MAUSAM, **57**, 4 (October 2006), 609-618

551.511 : 551.509.57 : 551.501.81

On forecasting tracks of tropical disturbances using ATOVS data over Bay of Bengal

R. SURESH*, S. K. KUNDU, A. K. BHATNAGAR and R. C. BHATIA

** India Meteorological Department, Chennai – 600 001, India*

India Meteorological Department, New Delhi – 110 003, India

(*Received 1 February 2005, Modified 1 March 2006*)

e mail : suresh.imd@gmail.com

सार –एक उष्णकटिबंधीय अवदाब के जीवन चक्र के आंकड़े तथा दो उष्णकटिबंधीय चक्रवाती तूफानों के वर्ष 2002–03 की अवधि के आंकड़े उच्च टी. ओ. वी. एस. (ए. टी. ओ. वी. एस.) ध्रुवकक्षीय उपग्रहों एन. ओ. ए. ए 15 तथा 16, जिनमें उच्च सूक्ष्म तरंगीय परिज्ञापन इकाई (ए. एम. एस. यू) लगी हुई हैं से प्राप्त किए गए हैं जिनका विश्लेषण इन तूफानों के मार्ग का पूर्वानुमान करने के लिए किया गया है। इन मौसम विक्षोभों के 700–400 हेक्टापास्कल (हे.पा.) स्तर में मध्य क्षोभमंडलीय उष्णता मध्य स्तरी बाहिर्वाह के कारण होती है जो तूफान के 200–700 कि.मी. आगे तक विस्तारित होती है तथा विक्षोभों की गतिशीलता का करीब 6 से 24 घंटे पहले पूर्वानुमान करने में पूर्व संकेतक का कार्य करती है। यह विक्षोभ लगभग उसी अक्ष को अनुगमन करता है जो मध्य क्षोभमंडल में विस्तारित (आगे बढ़े हुए) जिह्वाकार उष्ण क्षेत्र को केन्द्र से जोड़ता है। मध्यम तीव्रता वाले दो भूमंडलीय चक्रवातों की स्थिति में जब 7° से 13° सेल्सियस तापमान का उष्मकोर ऊपरी क्षोभमंडलीय स्तर (250–200 हे.पा.) के करीब केंद्रित रहा उस समय अवदाब की स्थिति में किसी विशेष उष्णता का पता नहीं चला है।

ABSTRACT. Advanced TOVS (ATOVS), comprising the Advanced Microwave Sounding Unit (AMSU), data obtained from polar orbiting satellites NOAA 15 and 16 during the life cycle of a tropical depression and two tropical cyclonic storms during 2002-03 have been analysed to predict the track of these disturbances. The mid-tropospheric warming due to altostratus outflow from these weather disturbances in the layer 700 – 400 hPa which protrudes about 200 -700 km ahead the storm acts as a pre-cursor to predict the movement of the disturbances with a lead time of about 6 to 24 hours. The disturbance almost follows the axis connecting the centre with the warm tongue that protrudes ahead of the disturbance in the mid-troposphere. While warm core of 7 to 13° C is centered around the upper tropospheric level (250 – 200 hPa) in the case the two moderate intensity tropical cyclones, no significant warmness could be seen in the depression stage.

Key words – Tropical cyclone, Depression, Track forecast, ATOVS, AMSU, Doppler Weather Radar, Mid-tropospheric warmness, Altostratus outflow.

1. Introduction

Tiros Operational Vertical Sounder (TOVS), comprising of 20 channel High Resolution Infra-red Sounder (HIRS), 4 channels Microwave Sounding Unit (MSU) and 3 channels Stratospheric Sounding Unit (SSU), onboard NOAA series of polar orbiters (upto NOAA-14) provides vertical profiles of temperature, humidity and geo-potential heights at standard pressure levels besides columnar ozone, precipitable water vapour and outgoing longwave radiation. The technical details, processing algorithm, retrieval procedures and usefulness and limitations of TOVS data have been excellently documented in Kidder and Vondar Harr (1995) and Cracknell (1997).

1.1. *Validation and utilisation of TOVS data in Indian weather conditions*

The validation of TOVS derived atmospheric parameters over the Indian region has been done by Khanna and Kelkar (1993), Gupta *et al*. (1996) and Suresh and Rengarajan (2001). As the Root Mean Squared Error (RMSE) between TOVS derived temperature and that obtained through Radio sonde are smaller than the natural variability (*i.e.*) the standard deviation of radio-sonde data, satellite soundings can be used in operational weather analysis as they explain a substantial fraction of variance of atmospheric temperature. Hence these data were used to study the thermodynamics of northeast and southwest monsoon by Suresh and Raj (2001) and Suresh *et al.* (2002). Since the RMSE of less than 2.0° C is quite low to monitor the thermal structure of tropical cyclones (Kidder *et al*., 2000), TOVS data has been successfully used to study the movement of tropical cyclones over Bay of Bengal and Arabian Sea by Suresh and Rengarajan (2002).

1.2. *Advanced TOVS (ATOVS)*

The TOVS instrumentation had gone a substantial change from NOAA-15 (launched during May 1998). The

