropical cyclones (Evans and Stephans, 1993; Kummerow *et al.*, 1996). The brightness temperature is used to determine Estimated Central Pressure (ECP) and Maximum Sustained Wind (MSW) of the storm (Kidder, 1979; Goodberlet *et al.*, 1989 and Bessho *et al.*, 2006). Studies have also been carried out for horizontal and vertical thermal structure of cyclones and found that there is well defined warm temperature anomaly at upper levels in fully developed cyclones (Gray and Shea, 1973; Frank, 1977).

Though there are studies on application of microwave imageries and their product like brightness temperature in other ocean basin, the studies are limited over NIO on the relationship of brightness temperature with ECP and MSW. Singh (2008) studied cyclones over NIO during 28th November – 1st December 2005 using Advanced Microwave Sounding Unit (AMSU) data of National Oceanic Atmospheric Administration (NOAA) polar satellite series of 15, 16 & 17 and found that cyclones have deep tropospheric layer of warm core anomalies relative to surrounding near 300-250 hPa and maximum wind speed near surface. These findings agree with the finding over other regions.

Considering the importance of the microwave imageries and the availability of tools to analyse them, the microwave imageries have been operationally introduced for monitoring of CDs over NIO from 2010. In this application, the ECP and MSW estimated by the NOAA are utilized. As there is no aircraft reconnaissance over the NIO, the relationship of brightness temperature with the ECP and MSW has not been validated over the NIO and hence the relationship developed for the north Atlantic is utilized over the NIO.

The objective of this paper is to investigate relationship of brightness temperature with the MSW and ECP as estimated in the best track published by IMD. Further the location and intensity (MSW and ECP) based on estimates from microwave brightness temperature imageries have been compared with those based on best track estimates published by IMD. For this purpose, the CDs in the intensity stage of Depression (D), Deep Depression (DD), Cyclonic Storm (CS), Severe Cyclonic Storm (SCS) and Very Severe Cyclonic Storm (VSCS) during forecast demonstration project (FDP) on landfalling cyclones over the over Bay of Bengal conducted during 15th Oct – 30th Nov in 2008 – 2010 have been considered. The MSW of 17- 27, 28-33, 34-47, 48-63, 64-119 and $\geq$ 120 knots at surface level correspond to D, DD, CS, SCS, VSCS and Super CS respectively over NIO (IMD, 2003). Total five cyclones formed during

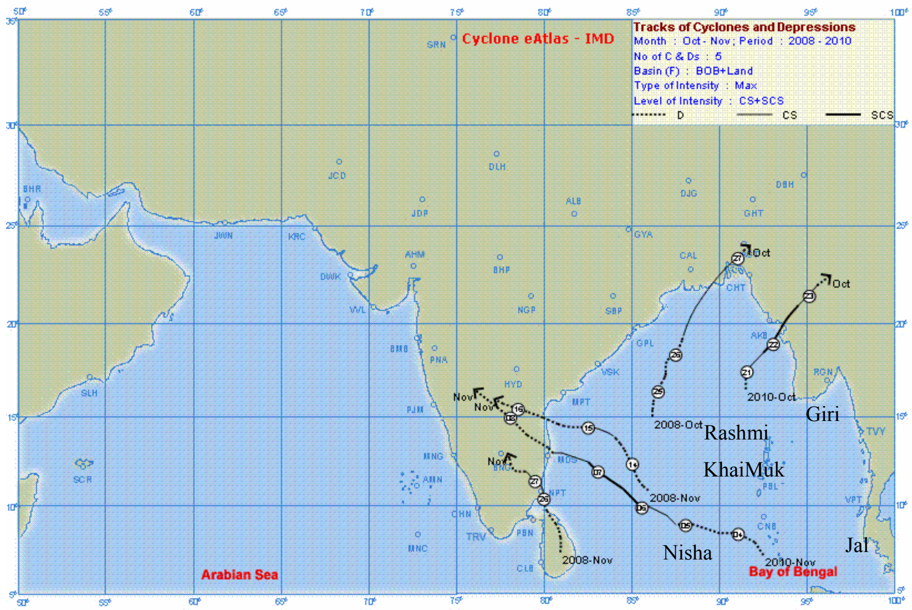


Fig. 1. Tracks of cyclones considered in the study

FDP period of 2008-2010. Hence, these five cyclones have been considered in this study. This study can be utilized in better interpretation of microwave based brightness temperature imageries and the derived product like MSW and ECP for estimating intensity of cyclone.

