# Foreshadowing the tracks of tropical depressions and cyclonic storms and understanding their thermodynamical structure over
# Bay of Bengal and Arabian Sea using TOVS and ATOVS data

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## Abstract

Upper atmospheric meteorological information such as steering flow, cirrus outflow and warming, mid-tropospheric warming etc have been used as pre-cursors to predict the movement of cyclonic storms throughout the world with mixed rate of success. Soundings from aircraft reconnaissance flights revealed that mid-tropospheric warming due to altostratus outflow is more significant than the cirrus outflow and such warming protrude atleast 400 km ahead of the storm (Simpson, 1954). This concept has been analysed in depth to study the movement of eight cyclonic disturbances over Bay of Bengal and Arabian Sea.

Mid-tropospheric warming between 700 and 400 hPa due to Altostratus outflow protrudes as far ahead as 400 to 700 km in spatial scale and 3 to 12 hours in temporal scale (Suresh and Rengarajan, 2002). The protrusion of this warm tongue well-neigh matches with the best track finalised by the India Meteorological Department (IMD) and the land fall has also been predicted within $\pm 30$ km from the actual. Relatively a rare southward movement of a cyclonic storm was also predicted correctly by this technique. While significant warmness (7 to 13 $^{o}$C) in the upper troposphere (250-200 hPa) characterises a cyclonic storm, no significant warmness could be identified in the depression stage. Weak convective instability and relatively high warmness in the lower troposphere (upto 700 hPa) at farther ranges (150 – 200 km from the storm centre) together with long sea travel aid the intensification of a weather system into a cyclonic storm.

## Introduction

Foreshadowing the track and movement of tropical weather disturbances such as depressions and cyclonic storms, with the limited radio sonde data, is a great challenge to the operational weather forecasters. The vast expanse of oceanic surface from where the genesis of weather disturbances take place practically do not have upper atmospheric radio sonde information. More over, for predicting the movement of the storms, the available radio sonde data over the land area have to be interpolated / extrapolated and made available over the oceanic area with limited accuracy through objective analysis and optimum interpolation, over coarse grids, which may not be a true representative of the mesoscale variability of the atmospheric motion. Upper atmospheric TOVS data obtained from NOAA satellites promises a good spatial coverage over the oceanic region to understand the structure of the weather disturbances provided such soundings exist over those disturbances. Despite the limitations such as the coverage of a particular area of interest just once in 12 to 24 hours from a particular polar orbiter, the sounding information may be used to predict the movement of the disturbances with a reasonable degree of accuracy by pooling the sounding data from other polar orbiters viewing the areas of interest.

Estimating the profiles of temperature and trace gas concentration from the observed radiance is often called as inverse problem or retrieval problem. The retrieval problem aims at finding temperature profiles that satisfy the radiative transfer equation(RTE). However, unique solution to the RTE would not be guaranteed, even if we get radiance data at all wavelengths from noise-free radiometer (Chahine, 1970) and infinite number of solutions are quite possible consistent with measured radiances since the radiation measurements are often contaminated with noise (Eyre, 1990). As the surface and upper air guess profiles have effect on quality of soundings (with larger impact at lower levels and relatively lesser impact over middle and upper troposphere), a judicious initial guess, may be from climatology or numerical forecast or regression estimate from stratospheric level channel data, has to be made to solve the RTE. It has been reported that a reasonable degree of accuracy is attainable by using the initial guess for surface temperature or 1000 hPa level (for example, see Khanna and Kelkar, 1993). However, in the absence of getting efficient numerical upper air forecast in real time for use as initial guess for each satellite pass TOVS retrieval, the climatology is normally used as initial guess in operational mode of TOVS processing at many direct read out HRPT ground stations.

## Tiros Operational Vertical Sounder (TOVS)

Tiros Operational Vertical Sounder(TOVS), comprising of 20 channel High Resolution Infrared Sounder (HIRS), 4 channels Microwave Sounding Unit (MSU) and 3 channels Stratospheric Sounding Unit (SSU), onboard NOAA series of polar orbiters (upto NOAA14) provide 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 (Smith et al., 1979), retrieval procedures (Chahine, 1970) and usefulness and limitations of TOVS data have been excellently documented in Kidder and Vondar Harr(1995). 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).

Fig. 1 shows the temperature bias between TOVS derived and that obtained from a few collocated Radio sonde stations (within ±100 km and ±2 hours of ascent) selected at random from peninsular India. This sort of comparison was done on a routine basis during 1996-1998 at HRPT direct read out ground station at Chennai ($13^o$ $04^/$ N / $80^o$ $14.7^/$ E). Climatological values were used as initial guess to solve RTE using version 4 of International TOVS Processing Package (ITPP). The temperature retrieval was found to be within a root mean squared error (RMSE) of 1.0 to 2.5 $^o$C at different levels from that obtained through the collocated Radio-sonde and the agreement was quite good between 850 and 200 hPa. As the root mean squared biases are smaller than the natural variability (i.e.) the standard deviation of radio-sonde data (India Meteorological Department (IMD),1988), satellite soundings can be used in weather analysis and forecast as they explain a substantial fraction of variance of atmospheric temperature. However, in view of the facts that the timings and sounding techniques of satellite and radio-sonde are different and the inherent instrumental errors from radio-sondes have also been taken into account for inter-comparison, overestimates of RMSEs are quite probable and hence it may be concluded that satellite soundings are

complementary and not competitive to RS/RW soundings (Cracknell, 1997). Hence these data were independently used to study the thermodynamics of northeast and southwest monsoon by Suresh and Raj (2001) and Suresh et al. (2002). Fig. 2 shows the mean monthly root mean squared differences between TOVS derived and Radio Sonde measured temperature values at standard pressure levels.
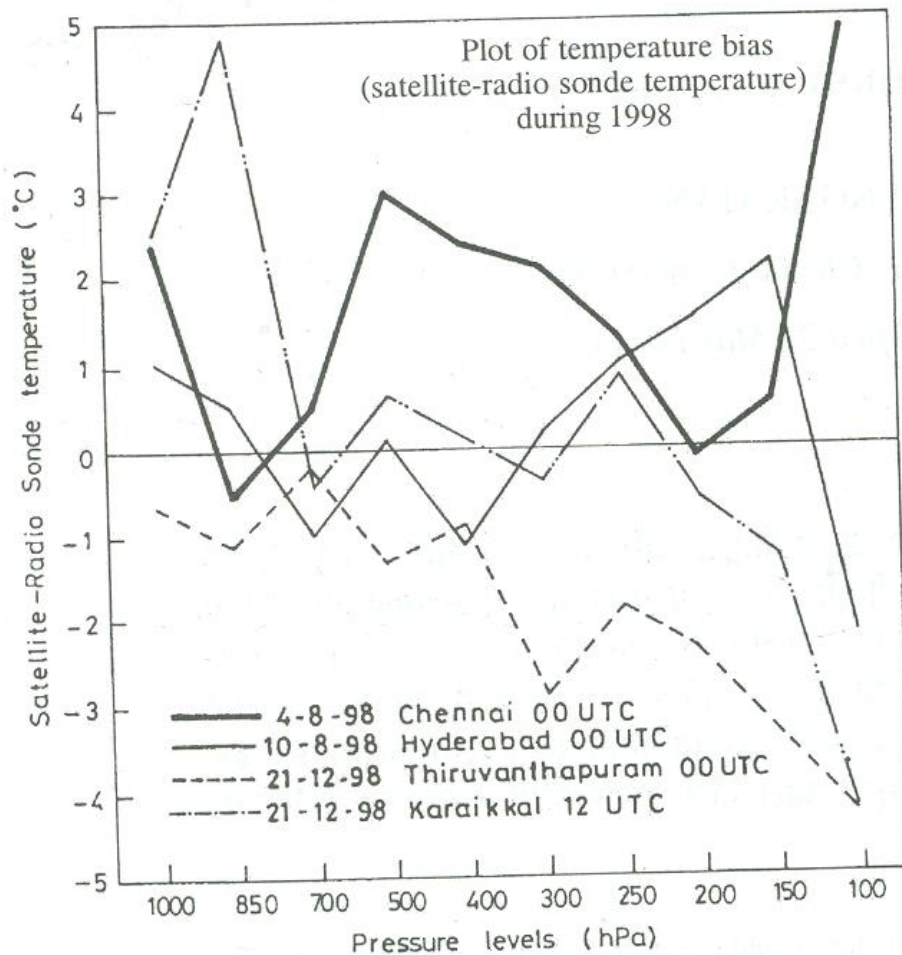


Fig. 1. Comparison of temperatures at standard pressure levels. The difference between that estimated from TOVS and collocated Radio Sondes[@], samples selected at random, over southern peninsular India during 1998 have been presented. [@]Chennai(13.0 $^o$N / 80.18 $^o$E); [@]Hyderabad (17.27 $^o$N / 78.28 $^o$E); [@]Thiruvananthapram (8.48 $^o$N / 76.95 $^o$E); [@]Karaikal (10.91 $^o$N / 79.83 $^o$E);