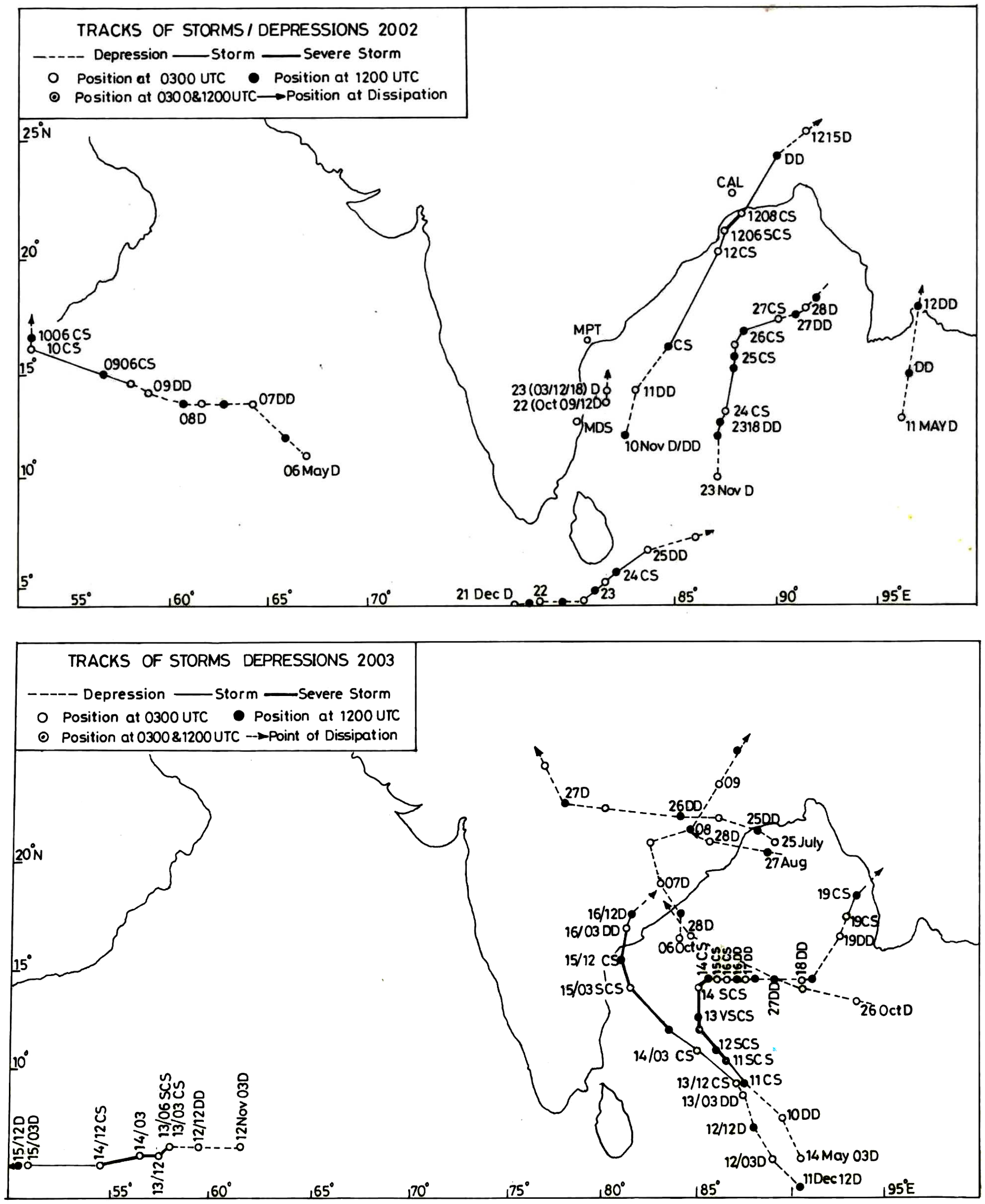

Fig. 1. Finalised tracks of tropical disturbances of 2002 –2003 (*Source* : India Meteorological Department)

Advanced TOVS (ATOVS) consists of improved HIRS and Advanced MSU (AMSU). The improvement in HIRS sensors include the radiant cooler operation at 95 °K, the reduction in internal field of view to 10 km, the inclusion of a fifth internal warm target temperature sensor and an additional tertiary telescope temperature sensor. The 4 channel MSU and the 3 channel SSU of TOVS have been replaced by a 20 channel AMSU. AMSU has two components, AMSU-A comprising 15 channels (channels 1 to 15) for upper air temperature retrieval and AMSU-B comprising 5 channels (channels 16 to 20) for moisture parameters retrieval. AMSU-A is a cross-track, line-scanned instrument designed to measure scene radiances in 15 discrete frequencies (23.8 to 89.0 GHz). AMSU-A is further classified as AMUS-A1 (channels 3 through 15, with frequencies 50.3 to 89.0 GHz) which is used for the calculation of the vertical temperature profile from the earth's surface to about 3 hPa (45 km) and AMSU-A2 (K band, channel 1 at 23.8 GHz and Ka band, channel 2 at 31.4 GHz) for the retrieval of all forms of atmospheric water except small ice particles. At each channel frequency, the antenna beam width is 3.3°. Each scan covers 50° on each side of the sub-satellite path and samples thirty contiguous scene resolution in stepped-scan fashion in eight seconds periodicity. These scan patterns and geometric resolution translate to a 48 km diameter cell at nadir and a 2,179 km swath width from the 833 km nominal orbital altitude.

The AMSU-B is also a cross track, line scanning instrument designed to measure scene radiances from 89 to 183 GHz frequencies. The beam width at each channel frequency is 1.1°. The AMSU-B instrument consists of a scanning parabolic antenna which is rotated once every 8/3 seconds to measure the radiance. Each scan covers 50° on either side of the sub-satellite path and samples ninety contiguous scene resolution in a continuous fashion. These scan patterns and geometric resolution translate to a 16 km diameter cell at nadir at a nominal altitude of 850 km. While channels 16 (89 GHz) and 17 (150 GHz) enable deeper penetration through the atmosphere upto the earth's surface, channels 18 to 20 (operating at 183.3 ± 7 GHz) span the strongly opaque water vapour absorption line. Thus the AMSU-B receives radiation from different geo-physical layers of the atmosphere and help us to estimate the humidity profiles on a global scale. Technical description of ATOVS is beyond the scope of this paper and interested readers may have it from http://www2.ncdc.noaa.gov/docs/klm.

1.3. *Validation and utilisation of ATOVS retrievals*

The major advantages of ATOVS are the very high spatial resolution and radiometric accuracy. AMSU is quite capable of measuring / deriving main tropical cyclone parameters of interest such as storm location, liquid water content and thermal anomalies in view of the fact that clouds are well-neigh transparent to microwave radiation. Algorithms for the errors in estimation caused by antenna side lobes (Mo, 1999) and limb adjustment due to increased path length (Wark, 1993) need to be applied to get the best estimation. Details of limb adjustment, temperature retrieval procedure and validation of ATOVS data may be seen from Goldberg(1999) and Jun Li *et al.* (2000). Validation of ATOVS derived temperature with that obtained through collocated radio sondes in the domain Equator – 30° N during September – November, 1998 indicated a root mean squared error of less than 1.75° C from 1000 to 150 hPa (Kidder *et al.*, 2000).

ATOVS data received from NOAA-15 and 16 satellites at the direct readout ground station at India Meteorological Department (IMD), New Delhi have been used in this paper to study the thermo dynamical structure of two tropical cyclones and one tropical depression over Bay of Bengal during 2002-2003. Moreover, tracks of these tropical disturbances have been studied in this paper using the temperature profile obtained from the AMSU.