2. Data and methodology

Data on location of centre (latitude and longitude), ECP and MSW and brightness temperature derived from microwave radiance measurement in respect of 5 cyclones *viz*., Rashmi, Khai Muk, Nisha, Giri and Jal during 2008-10 have been extracted from website of U S Navy (www.nrlmrv.navv..mil/). These are available in respect of NOAA and FY-1 Series polar satellites passing over the Bay of Bengal. Track of the five cyclones considered in the study are shown in Fig. 1. Brief life history of these cyclones is discussed in next section. Best track data for the storms have been collected from Regional Specialized Meteorological Centre (RSMC), New Delhi. Due to intense observations and modernization of IMD, the availability of data was relatively better during the FDP period of 2008-10 than during past years. So best track estimation of cyclones during this period of study is more improved and can be considered as standard for comparison of parameters derived from microwave products. Best track parameters are available at 3/6 hours interval. The microwave cloud imageries are available after a gap of several hours at odd interval of time. Thus, microwave parameters like ECP, MSW and location under the scope of the investigation are interpolated at every 6 hourly intervals using finite differencing scheme in order to make it compatible with the best track data for comparison. ECP and MSW extracted from best track data set of IMD and microwave imageries are scrutinized before analyzing their relationship. Mean MSW and ECP based on both microwave imageries and best track estimates of IMD corresponding to different stages of intensity like D, DD, CS, SCS and VSCS have been analysed. For this purpose, the difference between the two estimates for ECP and MSW has been calculated.

Using hydrostatic equation and carrying out mathematical rearrangement and simplification relationship between pressure drop and brightness temperature anomaly is deduced following Palmen and Newton (1969).

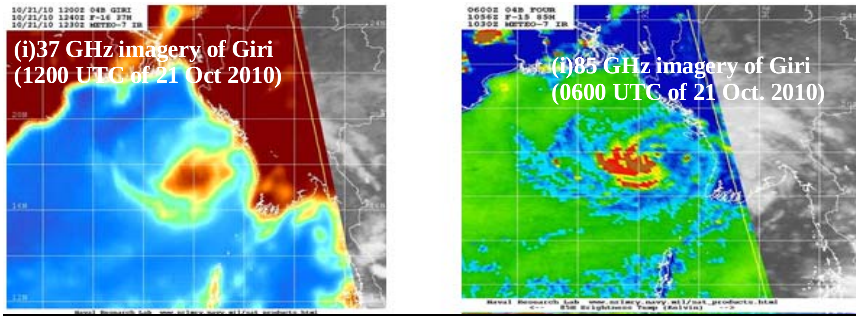
$$\Delta P = - 0.0055 * P^{env} * \Delta T \qquad (1)$$

Where ΔP = Pressure drop = (P^{eye} - P^{env}) and P^{env} is outermost closed isobar of cyclone,

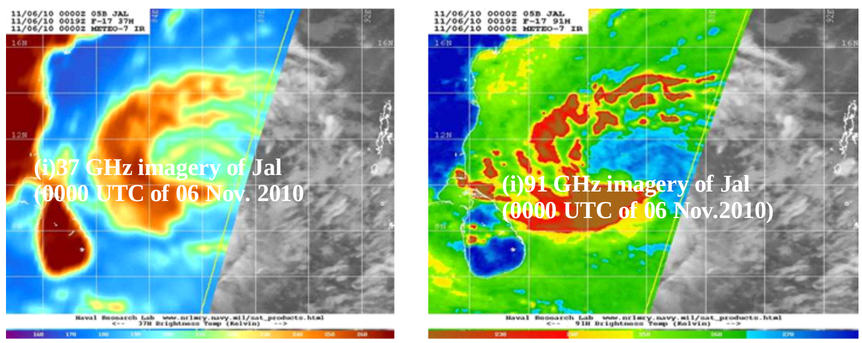
ΔT = (T^{eye} - T^{env}) and all terms signify their usual meaning.

T^{eye} is the warmest brightness temperature in the eye region and T^{env} is the average brightness temperature in the closed eye wall region. Utilizing pressure drop and ECP based on best track data of IMD, outermost pressure is derived and brightness temperature anomaly (ΔT) has been calculated in respect of different stages of cyclonic disturbances using equation-1 and analysed. The mean wind speed and the mean ECP corresponding to different stages of intensity

(a) 37 and 85 Ghz imagery of Giri



(b) 37 and 85 Ghz imagery of Jal



Figs. 2(a&b). 37 and 85/91 GHz microwave imageries during intensification period of (a) VSCS GIRI on 21st October 2010 and (b) SCS JAL on 6th November 2010

like D, DD, CS, SCS and VSCS has been analysed with respect to mean brightness temperature anomaly. All the above aspects have also been analysed for the individual SCS, Jal and VSCS, Giri, apart from the analysis of composite pattern based on all five cyclones.