Since the RMSE of less than 2.0 $^o$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). A few of the results are described in this paper.
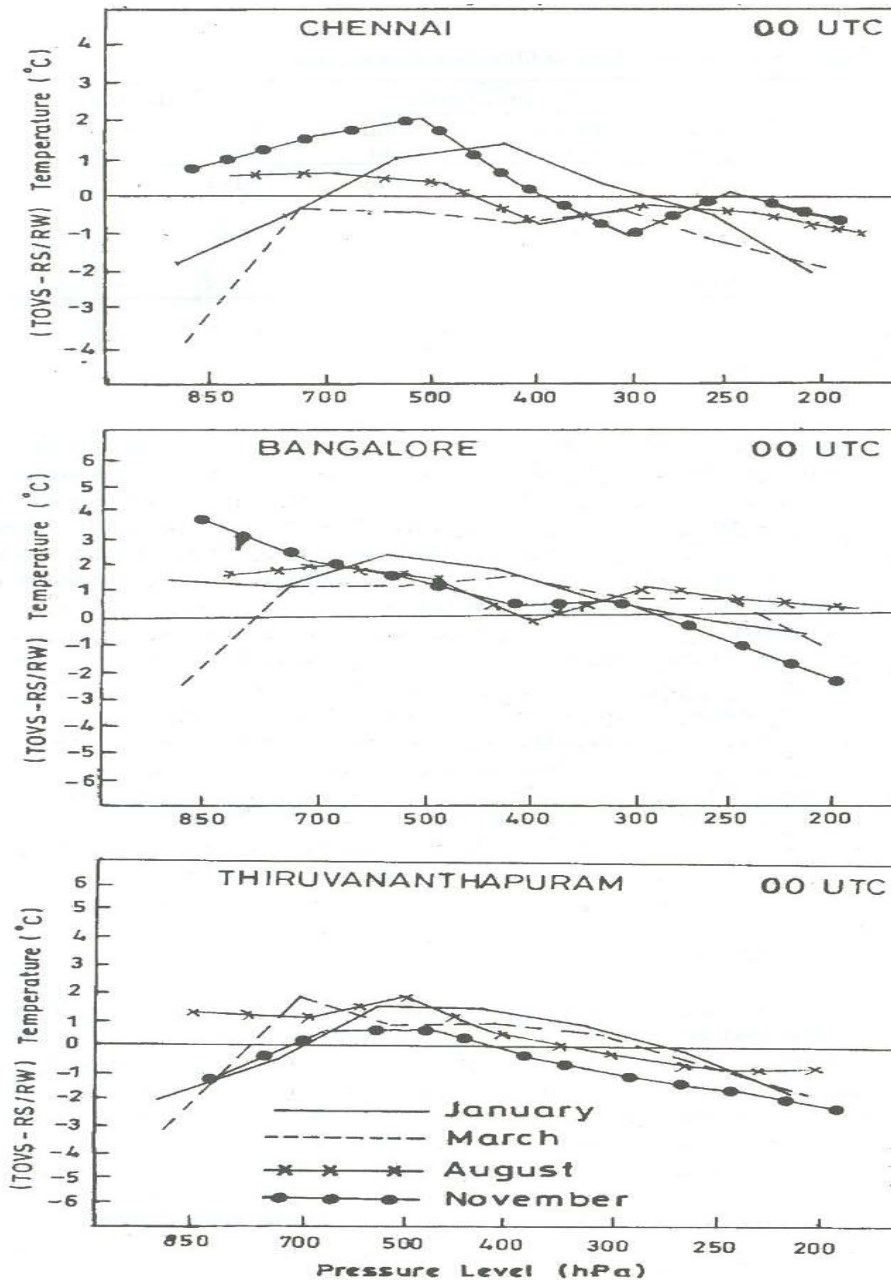
Fig. 2. Plots of mean monthly root mean squared differences between temperature estimated from TOVS and collocated Radio sondes[@] at various pressure levels over Indian region during 1996-1998. [@]Chennai(13.0 °N / 80.18 °E); @Bangalore (12.58 °N / 77.35 °E); @Thiruvananthapram (8.48 °N / 76.95 °E);

## Advanced TOVS (ATOVS)

Since the MSU of TOVS has a coarse resolution of 148km at the nadir, Advanced MSU(AMSU) was planned to have a finer resolution and flown as Advanced TOVS(ATOVS) instrumentation onboard NOAA-15 satellite (launched during May 1998) onwards. Fifteen channels Advanced MSU- A (AMSU-A) has a 48 km resolution and five channels Advanced MSU- B (AMSU-B) has a resolution of 16 km at nadir. Besides the major advantage of 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 data over Indian region has been attempted by Singh et al. (2003) and Das Gupta et al. (2003).

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 thermodynamical structure of two tropical cyclones and one tropical depression over Bay of Bengal during 2002-2003. More over, tracks of these tropical disturbances have been studied in this paper using the temperature profile obtained from the AMSU.

## Data

TOVS derived temperature data in the domain ($2^o$ to $26\ ^oN$; $64\ ^o$ to $90\ ^oE$) during May, June and October to December,1998 have been used in this study to foreshadow the cyclonic storms which formed over the Bay of Bengal and Arabian Sea. Nearly 400 to 500 soundings from each satellite pass (NOAA 12 and 14 satellites) during the cyclonic storm period have been analysed. This voluminous data, especially over the data sparse oceanic area has been of tremendous use in analysing the cyclonic field and to foreshadow the track of the cyclone. Climatological normals of radio-sonde data for the Indian region published by the India Meteorological Department(IMD,1988) and annual cyclone review report of IMD for the period 1998 have been consulted. TOVS data during the period November - December 1996 has also been used in this study to verify the technique developed for a rare southward moving cyclone over the Bay of Bengal.

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 ($16.2^o$ N / $81.15^o$ E) cyclone, 13-15 December 2003) and for a tropical depression on 23 October 2002. 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.

## Analysis of mid-tropospheric warmness

In one of the earlier studies on the structure of tropical cyclones using aircraft reconnaissance, Simpson(1954) has postulated the concept of protrusion of midtropospheric (700-500hPa layer) warmness, due to altostratus outflow, upto a distance of 400 – 1000 km ahead of the storm. Simpson argued that altostratus outflow from the typhoons is more significant than the cirrus outflow in causing a significant warmness. In order to find out whether any significant warming has taken place in the mid troposphere, ahead of the storm, mean temperature and gpm thickness in the layers 500-850hPa, 500-700 hPa & 400-700 hPa were computed, plotted and analysed. In addition to the above, the temperature drop from 850 to 500 hPa has also been worked out to find out pre-cursor(s), if any, to forecast the cyclone track over Bay of Bengal and Arabian Sea during 1998.

Upper air climatology of 1200 and 0000 UTC has been used as first guess profile to solve RTE for NOAA 14 passes over Chennai region (during 07-09 and 19-21 UTC) as there are no 06 and 18 UTC radio sonde data available. Since the warm/hot lower levels generally prevailing almost throughout the year and high seasonal variability of moisture in the equatorial latitudes during afternoon offer varying transmittances, an increase in temperature at lower and mid tropospheric level are encountered in NOAA 14 retrievals. Hence temperature correction profiles, based on the upper air climatological data of 0000 and 1200 UTC data (IMD,1988), have been estimated and subtracted the same from the TOVS derived temperature to have continuity with climatology and NOAA 12 derived values.
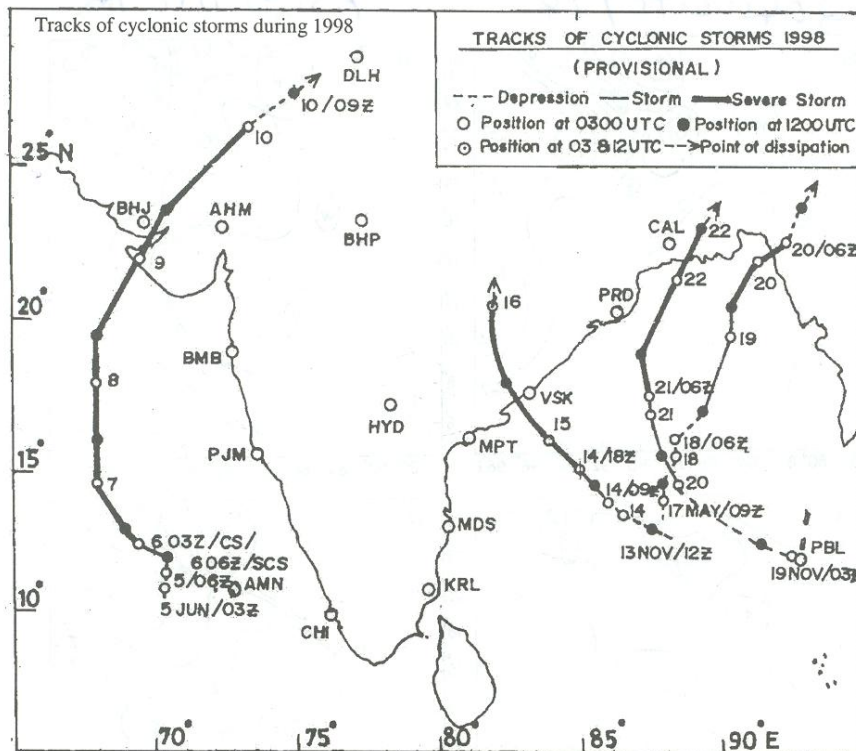


Fig. 3. Tracks of cyclonic storms during 1998.

## Tracks of cyclonic storms during 1998 over Bay of Bengal and Arabian Sea

Tracks of cyclonic storms during 1998 have been taken from the published records of IMD and shown in Fig. 3.