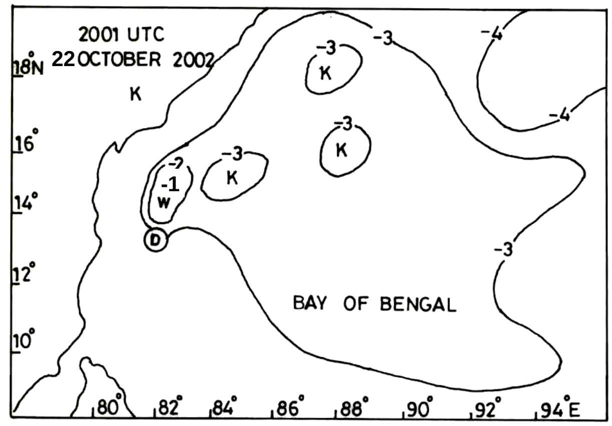

Fig. 2. Analysis of 700 – 400 hPa layer mean temperature (°C) at 2001 UTC / 22 October 2002

2. Data

Fig. 1 shows the best tracks of tropical disturbances over Bay of Bengal during 2002 and 2003 as finalised by the apex National Meteorological and Hydrological services of India, *viz.*, IMD, during its Annual Cyclone Review Meetings. Due to technical problems and limitations, ATOVS data were not available in the direct readout ground station at IMD, New Delhi for all the disturbances shown in this figure. The available ATOVS data from NOAA 15 and 16 satellites have been antenna side lobe corrected, limb corrected and processed for two tropical cyclones (Kolkata cyclone, 11-12 November 2002 and Machilipatnam cyclone, 13-16 December 2003) and for a tropical depression on 23 October 2002. AMSU soundings over the domain 6 to 22° N / 72 to 96° E have been used to derive temperatures at 1000, 975, 950, 925, 900 hPa, and thereafter at every 50 hPa interval upto 100 hPa, and then at 70, 50, 30, 20 and 10 hPa. In all as many as 9,500 records have been analysed, of which 1950 pertains to the Bay depression on 23 October 2002, more than 3000 pertain to Kolkata cyclone during 2002 and 4550 correspond to the Machilipatnam cyclone during 2003. Imageries from the geo-stationary satellite (METEOSAT) that had been obtained in real time from Dundee University website (http://www.sat.dundee.ac.uk) during the said period are consulted wherever necessary to identify the intensity of the disturbances. Data obtained by Doppler Weather Radars (DWR) at Chennai and Kolkata have also been considered to identify the structure of the disturbances.

3. Methodology

Simpson (1954), using aircraft reconnaissance, has postulated the concept of protrusion of mid-tropospheric warmness due to altostratus outflow far ahead of typhoons. Simpson argued that altostratus outflow from the typhoons is more significant than the

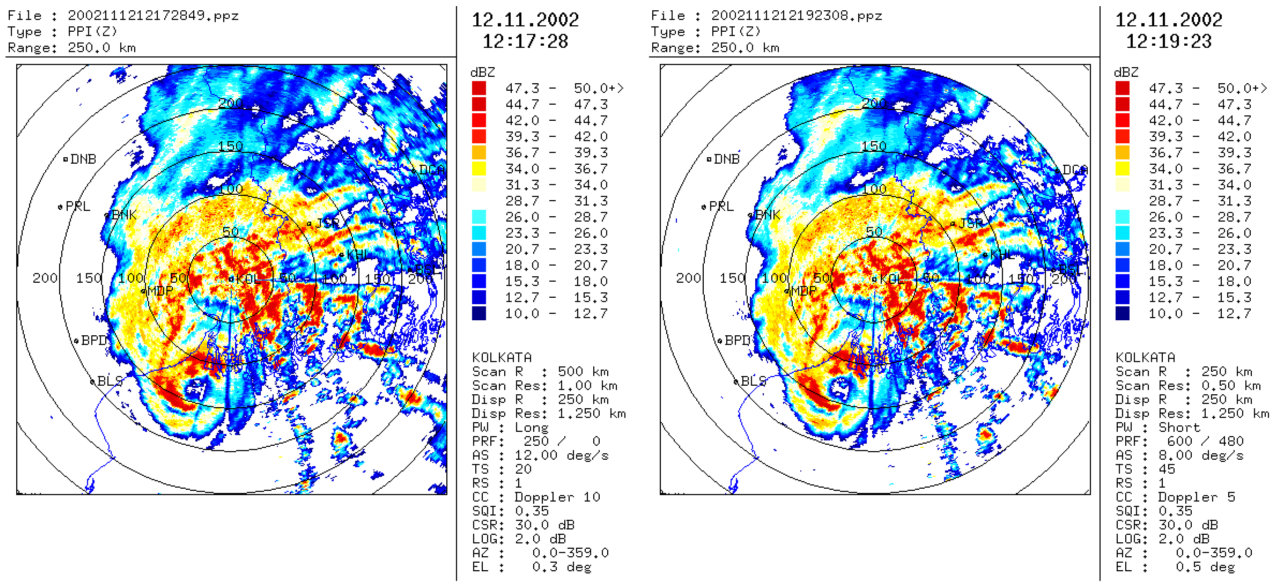

Fig. 3. Panoramic view of severe cyclonic storm tracked by Doppler Weather Radar at Cyclone Detection Radar station, Kolkata at 1217 hrs (IST) (0647 UTC) and 1219 hrs (IST) (0649 UTC) on 12 November, 2002 when the cyclone attained T4.5 intensity on Dvorak's scale

cirrus outflow in causing a significant warmness in the 700-500 hPa layer at a distance from 400 km to as far away as 1000 km ahead of the storm. As opined by Simpson, the altostratus outflow causes the protrusion of warm tongue ahead of the disturbance and the tropical disturbance follows the track obtained by joining the centre of the disturbance with the relatively warm mid-tropospheric locations. This concept has been studied in-depth by Suresh and Rengarajan (2001 and 2002) and they established that the layer mean 700-400 hPa warmness protrudes about 300 to 700 km ahead of the storm and acts as precursor to foreshadow the storm movement and predict the landfall about 6 to 24 hrs in advance over Bay of Bengal and Arabian Sea. They have also demonstrated that this technique could predict the rare southward movement of Bay of Bengal cyclone, 28 November – 7 December, 1996. The 700-400 hPa layer mean temperature computed from ATOVS data have been plotted and isothermal analysis carried out. The average layer mean temperature in the analysis domain varies from –3 to –5.5° C. However, it has been observed that in the vicinity of a tropical disturbance (tropical depression / tropical cyclone), the 700-400 hPa layer is warmer by 0.5 to 4.0° C indicating that adequate warming takes place in the mid-troposphere in association with the disturbance.