Microwave radiation at higher frequency interacts with cold clouds and suffers scattering which would produce comprehensive physical state of clouds namely texture, brightness temperature, cluster and cluster distance around the centre of the storm. Microwave radiometer works on the principle that the radiance perceived by sensor is the function of radiation emitted by cloud and radiation emitted and absorbed by intervening atmosphere carrying out radiative transfer equation. Radiation emitted by cloud is function of given wavelength and emissivity of atmosphere (Alley and Nilson, 1999; Plank, 1901). Therefore brightness temperature is defined as the temperature that a black body would have in order to produce radiation observed from the cyclonic cloud. Brightness temperatures around the system centre (*i.e.*, wall cloud region) are derived using the cloud imagery to analyze ECP and MSW. There are usually two frequency bands namely 37 and 85 GHz for the microwave scanning of clouds. Figs. 1(a&b) show microwave cloud imageries of VSCS GIRI and SCS JAL in frequency range of 37 and 85 GHz as examples. As evident from the two figures, the cloud brightness temperature and its clusters organization are not visible distinctly at 37 GHz. An overlying cirrus canopy associated with tropical cyclone outflow typically obscures inner-core structure at 37 GHz, but the cloud layer is largely more clearly visible in the 85-GHz channel. Scattering of large precipitation particles provides a snapshot of the inner core precipitation structure in the 85-GHz channel. Cloud pattern together with centre of the system is also depicted clearly as the satellite sensed microwave emitted from low (warm) cloud at 37 GHZ whereas in 85 GHz channel, location and brightness temperature of each cloud cluster can be analysed for cold cloud. Hence 85 GHz cloud imagery is preferred to fix centre of the system superimposing microwave imagery over Bay of Bengal in cyclone module integrated with synergie system of weather forecasting on real time. In this study all the microwave imageries of 85 GHz pertaining to the system have been analyzed to make out utility of the cloud imageries in estimation of ECP and MSW.

TABLE 1

Mean difference in location based on (a) best track and microwave estimates and (b) best track and Dvorak's technique estimates

Stages of cyclonic disturbance	(a) Difference (km) in location based on best track and microwave estimates	(b) Difference (km) in location based on best track and Dvorak's technique estimates
Depression	25	34
Cyclonic storm	22	35
Severe cyclonic storm	21	27
Very severe cyclonic storm	18	42

TABLE 2

Mean Estimated Central Pressure (ECP) based on (a) microwave and (b) best track estimates

Stages of cyclonic disturbance	(a) Microwave based ECP (hPa)	(b) Best track based ECP (hPa)	Difference (a-b) in hPa
Depression	998	1002	-4
Cyclonic storm	985	994	-9
Severe cyclonic storm	970	988	-18
Very severe cyclonic storm	935	960	-25

TABLE 3

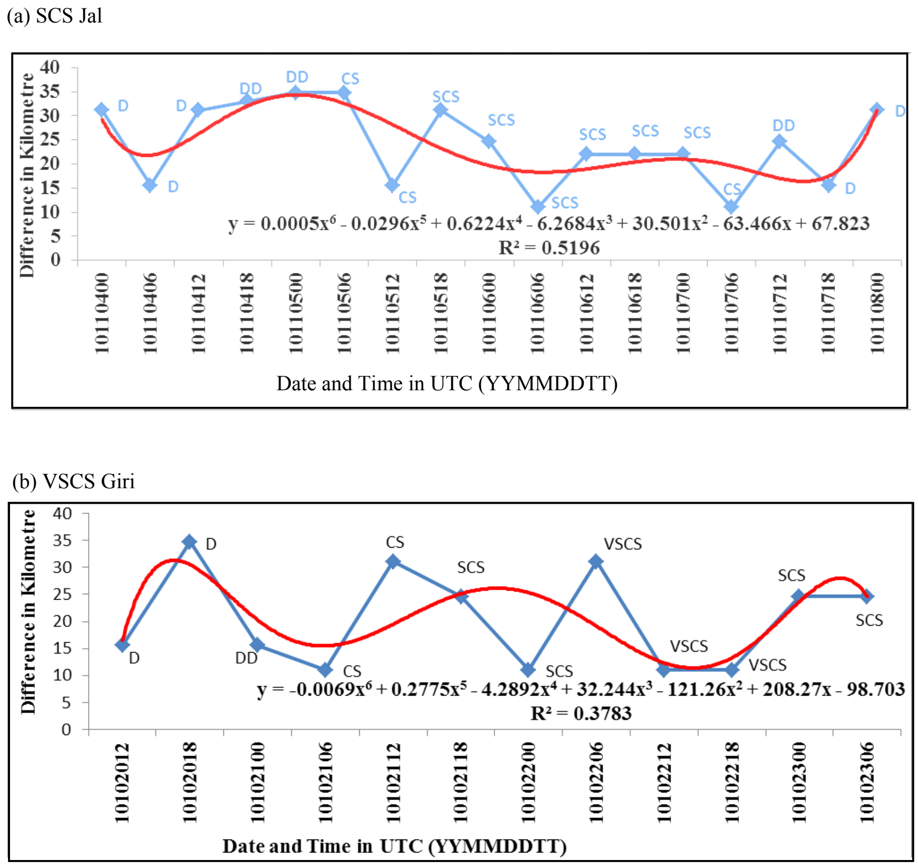
Mean MSW (knots) based on (a) microwave, (b) Dvorak's technique and (c) best track