## Pre-monsoon cyclonic storm (17.5.98 to 20.5.98)

A depression formed over central Bay at 0300 UTC on 17 May 1998 and intensified into a cyclonic storm at 1200 UTC on 18th . Analysis of the mean temperature between 700 and 400hPa level at 2045 UTC on 18th indicates that the storm will move in northerly to north northeasterly direction and the actual movement of the storm confirmed this till 19th. The probable track was predicted when the storm was atleast 400 km away from the coast with a lead time of more than 28 hours. Further analyses based on 2336 UTC of 18th (analysis not shown) and 0757, 1224 and 2032 UTC of 19th also confirmed the cyclone movement atleast 24 hrs in advance and the landfall was also predicted within 20 km from the actual landfall. Fig. 4 depicts the mean temperature analyses.

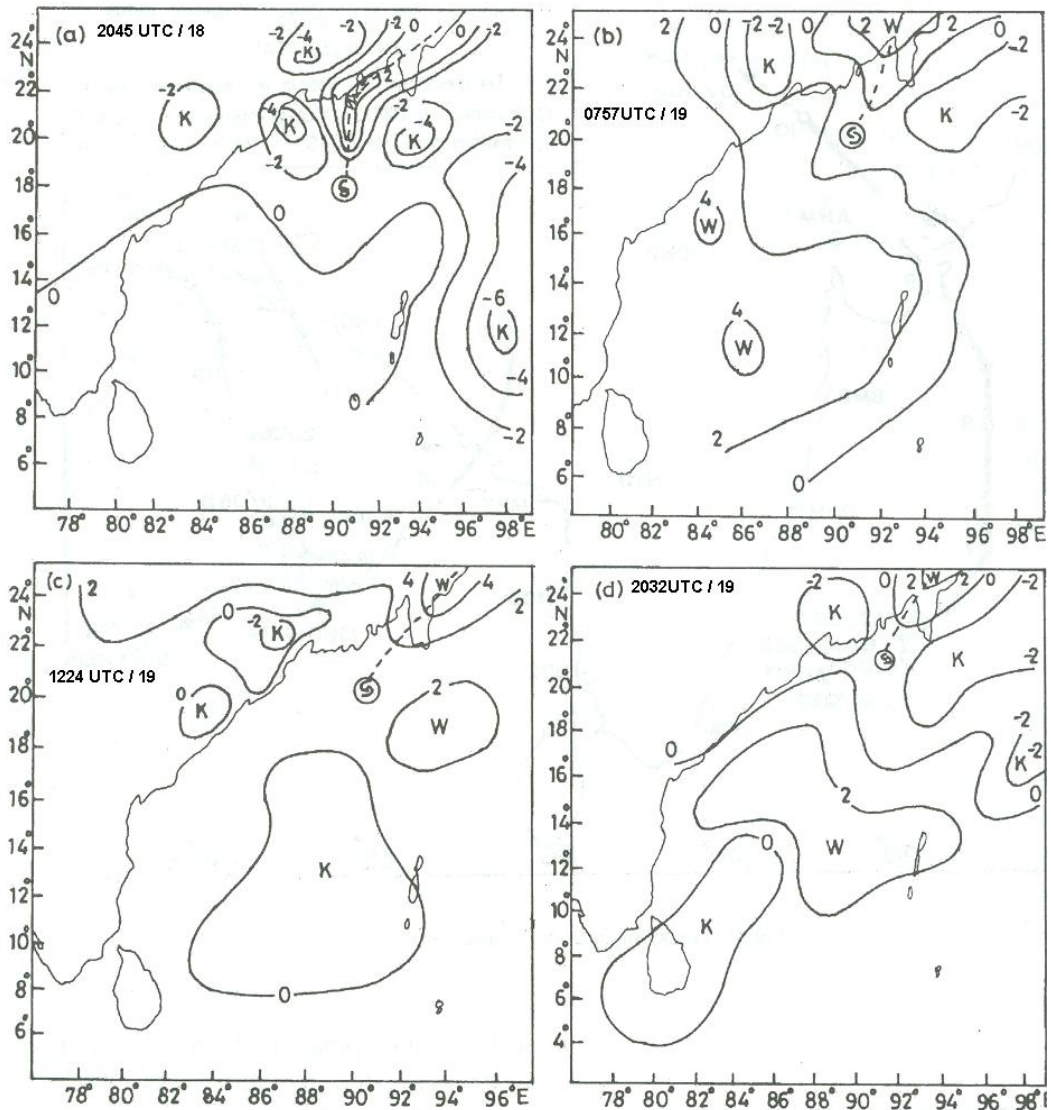Analyses of 700-400 hPa layer mean temperature during 17 – 20 May, 1998



Fig.4. Analyses of 700-400hPa layer mean temperature during 17-20 May 1998.

## Cyclonic storm during monsoon season (5.6.98 to 10.6.98)

The deep depression observed over Arabian Sea at 0300 UTC on 5th June'98 intensified into a cyclonic storm at 1200 UTC and moved in northwesterly direction initially.

700-400 hPa layer mean temperature analysis of 0142 UTC on 5th (Deep Depression stage), 0118 and 0937UTC on 6th and 0056 and 0928UTC on 7th clearly foreshadowed the storm track. The analyses have been presented in Fig. 5.
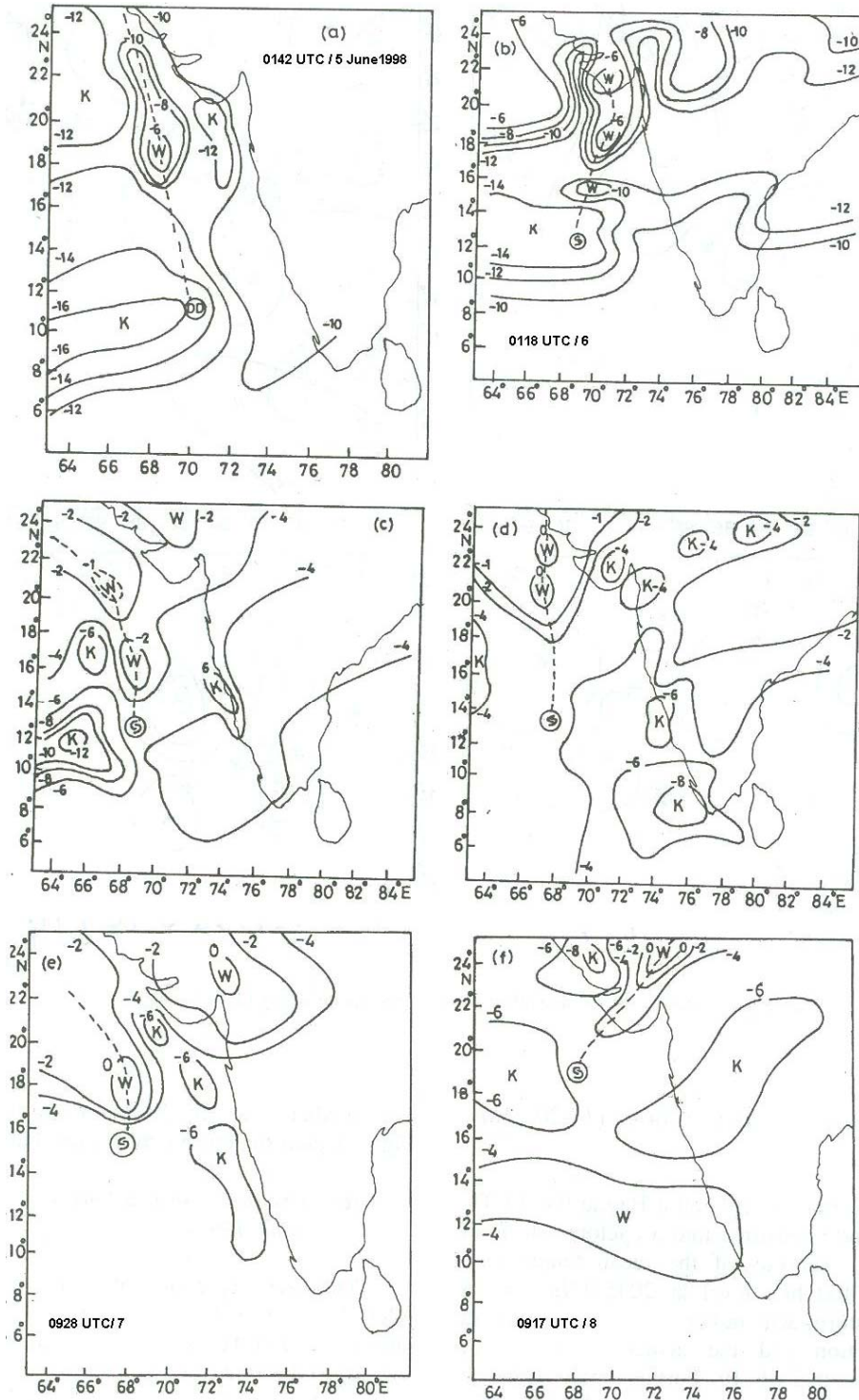
Fig. 5. Analyses of 700-400hPa layer mean temperature during 5-10June1998

The storm has crossed coast around 03 UTC on 9th. The probable landfall has been predicted based on  0917 UTC soundings of 8th (about 18 hours in advance and when the storm was away from the coast by 350 km) within an error of  within about 35 km.