3.1. *Tropical depression 22-23 October 2002*

A tropical depression, with intensity T1.5 in Dvorak's scale, Dvorak (1975), formed at 0900 UTC on 22nd October 2002 over Bay of Bengal remained practically stationary at 13.5° N / 81.5° E upto 1200 UTC and subsequently intensified into T2.0. It had a very slow northward movement and located at 14.0° N / 81.5° E at 1800 UTC / 22nd . The depression remained practically stationary upto 1200 UTC of 23rd and thereafter weakened in Bay itself. Fig. 2 shows the layer mean temperature of 700-400 hPa obtained from NOAA-16 AMSUs at 2001 UTC on 22nd. A localised mean layer warmness of 3° C (in comparison to the surroundings) was observed at about 50 – 100 km north of the disturbance. The possible direction of movement of the depression (line joining the centre of depression and the protrusion of maximum warmness) was in total agreement with that finalised by IMD. However, there is an eastward shift of about 0.5° in locating the centre of the storm based on ATOVS data albeit the latitude fixation agrees with that of IMD.

3.2. *Kolkata cyclone, 11-12 November 2002*

A depression formed at 12.0° N / 82.5° E at 0300 UTC on 10 November, 2002 intensified into a cyclonic storm at 1200 UTC on 11th and lay centered at 16.0° N / 84.5° E with intensity T3.0 on Dvorak's scale. The cyclone intensified further and became a severe cyclonic storm at 0600 UTC on 12th with T4.5 and centered at 21.0° N / 87.5° E. Fig. 3 depicts the plan position indicator (PPI) plots of logarithmic radar reflectivity factor (Z) as tracked by DWR at Kolkata at 0647 and 0649 UTC on 12th when the storm attained its maximum intensity of T4.5. The storm then weakened into a cyclonic storm (21.7° N / 88.3° E) at 0800 UTC and crossed the West Bengal coast. The system had

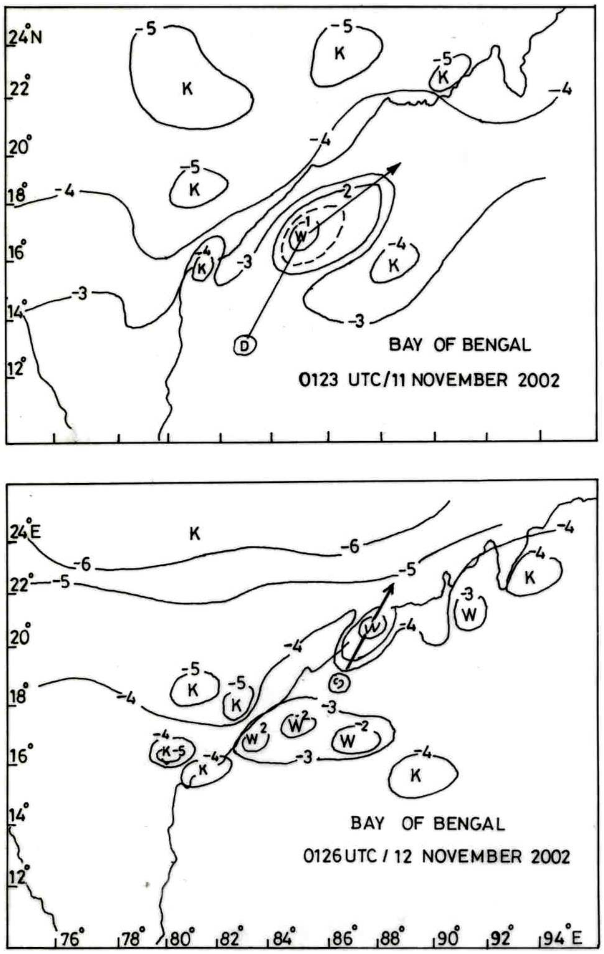

Fig. 4. AMSU derived mid-tropospheric (700 – 400 hPa) warmness (°C) that shows the possible track of cyclonic storm on 11th and 12th November 2002

northnortheast to northeastward movement almost throughout its sea travel from its cyclonic intensity stage. Fig. 4 illustrates the analyses of ATOVS derived 700-400 hPa mean temperature and the protruding mid-tropospheric warmness ahead of the storm on 11th and 12th. However, localised warmness was also seen in about 200 km south of the storm at 0126 UTC on 12th and there are large data gaps between 18 and 20° N / 84 and 90° E. As such the exact warmness in the northern sector of storm could not be clearly found out. Nonetheless, going by the tendency as well as climatology of the storm, the possible track has been marked towards the northern mid-tropospheric warmness. Track as estimated from the analyses of temperatures derived from AMSU onboard NOAA-15 satellite at 0123 UTC on 11th and 0126 UTC on 12th almost coincided with that the actual track of the storm as observed by the DWR at Kolkata and the best track that has been finalised by IMD (IMD, 2003).

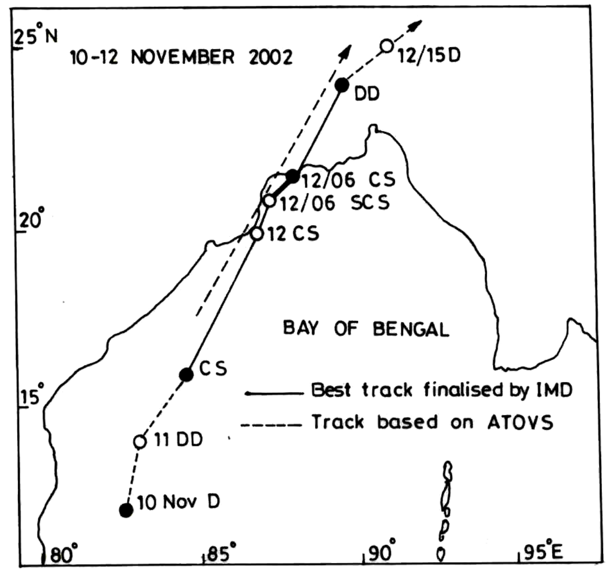

Fig. 5. Possible track predicted by AMSU compared with track as finalised by IMD

Due to scan geometry limitations of the polar orbiters, only a portion of the storm could be detected by the day time NOAA 16 passes, *viz.*, 0712 UTC on 11th and 0839 UTC on 12th. The core region of the storm was missed by these passes. Hence analyses of data obtained from these passes have not been presented in this paper. The land fall was predicted from the mid-tropospheric warmness (based on 0126 UTC of 12th NOAA15 data) about six hours in advance. The possible track of the storm as derived from AMSU data (based on 1951 UTC/ 10th, 0123 UTC/11th and 0126 UTC/12th satellite passes) compared with that finalised by IMD has been shown in Fig. 5. For this purpose, the first warmest mid-tropospheric location ahead of the storm (*i.e.*, the southern most point of the warm tongue, ahead of the storm) has been joined with the known storm centre just prior to and/or at the time of the satellite pass and the track thus obtained has been extended along the warmest locations of the warm tongue. While the direction of storm's movement can be predicted from the track thus obtained, the speed of the storm can be estimated from persistence/ immediate past movement.