Stages of cyclonic disturbance	(a) Microwave based MSW	(b) Dvorak's technique based MSW	(c) Best track based MSW	Difference in MSW (a-c)	Difference in MSW (b-c)
Depression	35	25	27	8	-02
Cyclonic storm	46	39	40	6	-01
Severe cyclonic storm	63	55	56	7	-01
Very severe cyclonic storm	116	98	88	28	10

3. Brief life history of cyclone under study

Out of the five tropical cyclones considered in the study, three could intensify upto CS (Rashmi, Nisha and Khai muk) ; one upto SCS (Jal) and one upto VSCS (Giri). Considering CS, 'Rashmi', it developed from a low pressure area formed over west central Bay of Bengal on 24th Oct 2008 and concentrated into a depression at 0300 UTC of 25th Oct. Moving in a north-northeasterly direction, the system intensified into CS and crossed Bangladesh coast about 50 km west of Khepupara (RSMC, New Delhi, 2009) . Similarly the CS, 'Khai muk' formed from a low pressure area over southeast Bay of Bengal on 13th November 2008. Moving northwestwards, the system intensified into a CS at 1200 UTC of 14th November over west central Bay of Bengal. Continuing to move northwestwards the system weakened into DD on 15th November over west central Bay of Bengal due low ocean thermal energy and high wind shear. Moving then west-northwestwards, it crossed south Andhra Pradesh coast to the north of the town of Kavali (RSMC New Delhi, 2009). The CS, 'Nisha' over the Bay of Bengal during 2008 developed from a low pressure area over Sri Lanka on 24th November 2008 which concentrated into a depression over the same region, centred to southwest of Trincomalee on 25th November. It intensified into CS over southwest Bay of Bengal at 0300 UTC of 26th November. It moved northwestwards and crossed south Tamil Nadu coast near Karaikal in the early morning of 27th November 2008.

During 2010 cyclone, 'Giri' originated from a low pressure area over east central Bay of Bengal on 19th Oct 2010 which concentrated into depression on 20th. It intensified into CS on 21st Oct 2010. Moving northeastwards it intensified into SCS at 0300 UTC of



Figs. 3(a&b). Difference between microwave and best track location of (a) SCS 'JAL' and (b) VSCS 'GIRI'

22nd October 2010 and rapidly intensified into VSCS on the same day. The system continued to move in the same direction and crossed Myanmar coast between Sittwe and Kyakpyu around 1400 UTC of 22nd October 2010. The last Cyclone, 'Jal' originated from a low pressure area formed over south Andaman Sea on 2nd November 2010 under influence of a remnant of a depression over northwest Pacific . It organized into well marked low pressure area on 3rd November 2010. Moving west-northwestwards, it concentrated into a depression at 0000 UTC of 4th November 2010 over southeast Bay of Bengal and intensified into CS at 0600 UTC of 5th November. It further intensified into SCS in the early morning of 6th November. Due to low ocean thermal energy and moderate to high wind shear, the SCS weakened into CS at 0600 UTC of 7th November; further weakened into DD and crossed north Tamil Nadu - south Andhra Pradesh coast close to north of Chennai (RSMC New Delhi, 2011). Detailed characteristics of these five cyclones are available in RSMC, New Delhi (2009 and 2011).

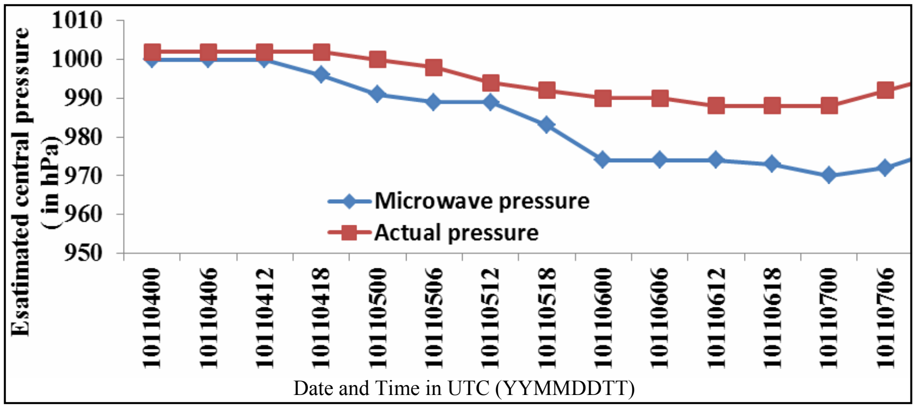
4. Results and discussion

Difference in location of CD based on microwave and best track estimate is presented and discussed in section 4.1. Similarly the difference in ECP and MSW are analyzed and presented in section 4.2 and 4.3 respectively. The relationship between brightness temperature and MSW is analyzed in section 4.4. The relation between brightness temperature anomaly and the intensity is presented and discussed in section 4.5.