## Post monsoon Cyclonic storm (13.11.98 to 16.11.98)

A depression formed over central Bay on 13th intensified into a cyclonic storm at 0900UTC of 14th  and moved on NW direction  and   crossed close to Visakhapatnam on 15th A/N. The 700-400 layer mean   temperature analysis of 0028UTC on 14th  indicates that the storm will  move  towards north Andhra coast and most likely  cross the coast close to

Visakhapatnam(17.5 °N;82.7 °E). This prediction has been done when the storm was away from the coast by at least 450 km and with 30 hours lead time before the landfall.. The 0823 UTC analysis of 14th reconfirms the movement of the storm towards north Andhra coast. The exact landfall had been predicted accurately based on 1136 and 2058 UTC analyses on 14th when the storm was out 300 and 200 km away from the coast. Fig. 6 shows the 700 - 400hPa mean temperature analysis.



Fig. 6. Analyses of 700-400hPa layer mean temperature during 13-16 November 1998
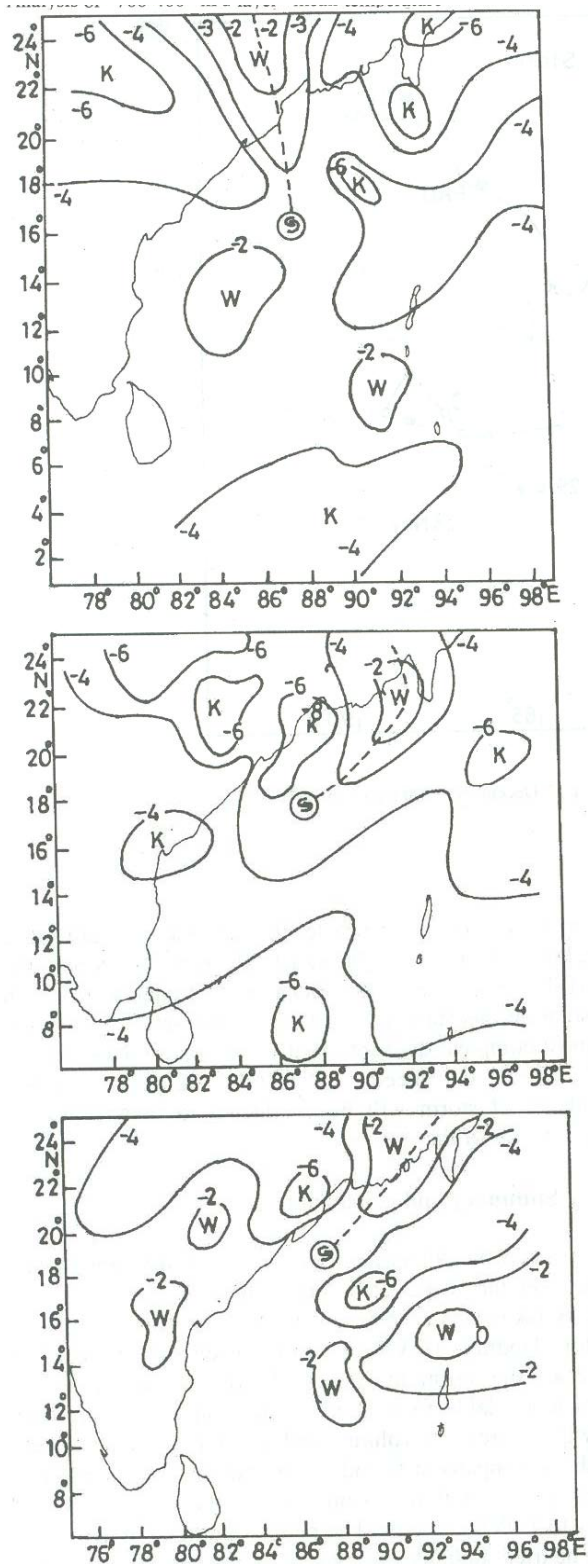
**Post monsoon Cyclonic storm (19.11.98 to 22.11.98)**



Fig. 7. Analyses of 700-400hPa layer mean temperature during 19-22 November 1998.

The depression formed over east central Bay on 19th initially moved in NW direction and changed its path to NNW over central and north Bay during 20th -21st and finally recurved and had its landfall close to Calcutta on 22nd F/N. The analyses have been depicted in Fig 7. The 2335 UTC /20th mid-tropospheric analysis indicated that the storm was heading towards little north of Paradip and the actual track was also confirming this prediction upto 1200 UTC/21. The recurvature was predicted based on 0844 UTC/21st NOAA 14 pass. The landfall was predicted based on 1223 UTC/21st NOAA 12 pass when the storm was away from the coast by more than 300km with a lead time of more than 18 hours.

## Southward moving Bay storm 28 November - 7 December, 1996

Fig. 8 shows the Bay storm during November 28 - December 7, 1996. This storm had a loop in the central Bay and had southward movement before its landfall. This storm could not be forecast correctly either by synoptic or by numerical weather prediction (NWP) methods. As such an attempt has been made to study the movement of this storm through the technique developed in this paper. In view of the non-availability of processed TOVS data during November 28 – December 2, 1996, the looping could not be diagnosed.
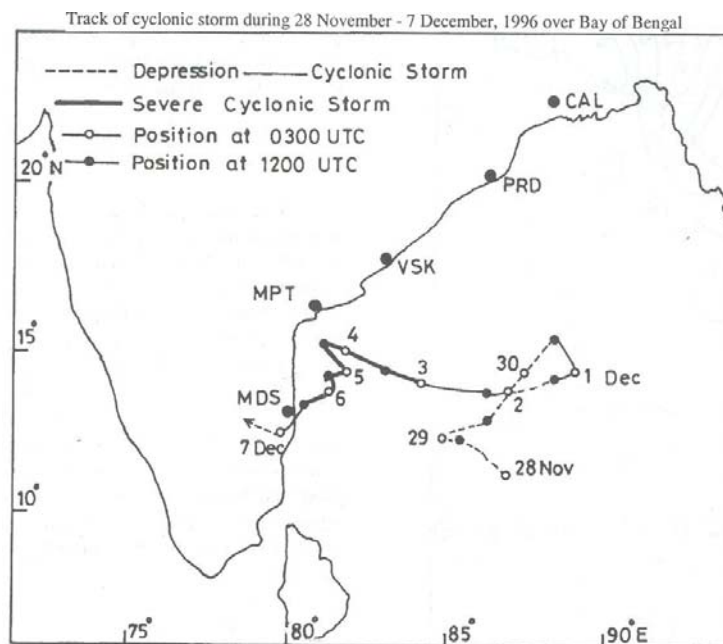


Fig. 8. Track of cyclonic storm during 28 November – 7 December 1996

The 0758 UTC/3rd satellite pass prediction was very much agreeing with the storm movement till 1200 UTC/4th (see Fig 9). However, 2035 UTC/3rd TOVS analyses indicated southwestward movement of the storm which may be quite strange and/or puzzle to the forecaster. Analysis of 0024 and 0205 UTC/4th TOVS data also reconfirmed the SSWward movement of the storm which had actually taken place from 1200 UTC/4th. 0747 UTC/4th pass(analysis not shown) predicted even the SEward movement of the storm about 6 hours in advance. The landfall within 25 km accuracy was very well predicted based on 2024UTC/4, 0738 & 0918 UTC and 2014 UTC/5th and 0728 UTC/6th NOAA 12 and NOAA 14 satellite passes. The lead time of the land fall prediction was as high as 46 hours in this case.
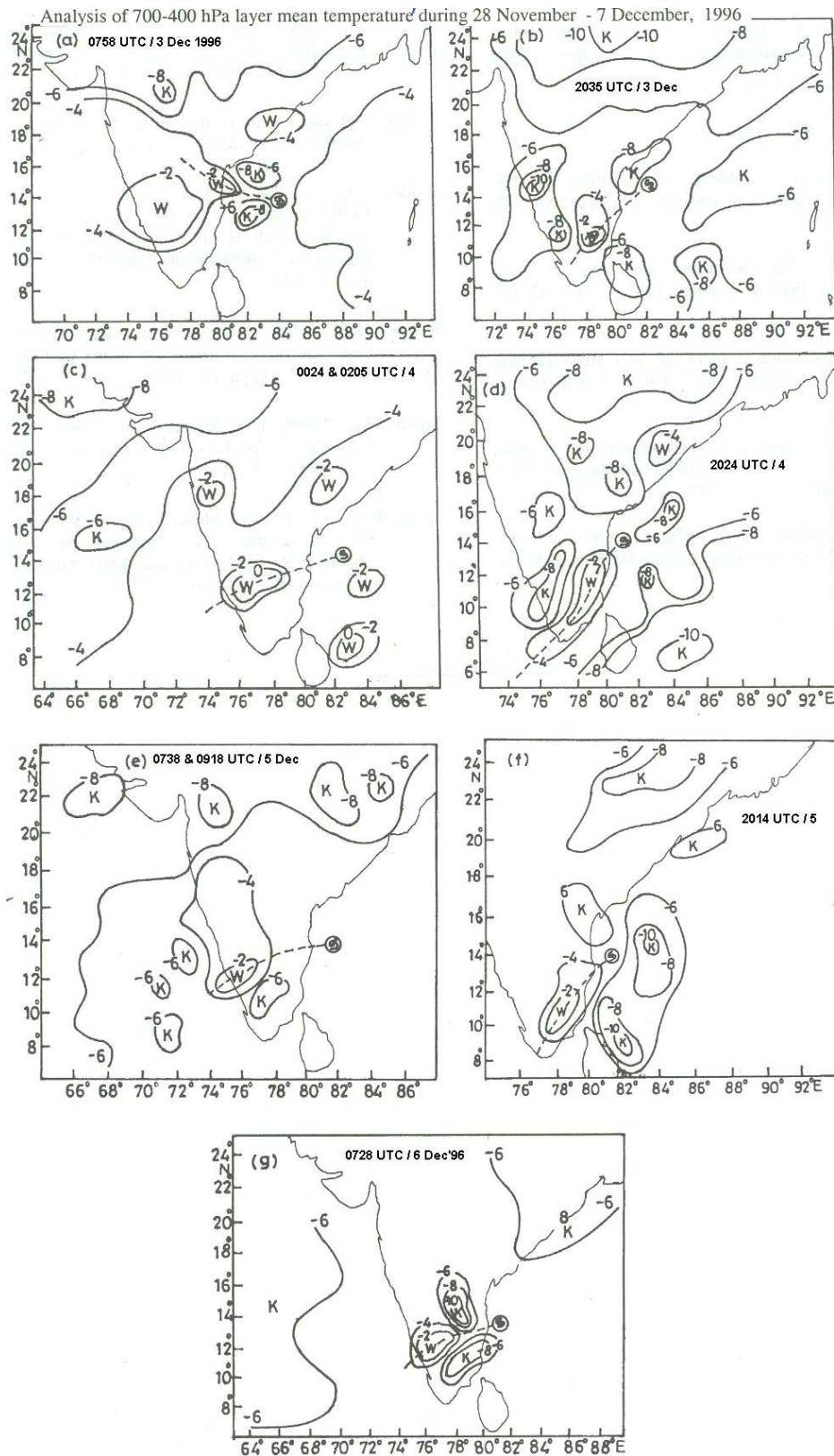
Fig. 9. Analyses of 700-400 hPa mean layer temperature during 28 November – 7 December 1996.