Since the mid-tropospheric warmness protrudes 200-700 km ahead of the storm (Simpson, 1954; Suresh and Rengarajan, 2002) and the tropical cyclones move over the oceanic area at an average speed of 10-30 kmph (IMD, 2003 and 2004), forecast based on ATOVS analyses can be issued with 9 to 24 hrs lead time depending on the nearest warm tongue location.

The nearest warmer location at 0123 UTC / 11th was at 16.18° N / 84.54° E with a layer mean temperature of

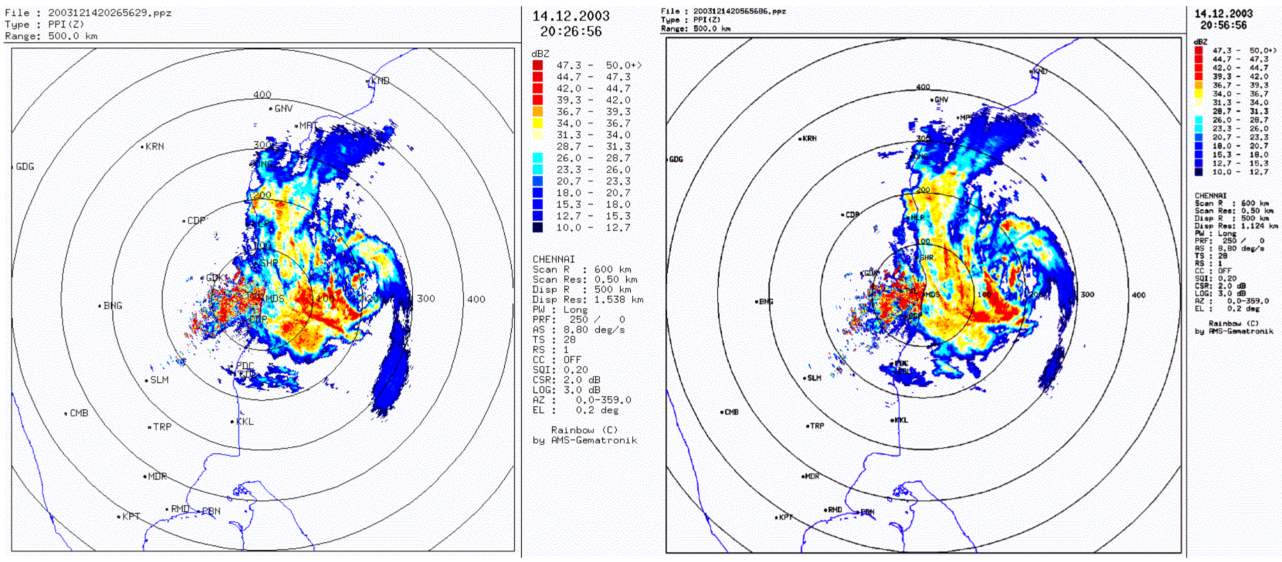

Fig. 6. Bay storm with severe cyclonic storm intensity (T3.5) at 2026 UTC and 2056 UTC on 14 December, 2003 as tracked by Doppler Weather Radar, Chennai

TABLE 1

Errors in estimating the track of Kolkata cyclone, 10-12 November 2002 using ATOVS data

Forecast position valid at (time / date)	Forecast position based on ATOVS	IMD's finalised position	Error in estimation (km)	Forecast lead time
1200 UTC / 11$^{th\ @}$	16.18° N/ 84.54°E	16.0° N/ 84.5° E	18	10 hrs 30 min
2100 UTC / 11$^{th\ @}$	17.60° N/ 84.85° E	16.5° N/ 84.0° E	139	19 hrs 30 min
0000 UTC / 12$^{th\ @}$	18.20° N/ 85.30° E	19.0° N/ 86.5° E	144	22 hrs 30 min
0600 UTC/12$^{th\ \#}$	21.68° N/ 87.20° E	21.0° N/ 87.5° E	74	04 hrs 30 min
0900 UTC / 12$^{th\ \#}$	22.20° N/ 88.20° E	22.5° N/ 88.5° E	42	07 hrs 30 min

Note : @ Forecast based on ATOVS data of 0123 UTC / 11th November 2002.
\# Forecast based on ATOVS data of 0123 UTC / 12th November 2002.
Forecast lead time = Time at which the forecast is valid – Time of availability of processed HRPT data.

–2.0° C which is 1.5 to 2.0° C warmer than the surrounding. This location is about 300 km ahead of the storm. Based on persistence, the forecast position at 1200 UTC has been fixed as this location. The IMD's track position at 1200 UTC / 11th was 16.0° N / 84.5° E. The forecast is in good agreement with the best track finalised by IMD. The warmest locations were 17.65° N / 84.4° E (with 700 – 400 hPa layer mean temperature of -1.15° C) and 17.55° N / 85.3° E (with -1.48° C mean temperature). These locations are warmer than the surroundings by more than 3.0° C and they are at a distance more than 420 km from the storm centre. By assuming the past speed of 20-25 kmph, the forecast positions at 2100 UTC / 11th and 0000 UTC / 12th have been made. In a similar way, the forecast position at 0600 UTC / 12th based on ATOVS data of 0126 UTC / 12th was fixed at 21.68° N / 87.2° E, having the layer mean temperature of – 1.85° C, which is in close agreement with IMD's 0600 UTC position, *viz.*, 21.0° N / 87.5° E . Forecast position at 0900 UTC, *viz.*, 22.2° N / 88.2° E was almost tallying with the landfall location near Sagar island around 0900 UTC / 12th. The positional errors with reference to the IMD's finalised track have been tabulated in Table 1. The storm, according to IMD(2003), had moved with a extremely rare and high speed of about 120 kmph from 16.5° N / 84.0° N at 2100 UTC / 11th to 19.0° N / 86.5° E at 0000 UTC / 12th. Hence the error in track prediction based on persistence, climatology and climatology and persistence (CLIPER) are not available for this storm in IMD (2003) for comparison. However, going by the available records the