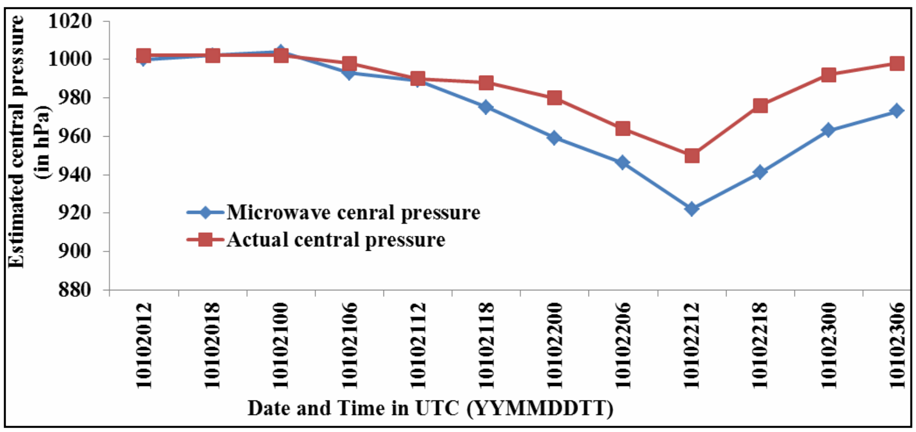
4.1. *Difference in location of cyclonic disturbance*

Table 1 shows mean differences of best track and Dvorak location compared to microwave imagery based location for each of the category of the systems. Difference of 25 km is found for D stage and 18 km for VSCS stage in case of location based on best track and microwave. The difference is 34 and 42 km for D and VSCS stages respectively with reference to the location based on Dvorak technique using infrared/visible cloud

(a) SCS Jal



(b) VSCS Giri



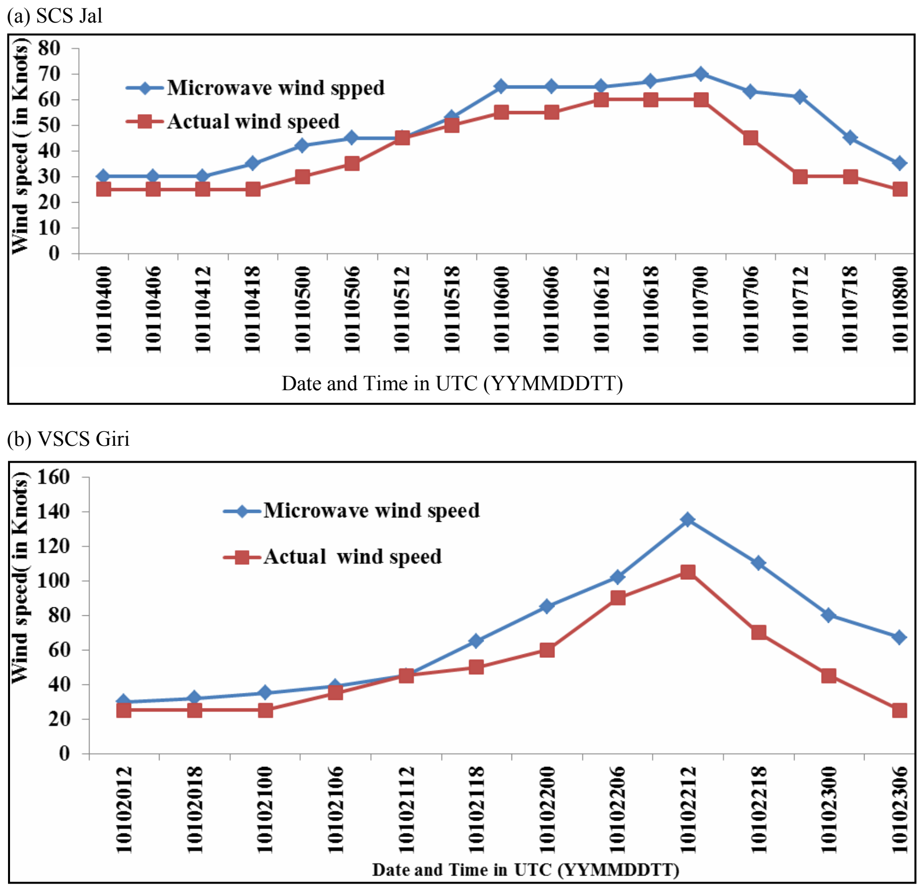
Figs. 4(a&b). ECP based on microwave and best track estimates in case of (a) SCS 'JAL' and (b) VSCS 'GIRI'

imageries and best track estimates. The lower difference of best track location from the microwave estimates may be attributed to the fact that the location estimation in the best track in recent years takes into consideration the available microwave imagery and products, buoy, ship, coastal and island observations and the wind observations based on Oceansat - II, ASCAT, Windsat, SSMI satellites etc, cloud motion vectors (CMV), water vapour based wind vectors (WVWV) from geostationary satellites in addition to the location estimates from the visible and infrared imageries.