## Analyses using ATOVS data for the cyclonic disturbances of 2002-2003

Fig. 10 shows the cyclonic disturbances of 2002-2003 over Bay of Bengal and Arabian Sea. With the available ATOVS data from IMD, New Delhi, the depression on

22 October 2002 and cyclonic storms during 11-12 November 2002 and 13-15 December 2003 have been analysed to see the pre-cursor, viz., protrusion of mid-tropospheric warm tongue, to predict the storm track in these cases as well.
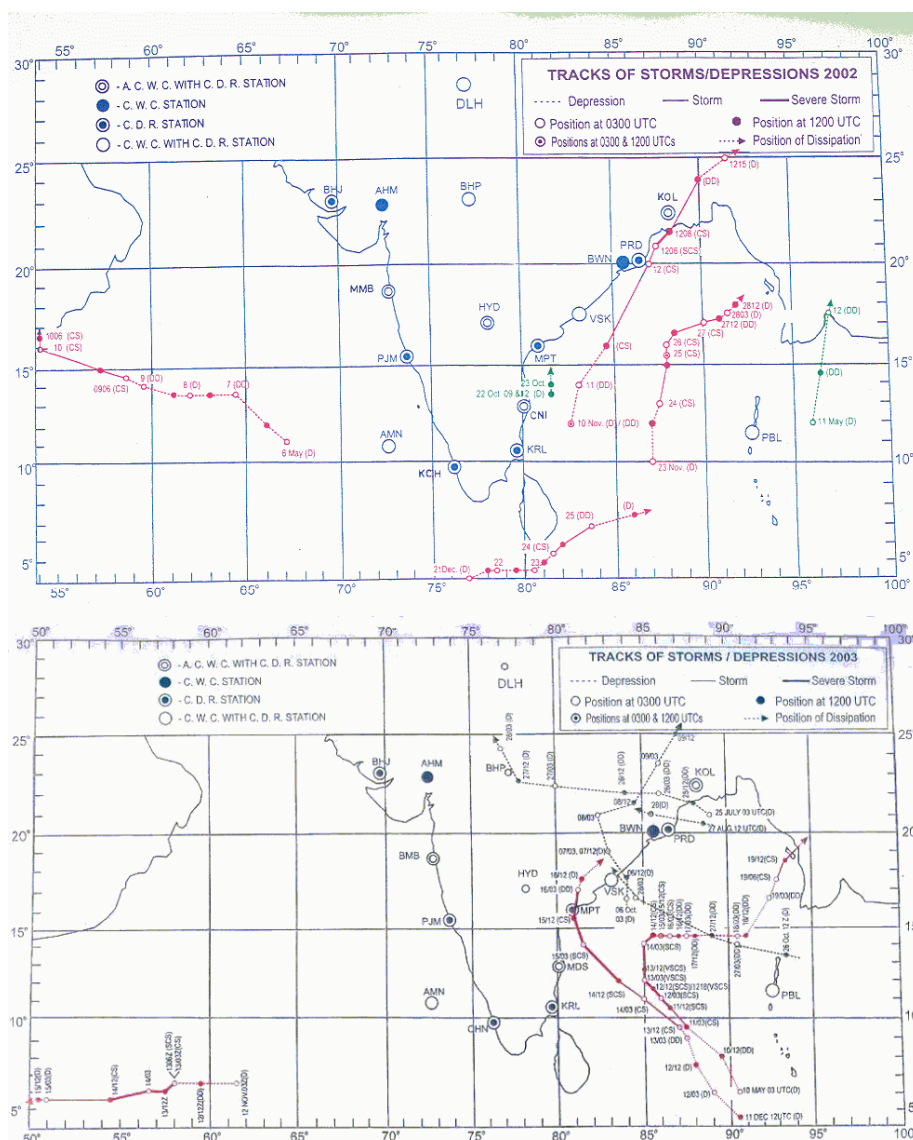


Fig. 10. Finalised tracks of tropical disturbances during 2002 –2003 by IMD.

## Tropical depression 22-23 October 2002

A tropical depression, with intensity T1.5 in Dvorak's scale (Dvorak(1975), formed at 09 UTC on $22^{nd}$ October 2002 over Bay of Bengal remained practically stationary at 13.5 $^{o}$N / 81.5 $^{o}$E up to 12 UTC and subsequently intensified into T2.0. It had a very slow northward movement up to 12 UTC of $23^{rd}$ October and thereafter weakened in Bay itself. Fig. 11 shows the layer mean temperature of 700-400 hPa obtained from NOAA16 AMSUs at 2001 UTC on $22^{nd}$. A 3 $^{o}$C mean layer warmness was observed at about 150 km ahead of the storm and the possible direction of movement of the depression (line joining the centre of depression and the protrusion of maximum warmness, similar to warm tongue) was in total agreement with that finalised by IMD. However, there is an eastward shift of about $0.5^{o}$ in

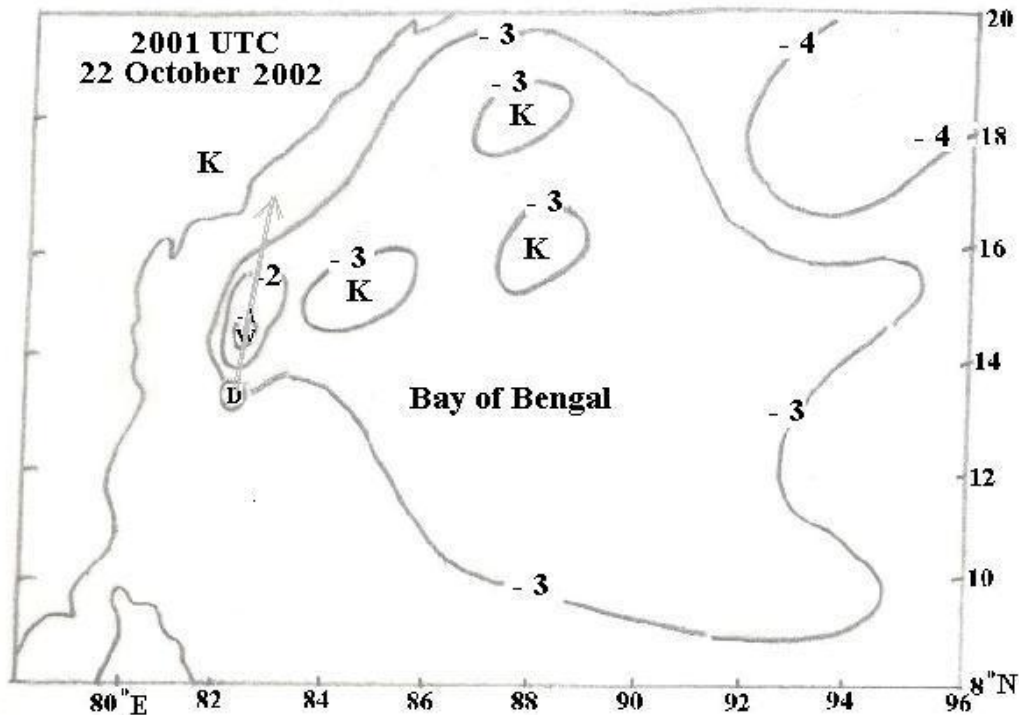locating the centre of the storm based on ATOVS data albeit the latitude fixation agrees with that of IMD.



Fig. 11. Analysis of 700 – 400 hPa layer mean temperature ($^{o}$C) of the Bay depression at 2001 UTC / 22 October 2002.