TABLE 2

Warmest locations at 0817 UTC and 2049 UTC on 13 December, 2003

0817 UTC / 13 December 2003			2049 UTC / 13 December 2003		
Latitude (°N)	Longitude (°E)	700-400hPa layer mean temperature (°C)	Latitude (°N)	Longitude (°E)	700-400hPa layer mean temperature (°C)
12.4	87.4	- 0.44	13.7	83.6	- 0.37
13.4	87.4	- 0.60	13.8	83.1	- 0.69
09.8	86.6	- 0.70	11.3	83.0	- 0.50
13.8	87.1	- 1.10	11.4	82.6	- 0.58
10.0	87.5	- 1.30	11.0	82.4	- 1.07
08.9	86.9	- 1.40	10.8	83.5	- 1.13
13.2	86.7	- 1.50	11.3	83.6	- 1.24

Note : The mean layer temperature about 300 – 500 km away from the disturbances are of the order of –3 to –5° C.

TABLE 3

Errors in estimating the track of Machilipatnam cyclone, 11-16 December 2003 using ATOVS data

Forecast position valid at (time / date)	Forecast position based on ATOVS	IMD's finalised position	Error in estimation (km)	Forecast lead time
1800 UTC / 13th @	10.00° N / 88.00° E	10.0° N / 87.0° E	100	09 hrs 30 min
2100 UTC / 13th @	10.50° N / 87.30° E	10.5° N / 86.5° E	80	12 hrs 30 min
0000 UTC / 14th @	10.60° N / 87.00° E	10.5° N / 86.0° E	104	15 hr 30 min
0600 UTC / 14th #	11.50° N / 85.50° E	11.0° N / 85.0° E	71	09 hrs
0900 UTC / 14th #	11.80° N / 84.60° E	11.5° N / 84.5° E	32	12 hrs
1200 UTC / 14th #	12.20° N / 84.20° E	12.0° N / 83.5° E	73	15 hrs
1800 UTC / 14th &	13.00° N / 82.90° E	12.8° N / 82.5° E	45	09 hrs 40 min
2100 UTC / 12th &	13.50° N / 82.80° E	13.4° N / 82.2° E	61	12 hrs 40 min
0300 UTC / 15th *	13.80° N / 82.00° E	14.0° N / 81.5° E	54	06 hrs 10 min
0900 UTC / 15th *	14.20° N / 81.20° E	15.0° N / 81.0° E	82	12 hrs 10 min
1200 UTC / 15th *	14.75° N / 81.08° E	15.5° N / 81.0° E	75	15 hrs 10 min
1500 UTC / 15th *	15.22° N / 81.18° E	15.8° N / 81.0° E	61	18 hrs 10 min
1800 UTC / 15th *	16.15° N / 81.40° E	16.0° N / 81.0° E	43	21 hrs 10 min

Note : @ Forecast based on ATOVS data of 0817 UTC / 13th December 2003.
Forecast based on ATOVS data of 2049 UTC / 13th December 2003.
& Forecast based on ATOVS data of 0805 UTC / 14th December 2003.
* Forecast based on ATOVS data of 2034 UTC / 14th December 2003.
Forecast lead time = Time at which the forecast is valid – Time of availability of processed HRPT data.

error in forecasting of the storm track through ATOVS is much comparable to that obtained using Quasi Lagrangian Model, persistence, climatology and CLIPER, *viz*., 150 to 330 km.

3.3. *Machilipatnam cyclonic storm, 13 – 16 December 2003*

The depression formed at 1200 UTC on 11th December 2003 (4.5° N / 90.5° E) had a long northwestward sea travel to become a cyclonic storm with intensity T 2.5 (9.5° N / 87.0° E) at 1200 UTC on 13th. It gained intensity as a severe cyclonic storm (T 3.5) at 1200 UTC on 14th and lay centered at 12.0° N / 83.5° E. Mosaic of two PPI(Z) displays obtained from DWR at Cyclone Detection Radar station, Chennai at 2026 and 2056 UTC / 14th has been presented as Fig. 6. Maximum Z was around 50 dBZ only corresponding to a rain rate (R) of 48 mm/hr using the well known Marshall – Palmer's original Z – R relationship. The severe cyclonic storm intensity was

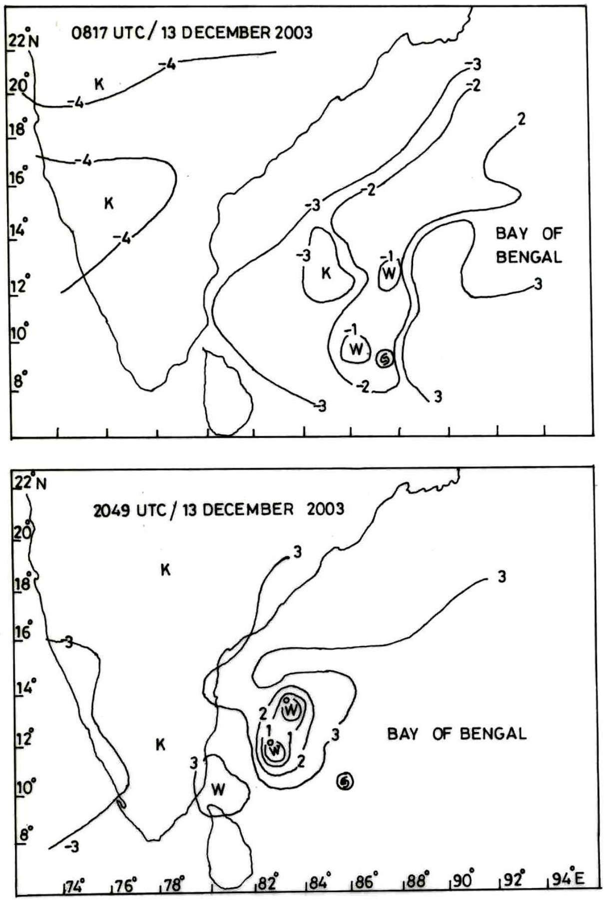

Fig. 7. Analysis of 700 – 400 hPa layer mean temperature (°C) at 0817 and 2049 UTC on 13 December 2003

maintained upto 1800 UTC of 15th and crossed coast near Machilipatnam as a cyclonic storm around 1800 UTC on 15th. The storm weakened into a deep depression at 0300 UTC on 16th and gradually weakened over north coastal Andhra Pradesh.