Considering individual SCS and VSCS, Figs. 3(a&b) show difference between microwave and best track estimated locations during the period of genesis and intensification of SCS, Jal and VSCS, Giri at every 6 hourly intervals. One can find generally higher difference in location during stage of D and DD. When the system intensified into CS, SCS and VSCS stages, the difference decreased gradually as evident from the sixth order polynomial fitted to the six hourly plots of difference in location. Reason of reduced difference may be attributed to distinct delineation of location in well- organized cloud system where cloud pattern is generally central dense overcast (CDO) or eye pattern. However, the reason for non-uniformity in the variation of difference in location needs further investigation. Possible reason may be due to diurnal variation in the characteristics of cloud pattern as observed in geostationary and polar orbiting satellites, which would result in error in recognizing the correct cloud pattern and location of the system. Further, the location estimated using the geostationary satellite products at night might have introduced more error in location estimation due to availability of only IR imageries.

4.2. *Difference in ECP*

All cases are examined to find out the difference in ECP based on microwave derivation and best track. It is found that the difference increases significantly during intensification of the system into CS, SCS and VSCS



Figs. 5(a&b). Microwave and best track estimated MSW in case of (a) SCS 'JAL' and (b) VSCS ' GIRI'

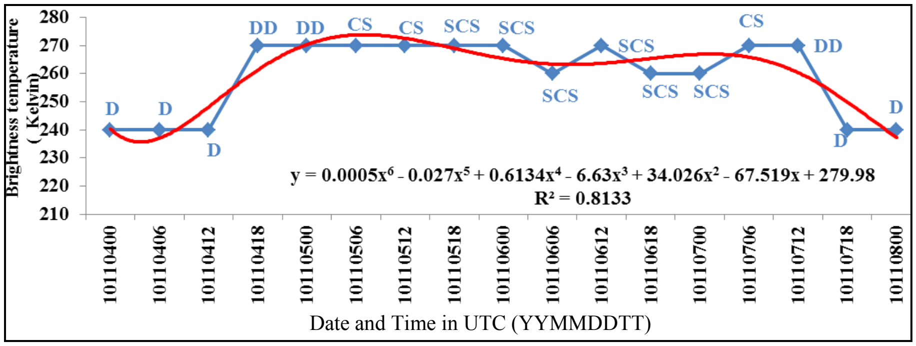
stages. The difference is about 9, 18 and 25 hPa in CS, SCS and VSCS stages respectively (Table 2). As long as the system is a D or DD, the mean difference is about 4 hPa (Table 3). Considering the individual SCS and VSCS, Figs. 4(a&b) show ECP of the SCS, Jal & the VSCS, Giri respectively. Similarly microwave ECP underestimated best track ECP for the remaining cyclonic storm too under investigation. According to microwave and best track estimations, the ECPs, are in phase. They gradually fall with intensification and rise during decay of the system. However, the difference in ECPs gradually increases with increase in intensity of the system and *vice versa.*

4.3. *Difference in MSW*

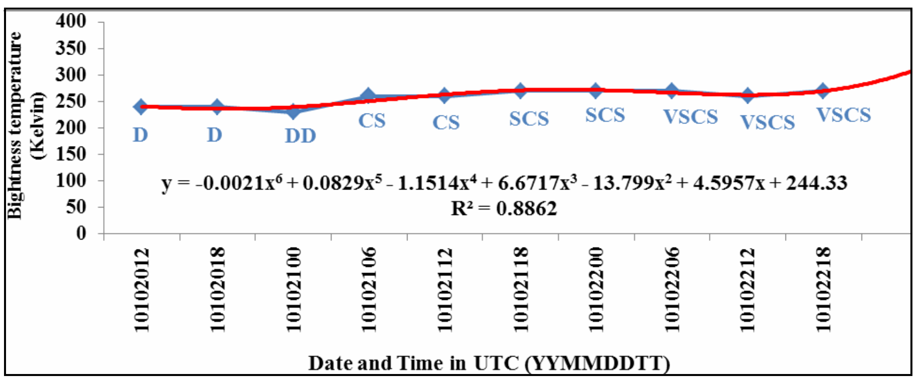
Table 3 shows mean MSW at D, DD, CS, SCS and VSCS stages based on microwave, best track and Dvorak estimates. There is a mean difference of 6-8 knots during D/CS/SCS stage and 28 knots during VSCS stage between the microwave and best track estimates. The difference is about 18 knots for VSCS stage between estimates based on Dvorak technique and best track estimates. It indicates that either Dvorak's technique may be underestimated or the estimates based on microwave may be over-estimated. The best track is dominated by Dvorak's technique estimates. Considering relative difference of microwave estimates with respect to best track estimates, the MSW is overestimated in microwave by about 12-15% in case of CS and SCS stage and by about 30% in VSCS stage.