## Kolkata cyclone, 11-12 November 2002

A depression formed at 14.0 $^{o}$N / 83.0 $^{o}$E at 0300 UTC on November 11, 2002 intensified into a cyclonic storm at 1200 UTC and lay centered at 16.0 $^{o}$N / 84.5 $^{o}$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 $^{o}$N / 87.5 $^{o}$E. The storm then weakened into a cyclonic storm (21.7 $^{o}$N / 88.3 $^{o}$E) at 0800 UTC and crossed the west Bengal coast. The system had northnortheast to northeastward movement almost throughout its sea travel from its cyclonic intensity stage. Analyses of temperatures derived from AMSU onboard NOAA-15 satellite at 0123 UTC on 11th and 0126 UTC on 12th clearly indicated the possible track of the cyclonic storm to incredibly coincide with the actual track of the storm as observed by the Doppler Weather radar (DWR) at Kolkata and the best track that has been finalised by IMD. Fig. 12 illustrates the protruding mid-tropospheric warmness ahead of the storm on 11th and 12th. However, localised warmness was also seen in about 200km south of the storm at 0126 UTC on 12th and there are large data gaps between 18 and 20 $^{o}$N / 84 and 90 $^{o}$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.
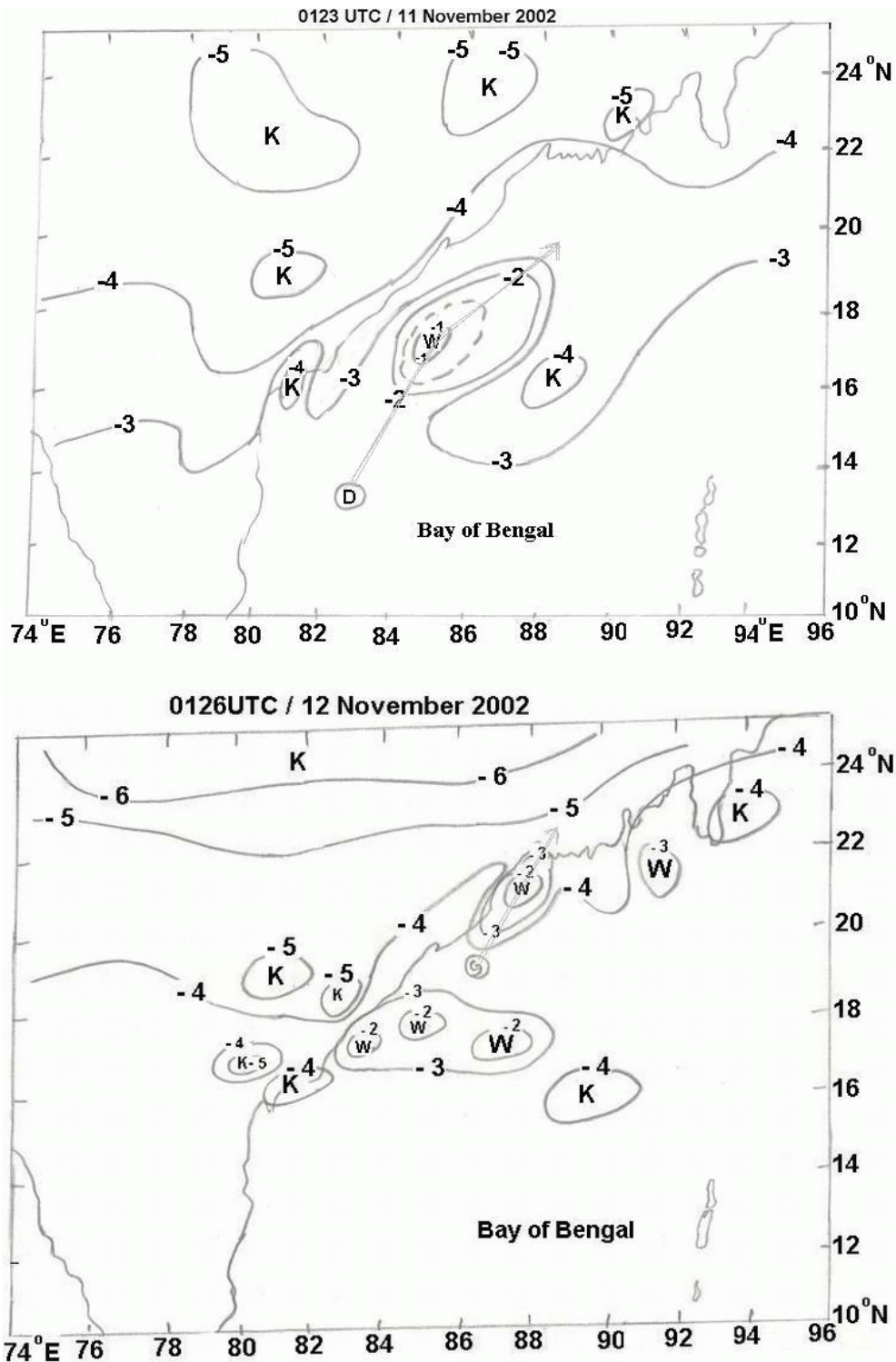
Fig. 12. AMSU derived mid-tropospheric (700 – 400 hPa) warmness that shows the possible track of cyclonic storm on 11th and 12th November 2002.

Only a portion of the storm fury could be detected by the day time NOAA 16 passes on 11th and 12th due to scan geometry limitations of the polar orbiters. The centre (eye) of the storm was just missed by these passes. 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 and 0126 UTC/11th satellite passes) compared with that finalised by IMD has been shown in

Fig. 13. The possible storm centre, based on maximum warmness, almost coincided with the storm's actual position as can be evidenced from the analyses of 0123 UTC of 11th and 0126UTC of 12th. The error in estimation is approximately between 30 and 50 km. The prediction based on AMSU clearly indicates that the track can be prognosticated with a reasonable degree of accuracy with 6 to 12 hrs lead time and 200-500 km ahead of the movement of the storm's core.
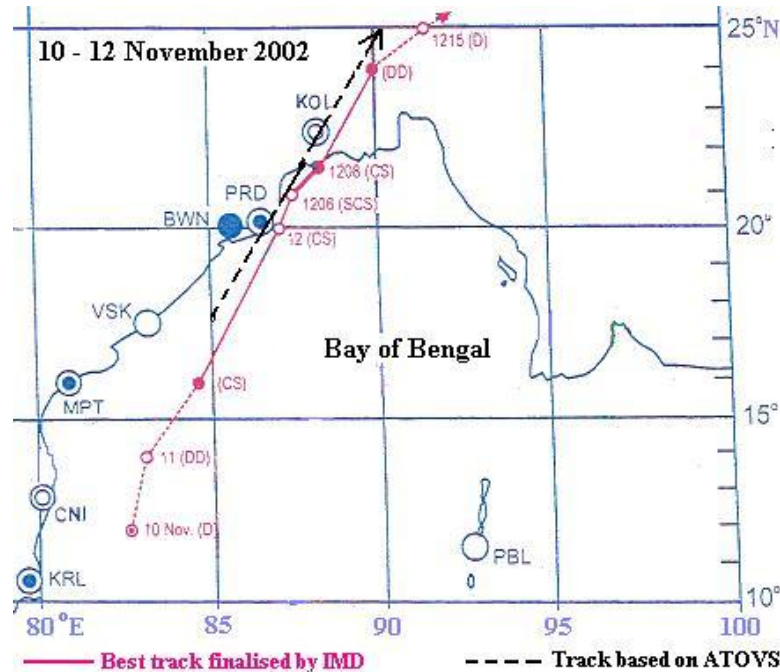


Fig. 13. Possible track predicted by AMSU compared with track as finalised by IMD.