Fig. 7 shows the analyses of mid-tropospheric warmness at 0817 and 2049 UTC of 13th. Based on 0817 UTC of 13th AMSU data, the maximum mid-tropospheric warmness of more than 2.5° C was concentrated over two regions suggesting that the storm may move towards northwest initially and then may change its path towards northnortheastward. Similarly, the 2049 UTC analysis also revealed that the mid-tropospheric warmness concentrated into two localised regions suggesting that the storm may move towards either of them or in between these two warm pools. The peak values of 700 – 400 hPa layer mean temperatures at various sounding points have been tabulated in Table 2.

The maximum warmness was observed more in the northern pool than the southern one suggesting that the storm had a tendency to move towards northwestward rather than westnorthwestward. Since the storm was away from the coast by more than 600 km during this period, ground based radars were of no help in tracking the storm. Satellite imageries from the METEOSAT at 1500, 1800 UTC / 13th could not suggest any clear cut movement of the storm since the storm centre was obscured by the dense overcast cloud mass.

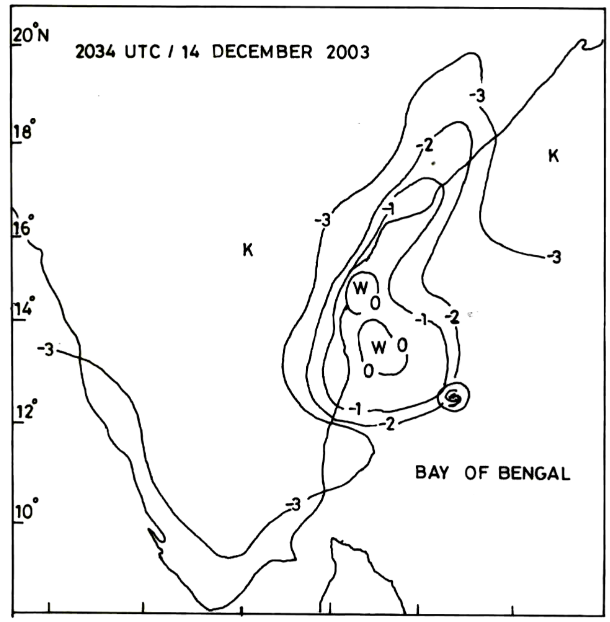

Fig. 8. Analysis of 700-400 hPa layer mean temperature (°C) at 2034 UTC on 14 December 2003

Based on the maximum mid-tropospheric warmness and persistence, the track position at 1800 UTC / 13th has been estimated (from 0817 UTC/ 13th ATOVS analysis) at 10.0° N / 88.0° E wherein the 700-400 hPa layer mean temperature was – 0.16° C. The positions at 2100 UTC / 13th and 0000 UTC /14th have also been estimated from the 0817 UTC / 13th ATOVS analysis. In a similar way, from the 2049 UTC / 13th ATOVS derived mid-tropospheric temperature analysis, storm's positions at 0600, 0900 and 1200 UTC / 14th have been estimated. The estimated positions reasonably agrees with the IMD's finalised track. The errors in estimation have been tabulated in Table 3.

The 0805 UTC / 14th ATOVS data revealed northwestward movement of the storm. The forecast position at 1800 and 2100 UTC / 14th estimated from this analyses agreed well with the finalised track. Fig. 8 shows the 700-400 hPa layer mean temperature at 2034 UTC on 14th. This analysis clearly indicates the northwestward movement of the storm and its likely heading towards Machilipatnam (16.2° N / 81.15° E) coast. Fig. 9 depicts

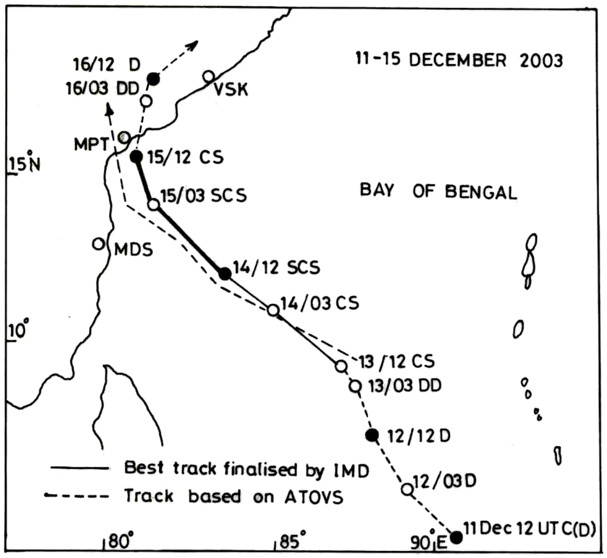

Fig. 9. Storm track estimated using ATOVS compared with actual track of Machilipatnam cyclone, 2003

the track of the storm estimated from ATOVS compared with the track finalised by IMD.

4. Warm core of the cyclonic storms

Temperature anomaly for the AMSU retrievals at various pressure levels have been worked out based on the method followed by Kidder *et al*. (2000) to estimate the extent warmness over the eye or core region of the storm. For this purpose the environmental temperature at 500 - 600 km away from the centre of the storm has been subtracted from the sounding temperature over the eye or core region of the storm for each pressure level. No significant warmness was observed over the core region of the tropical depression at 2001 UTC on 22 October, 2002. However in the case of the Kolkata cyclonic storm, at 250 hPa, a warming of 12.1° C at 62 km and 13.3° C at 124 km were observed at 0123 UTC on 12 November, 2002 during which period the storm had gained intensity T 3.5. Warming over the eye of the storm could not be estimated in view of non-availability of AMSU soundings for this storm. In the case of Machilipatnam cyclone, two soundings at 28 and 40 km from the storm centre at 0806 UTC on 14 December, 2003 revealed a 7.7° C warmness at 200 hPa. When the storm was having its peak intensity of T 3.5 at 2037 UTC on 14^{th}, a sounding at 45 km from the storm centre indicated a 9.1° C warmness at 200 hPa. In the absence of sounding data from reconnaissance flights, the above inference from the two cyclonic storms of marginal intensities supports the established facts that the tropical cyclones are warm core systems and the warmness of the core region extends from 10 to 16° C in the 200-250 hPa level [Hawkins and Rubsam (1968) and Asnani (1993)]. It may also be seen that the lower tropospheric warmness of about 2° C was also captured by the AMSU soundings over the region very close to the core / eye of the storm.

5. Limitations and challenges

Though the AMSU data provides us a wealth of information for understanding the thermodynamic features of the cyclonic storms and help us to predict the movement of the storm, it does have the following limitations.