For the individual SCS and VSCS, Figs. 5(a&b) shows microwave and best track estimated wind speed of SCS, Jal and VSCS Giri respectively. Microwave overestimated MSW, especially during intensification into CS, SCS and VSCS stages while the variations in the MSW during life cycle of the system are in phase. One can find that during D/DD stage, the differences are less compared with CS, SCS and VSCS stages. Differences of

(a) SCS Jal



(b) VSCS Giri



Figs. 6(a&b). 85 GHz Brightness temperature of (a) SCS and (b)VSCS GIRI

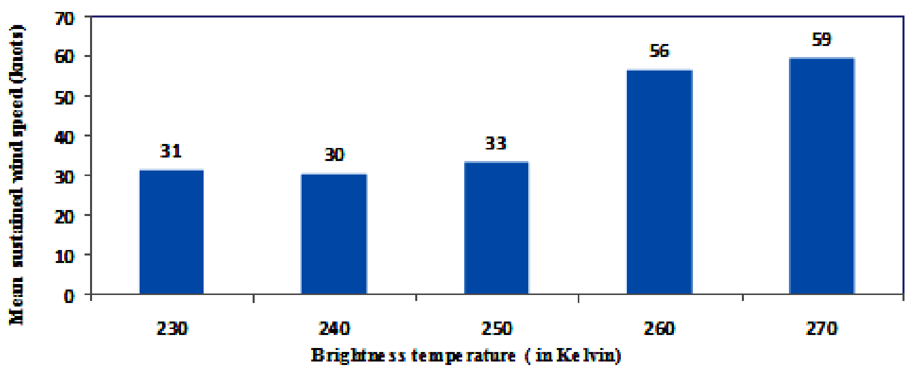


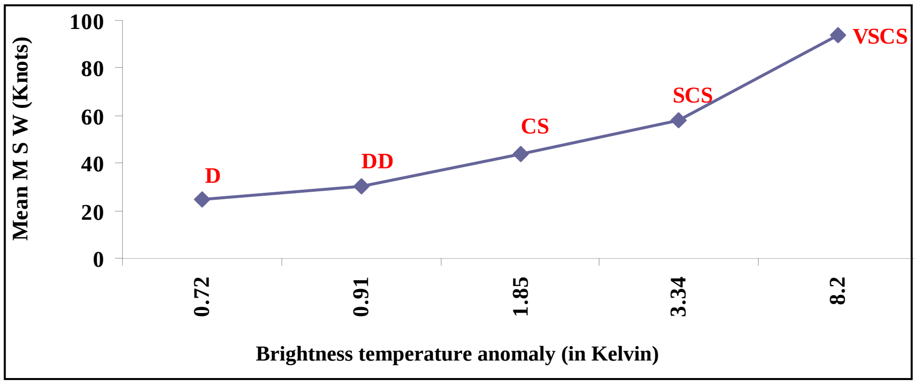
Fig. 7. Relation between Brightness temperature and Mean maximum sustained wind speed

5-10 knots are found in D and DD stages. However during SCS and VSCS stages, the differences are of the order of 20-40 knots. Comparing ECP and MSW differences (Tables 2 & 3), intensity is overestimated by microwave imageries compared to best track estimates.

4.4. *Relationship between brightness temperature and MSW*

Figs. 6(a&b) show variation of brightness temperature around centre of the systems during

(a) Mean wind speed



(b) Mean ECP

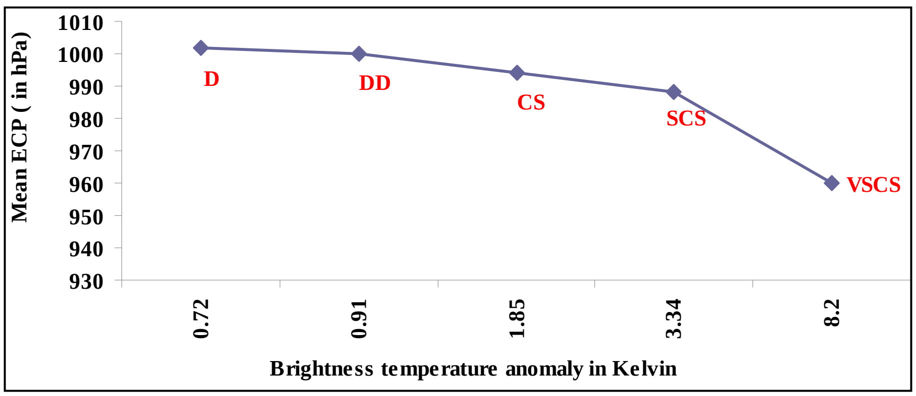


Fig. 8(a&b). Relation between brightness temperature anomaly at 85 GHz and (a) MSW and (b) ECP

intensification from D stage at 6 hourly interval till the SCS Jal and VSCS Giri crossed the coasts. Central brightness temperature is found in range of 230 – 270 Kelvin (K), the lowest is observed during intensification into D and highest of the order of 260-270 Kelvin (K) during VSCS stage. Similarly CSs, Rashmi, Khai muk and Nisha are also analyzed and the brightness temperature was found to be 230 K during depression and 260- 270 K during CS stage. One can find that there is continual rise of brightness temperature from D to VSCS stage.