## Machilipatnam cyclonic storm, 13 – 15 December 2003

The depression formed at 1200 UTC on 11th December 2003 (4.5 $^{o}$N / 90.5 $^{o}$E) had a long northwestward sea travel to become a cyclonic storm with intensity T2.5 (9.5 $^{o}$N / 87.5 $^{o}$E) at 12 UTC on 12th. It gained intensity as a severe cyclonic storm (T.3.5) at 1200 UTC on 14th and lay centered at 11.5 $^{o}$N / 84.0 $^{o}$E. The severe cyclonic storm intensity was maintained upto 1200 UTC of 15th and crossed coast near Machilipatnam as a cyclonic storm at 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. 14 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 $^{o}$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 localized regions suggesting that the storm may move towards either of them or in between these two warm pools. 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.
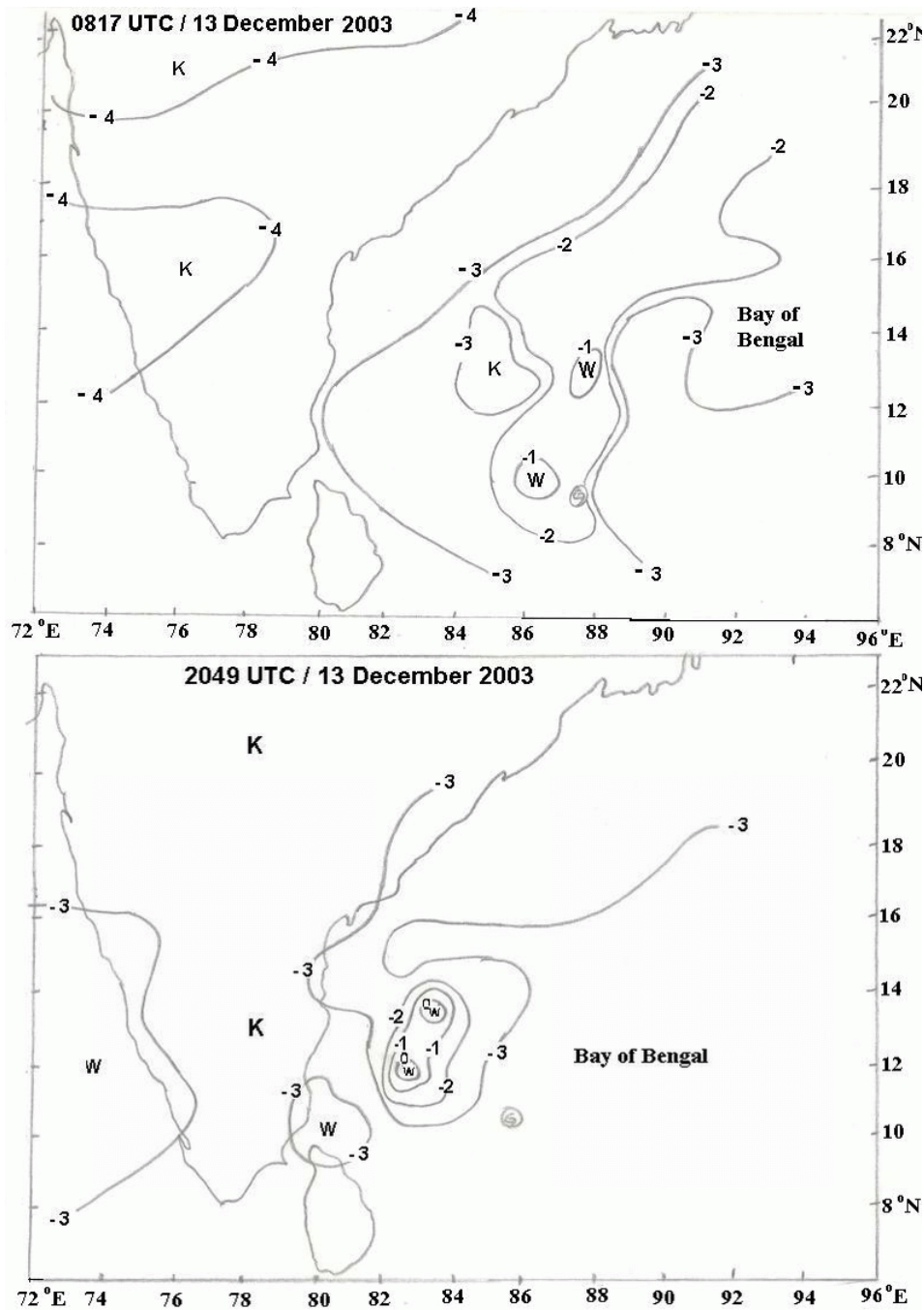
Fig. 14. Analysis of 700 – 400 hPa layer mean temperature at 0817 and 2049 UTC on 13 December 2003.

Since the storm was away from the coast by more than 600km during this period, ground based radars were of no help in tracking the storm. Satellite imageries from the EUMETSAT at 1500, 1800 UTC could not suggest any clear cut movement of the storm since the storm centre was obscured by the dense overcast cloud mass. However, the AMSU data at 2034 UTC of 14th clearly suggested that the possible movement was towards northwest and heading towards Machilipatnam (16.0 $^o$N / 80.8 $^o$E). Fig. 15 shows the 700-400 hPa layer mean temperature at 2034 UTC on 14th. Locating the storm track through subjective analysis when two warm pools were located at 0817 and 2049 UTC of 13th and going by the maximum warmness at 0805 and 2034 UTC of 14th, the track of the storm has been prognosticated and compared with the best possible track finalized by IMD (see Fig. 16). The ATOVS based prediction agrees well with actual storm track.
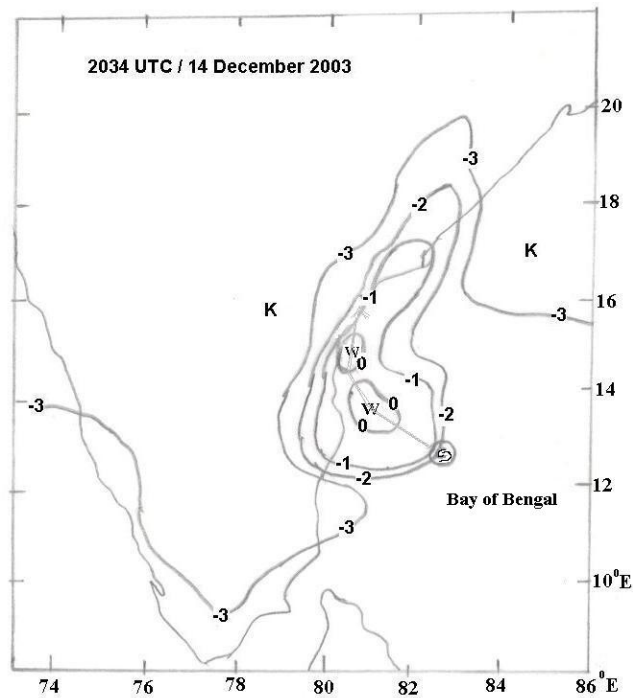
Fig. 15. Analysis of 700-400 hPa layer mean temperature at 2034 UTC on December 14, 2003.

## Thermal structure of the cyclonic disturbances

The temperature anomaly has been worked out based on Kidder et al(2000), viz., environmental temperature has been subtracted from the AMSU sounding temperature at each level. For this purpose the environment is considered as 500 - 600 km away from the centre of the storm. No significant warmness was observed over the core region of the tropical depression on October 22, 2002 at 2001 UTC. However, a 1.2 $^{\circ}$C warmness was observed at 550 hPa about 129 km away from the centre of the depression. The rain clouds around the depression could be the cause for either the insignificant warmness or the negative anomalies (coldness) within 120 km from the centre of the depression (13.7 $^{\circ}$N / 81.5 $^{\circ}$E). But in the case of the Kolkata cyclonic storm at 0123 UTC on November 12, 2002, a maximum warmness of 13.3 $^{\circ}$C was observed at 124 km (and 12.1 $^{\circ}$C at 62 km) from the storm centre at 250 hPa during which period the storm had gained intensity T3.5. Fig. 17 shows the temperature anomalies at 2001 UTC on October 22, 2002 and 0123 UTC on November 12, 2002.
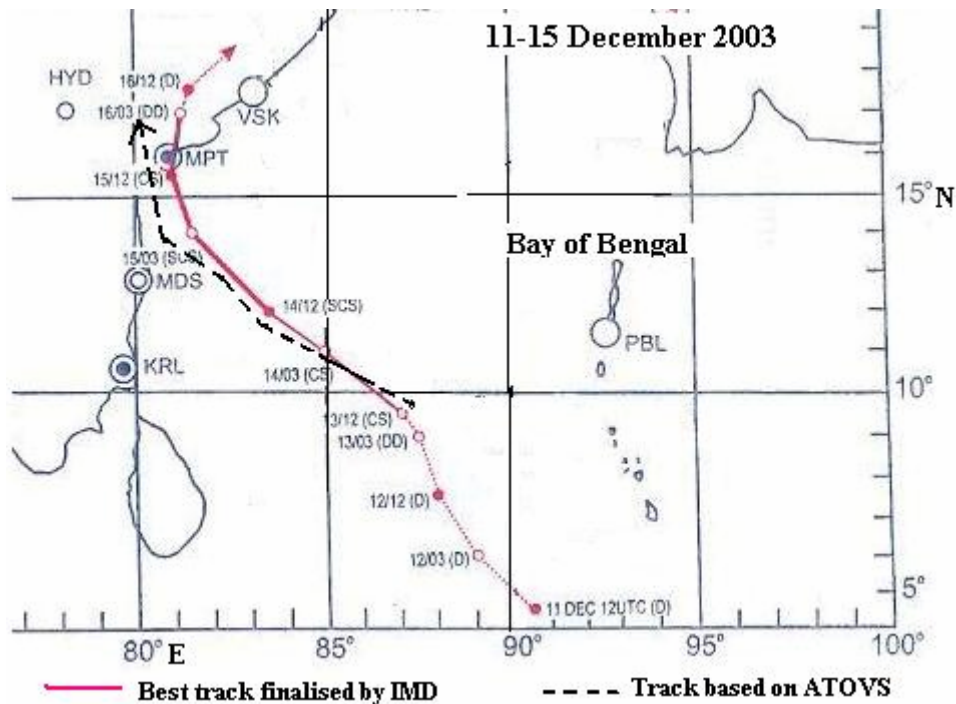
Fig. 16. Track prognosticated from ATOVS data (from 0834 UTC of 13th December to2034 UTC of 14th December, 2003) and compared with the best track finalized by IMD for the Machilipatnam cyclone, 11-15 December, 2003.

Unfortunately there was no sounding within the core region or eye (19.4 $^o$N / 86.7 $^o$E) of the storm. The negative anomalies at the lower levels, over the randomly selected sounding points, are the indicatives of intense precipitation over those locations since the AMSU channels 4 – 6 are contaminated with heavy precipitation (Kidder et al, 2000). It can also be seen that the warmness is very high at upper tropospheric levels at shorter ranges (than the farther ranges) from the storm centre. This sort of maximum warmness (due to subsidence) close to the centre of the storm between 250 and 200 km have been well documented in Kidder et al (2000).