(*i*) Since the eye of the cyclone is ordinarily far less than the highest 48 km AMSU resolution obtainable at nadir, thermo-dynamic features of the core region or eye of the cyclonic storm can not be completely understood with the ATOVS data.

(*ii*) Significant changes in the tropical disturbances can take place between two successive passes of polar orbiters viewing almost the same area with twelve hour periodicity.

(*iii*) Contiguity is not maintained in AMSU observations between two successive passes due to scan geometry limitations. Hence the disturbance may, at times, go unnoticed which is usually termed as 'storms fall in the crack' (Kidder *et al*., 2000).

The above limitations to certain extent have been addressed by scanning a little farther towards the limb and thereby making the 'gap between passes' as small as possible. Though this is being attempted from NOAA-16 onwards, gap between two passes still exists. In order to avert the 'gap' in sounding retrievals and to keep continuity, more number of polar orbiting satellites are needed to have a close watch for the analyses of tropical disturbances. More over, with the contemplated introduction of microwave payload in geo-stationary satellites, it is hoped that the temporal resolution as well the 'data gap' problem would be solved.

6. Conclusions

The mid-tropospheric warmness, about 200 to 700 km ahead of the tropical disturbances (tropical storm / depression) caused by the Altostratus outflow between 700 and 400 hPa may be used as a tool to forecast the tracks of these disturbances. The disturbance follows the axis connecting the centre of the disturbance with the warm tongue that protrudes ahead of it. The disturbance essentially passes through the location having maximum mid-tropospheric warmness. Based on the persistence / speed of past movement, forecast position of the disturbance can be estimated over a time period of 6 to 24 hours. The prediction accuracy is better than the other methods, *viz*., climatology, climatology and persistence, numerical methods, that are in operational use. The two moderate intensity cyclonic storms that have been analysed in this paper showed upper tropospheric (250 to 200 hPa) warmness of 7 to 13° C over the core region than the surrounding atmosphere at a distance of about 500-600 km from the storm centre. However, such an upper tropospheric warmness could not be seen in the depression stages. Since the AMSU retrievals are not obtained from a regularly placed grid locations and they have varying resolution (at the sub satellite points and at the edges of the swath) and it may take considerable time to plot the thousands of retrievals, objective analysis can be attempted to place the 700 – 400 hPa layer mean temperature values at regular grids, say, 1° Lat. × 1° Long. over the area of interest in an operational set up to issue the forecast.

Acknowledgements

The authors are thankful to the Deputy Director General of Meteorology (Satellite Meteorology), New Delhi for sparing the available ATOVS data for this study. Facilities extended by the Deputy Director General of Meteorology, Regional Meteorological Centre, Chennai are acknowledged with thanks. The authors are thankful to the referee for his comments.

References

Asnani, G. C., 1993, “Tropical Meteorology”, Vol. I and II, 822 Sindh Colony, Pune, India, p1202.

Cracknell, P. A., 1997, “The Advanced Very High Resolution Radiometer (AVHRR)”, Taylor & Francis Int. Ltd., Great Britain, p534.

Dvorak, V. F., 1975, “Tropical cyclone intensity analysis and forecasting from satellite imagery”, *Mon. Wea. Rev.*, **103**, 420-430.

Goldberg, M. D., 1999, “Generation of retrieval products from AMSU-A : Methodology and validation”, 10th Int. ATOVS study Conf., Boulder, CO., 219-229.

Gupta, H. V., Rengarajan, S., Suresh, R. and Gupta, R. C., 1996, “Reception of data from NOAA satellites at IMD Madras”, *Vayumandal*, **26**, 3&4, 56-59.

Hawkins, H. F. and Rubsam, D. T., 1968, “Hurricane Hilda, 1964, II, Structure and budegets of the hurricane on 1 October, 1964”, *Mon. Wea. Rev*., **96**, 617-636.

India Meteorological Department, 2003, Report on Cyclonic Disturbances over North Indian ocean during 2002, RSMC – Tropical Cyclones, New Delhi, January 2003, IMD, New Delhi, p31.

India Meteorological Department, 2004, Report on Cyclonic Disturbances over North Indian ocean during 2003, RSMC – Tropical Cyclones, New Delhi, January 2004, IMD, New Delhi, p49.

Jun Li, Wolf, W. W., Paul Menzel, W., Wenjian Zhang, Hung-Lung Huang and Achtot, T. H., 2000, “Global Soundings of the Atmosphere from ATOVS Measurements : The algorithm and Validation”, *J. Appl. Meteor*., **39**, 8, 1248-1268.

Khanna, P. N. and Kelkar, R. R., 1993, “Temperature sounding of the atmosphere over the Indian region using satellite data”, *Mausam*, **44**, 2, 167-174.

Kidder S. Q. and Vonder Harr, T. H., 1995, “Satellite Meteorology - An introduction”, Academic Press Inc., San Diego, CA, p466.

Kidder, S. Q., Goldberg, M. D., Zehr, R. M., Mark, D., Purdom, J. F. W., Veldon, C. S., Grody, N. C. and Kusselson, S. J., 2000, “Satellite Analyses of Tropical Cyclones Using the Advanced Microwave Sounding Unit (AMSU)”, *Bull. Amer. Met. Soc*., **81**, 6, 1241-1259.

Mo, T., 1999, “AMSU – A antenna pattern corrections”, *IEEE Trans Geosci. Remote Sens*., **37**, 103-112.

Simpson, R. H., 1954, “On the structure of tropical cyclone as studied by aircraft reconnaissance”, Proc. of the UNESCO symposium on Typhoons", Tokyo, 129-150.

Suresh, R. and Raj, Y. E .A., 2001, “Some aspects of Indian northeast monsoon as derived from TOVS data”, *Mausam*, **52**, 4, 727-732.

Suresh, R. and Rengarajan, S., 2001, “Validation of TOVS data and its utility in foreshadowing cyclone movement”, Proc TROPMET 2000, Cochin University of Science and Technology, Cochin, 309-314.

Suresh, R., and Rengarajan S., 2002, “On forecasting cyclone movement using TOVS data”, *Mausam*, **53**, 2, 215-224.

Suresh, R., Sankaran, P. V. and Rengarajan, S., 2002, “On thermodynamic structure of northeast monsoon over Tamilnadu and adjoining Bay of Bengal using TOVS data”, *Mausam*, **53**, 1, 75-86.

Wark, D. Q., 1993, “Adjustment of TIROS Operational Vertical Sounder data to a vertical view”, NOAA Tech. Rep., NESDIS 64, Washington, DC, p36.