Fig. 7 represents mean MSW based on microwave estimates and brightness temperature during different stages of intensity. The mean MSW of 30 knots is found at the temperature of 230-240 K and continue to increase with rise of the temperature. The highest MSW of 59 knots is found at the temperature of 270 K. MSW is directly proportional to brightness temperature for the well-developed cloud in intensifying CDs (Grody *et al.*, 1979).

4.5. *MSW and ECP in relation to brightness temperature anomaly*

Figs. 8(a&b) show relation of MSW and ECP with mean brightness temperature anomaly. The MSW increases and ECP decreases with rise in anomaly of brightness temperature. Values of mean brightness temperature anomalies are 0.72, 0.91, 1.85, 3.34 and 8.20 for D, DD, CS, SCS and VSCS stages respectively. The MSW is 25, 30, 44, 48, 58 and 94 knots respectively [Fig. 8(a)] for the corresponding anomalies as mentioned above and the corresponding ECP is about 1002, 1000, 994, 988 and 960 hPa. MSW rises and ECP falls abruptly as soon as the mean anomaly becomes 3.34 K.

Comparing derived brightness temperature anomaly from equation (1) and observed anomaly for the VSCS, Giri, it is found that observed anomaly lies in the range of 10-30 K against the calculated anomaly of 2-10 K. It indicates that either the best track estimates of intensity (MSW) are underestimated or there is overestimation of intensity (MSW) in microwave based estimates. This difference in temperature anomaly of observed and theoretical value may be attributed to the fact that there is no aircraft reconnaissance over the NIO. In the absence of that the relation between the brightness temperature and MSW as well as the relation between T number and MSW has not been validated over the NIO unlike north Atlantic Ocean. The relation developed over the north Atlantic Ocean is currently being used to estimate the intensity (MSW) based on both brightness temperature and the Dvorak's T number.

5. Conclusions

Microwave cloud imageries and derived products in the frequency of 85 GHz have been examined for five cyclones that occurred during FDP period (15 October- 30 November) of 2008-2010 over the Bay of Bengal to estimate the brightness temperature, brightness temperature anomaly, location of centre, MSW and ECP associated with cyclones in their different stages of intensification like D, DD, CS, SCS and VSCS stages. Also the observed brightness temperature anomalies are compared with the theoretically derived brightness temperature anomalies based on the best track estimates of ECP and outermost pressure for these cyclones. The location of centre, ECP and MSW based on microwave imagery estimates have been compared with those available from the best track estimates of IMD as well as Dvorak estimate and analysed. The following broad conclusions are drawn from the results and discussion.

(*i*) The difference in location of the centre of CD as estimated by microwave imageries and best track estimates decreases with intensification of the CD. The average difference in location varies from about 25 km in D stage to 18 km in VSCS stage. The difference in location based on visible/infrared imageries and the best track estimates is relatively higher. It indicates the location estimated by microwave is closer to best track estimates.

(*ii*) The MSW based on microwave estimates is higher than that of best track estimates by about 28 knots during VSCS and 6-8 knots during D/CS/SCS stage. Considering relative difference with respect to best track estimates, the MSW is overestimated in microwave by about 12-15% in case of CS and SCS stage and by about 30% in VSCS stage. Intensity based on Dvorak's technique is less than that by microwave estimates.

(*iii*) Brightness temperature of the order of 230 K is favourable for genesis (formation of D), 250 K for its intensification into CS, 260 K for intensification into SCS and 270K for its further intensification into VSCS stage over the Bay of Bengal. Detection of threshold value of brightness temperature may provide adequate lead time to forecast intensification of the system. Similarly, when brightness temperature anomaly exceeds 3 K, CS intensify into SCS and 8 K, it intensifies into a VSCS over Bay of Bengal.

(*iv*) The observed brightness temperature anomaly lay in the range of 10-30 K against the calculated anomaly of 2-10 K in case of VSCS, Giri over the Bay of Bengal. It indicates that either the best track estimates of intensity (MSW) are underestimated or there is overestimation of intensity (MSW) in microwave based estimates. This difference in temperature anomaly of observed and theoretical value may be attributed to the fact that there is no aircraft reconnaissance over the NIO. In the absence of that the relation between the brightness temperature and MSW as well as the relation between T number and MSW has not been validated over the NIO unlike North Atlantic Ocean. The relation developed over the north Atlantic Ocean is currently being used to estimate the intensity (MSW) based on both brightness temperature and the Dvorak's T number.

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