The thermal structure of the Machilipatnam cyclone during its depression stage was almost similar to that of October 2002 depression in the sense that no significant warmness was observed at mid-tropospheric and upper tropospheric levels albeit a 1.0 to 4.6 $^o$C warmness was observed at ranges 70 to 180 km from the depression centre (7.0 $^o$N / 88.2 $^o$E ) at the lower troposphere upto 700 hPa. When the disturbance attained cyclonic intensity, significant warmness was observed at higher levels, more precisely at 200 hPa. Fig. 18 shows the temperature anomalies during 12 – 14 December 2003. When the disturbance was attaining its cyclonic intensity of T.25 at 0817 UTC on 13th , a 9.0 $^o$C warmness was observed at 200 hPa at 143 km from the storm centre (9.5 $^o$N / 87.5 $^o$E). Two soundings at 28 and 40 km from the storm centre (11.5 $^o$N / 84.2 $^o$E) at 0806 UTC on 14th revealed a 7.7 $^o$C warmness at 200 hPa. It may also be seen that the lower tropospheric warmness of about 2 $^o$C was also captured by the AMSU soundings over the region very close to the core / eye of the storm. When the storm was having its peak intensity of T3.5 at 2037 UTC on 14th, there was one sounding well within the eye of the storm ( approx. centre 12.2 $^o$N / 82.8 $^o$E) which indicated a warmness of 8.7 $^o$C and another sounding at 45 km from the storm centre indicated a 9.1 $^o$C warmness at 200 hPa. Lower tropospheric warmness of more than 2 $^o$C

from 1000 to 900 hPa within the eye of the storm (5 km from the storm centre) and at 45 km from the storm centre upto 850 hPa has been well brought out by AMSU.
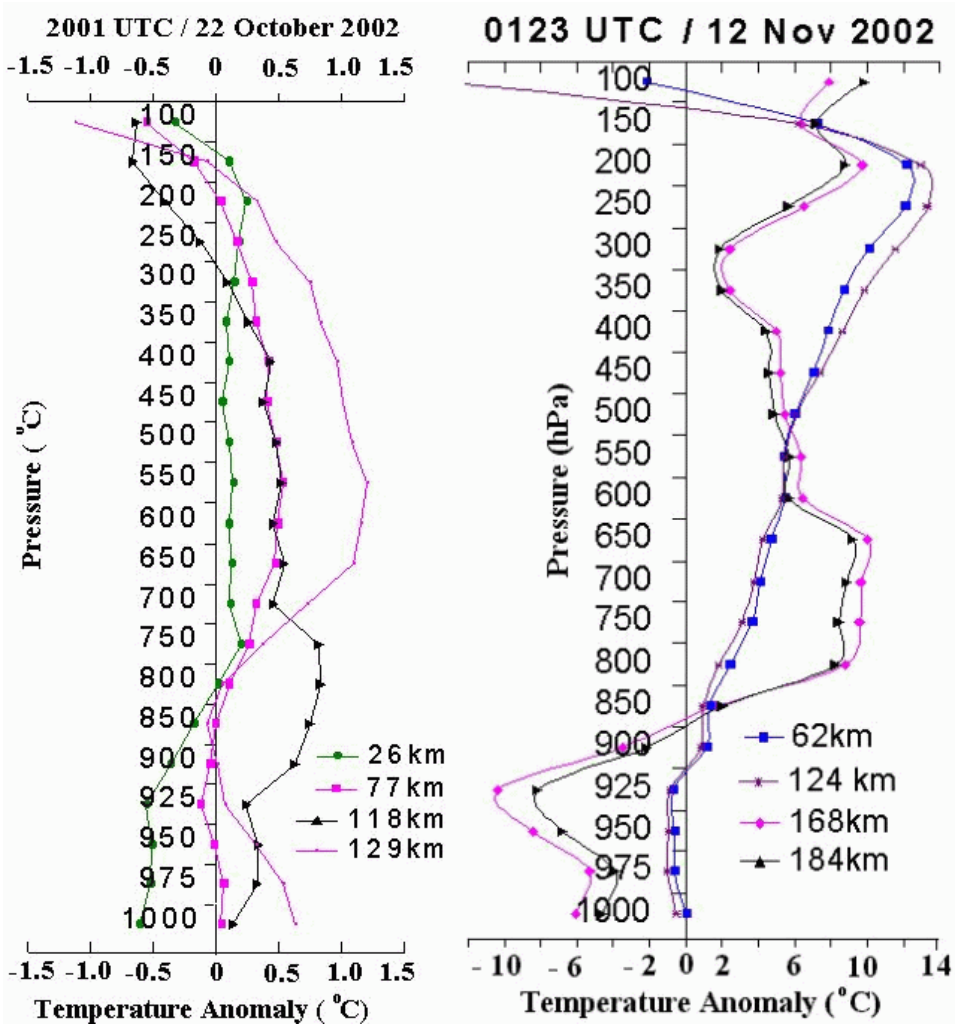


Fig. 17. Vertical cross section of temperature anomalies through a tropical depression (22 October 2002) and during a tropical cyclone (12 November 2002).
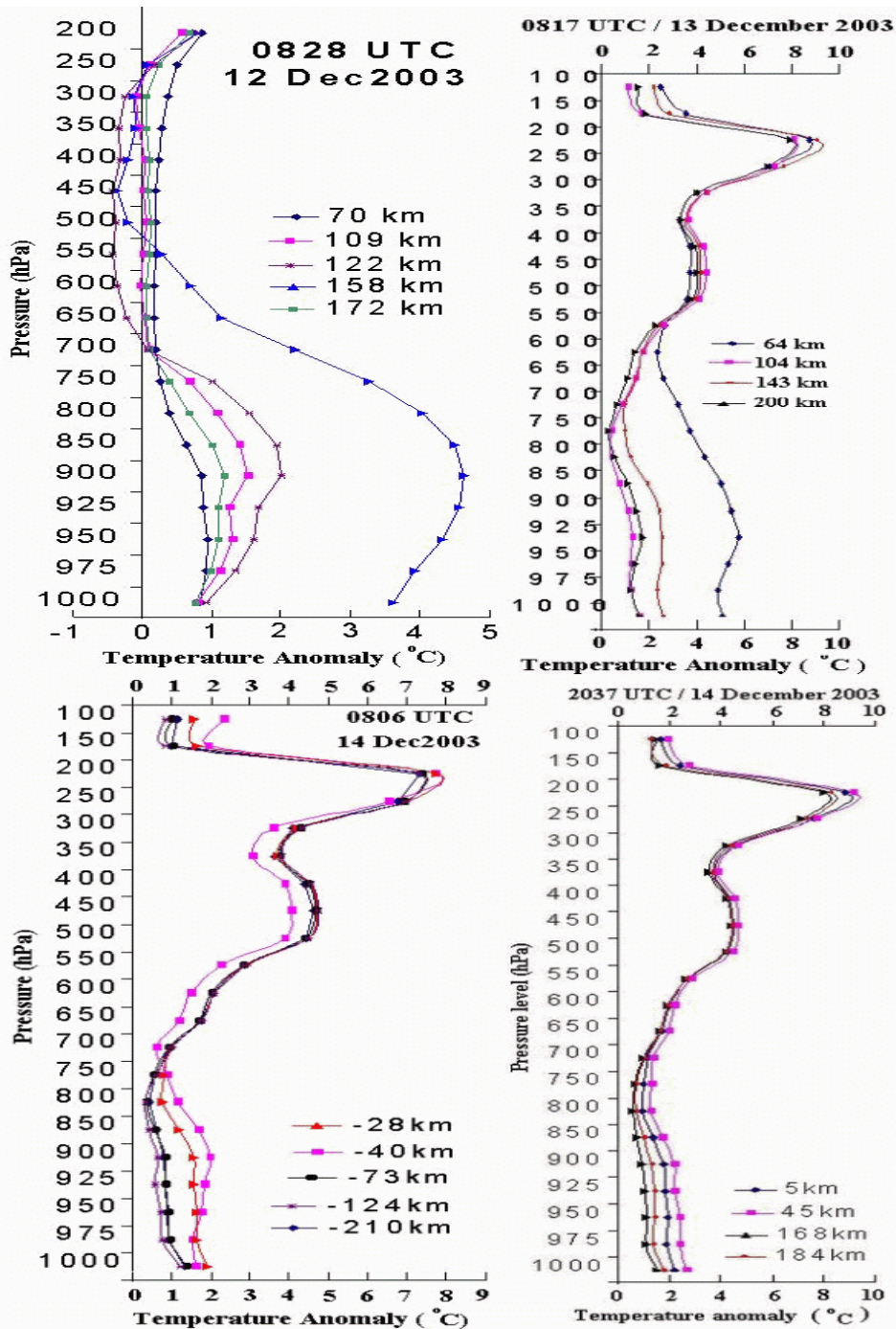
Fig. 18. Vertical cross section of temperature anomalies through the Machilipatnam cyclone (12 – 14 December, 2003).

## Convective instability

Equivalent potential temperature ( $\theta_e$ ) - a measure of moist static energy and conservable quantity during dry and saturated adiabatic processes - is an indicator of convective instability. $\theta_e$ has been computed numerically through a method outlined in World Meteorological Organisation(1986). Convective instability could be seen upto 700 hPa in the case of tropical depression on October 22, 2002 at farther ranges for the air entering the rainband and almost constant $\theta_e$ was observed aloft upto 350 hPa. This suggests that the convective instability is released in the form of cumulus convection (Malkus and Riehl, 1960; Barnes et al, 1983; Asnani, 1993).
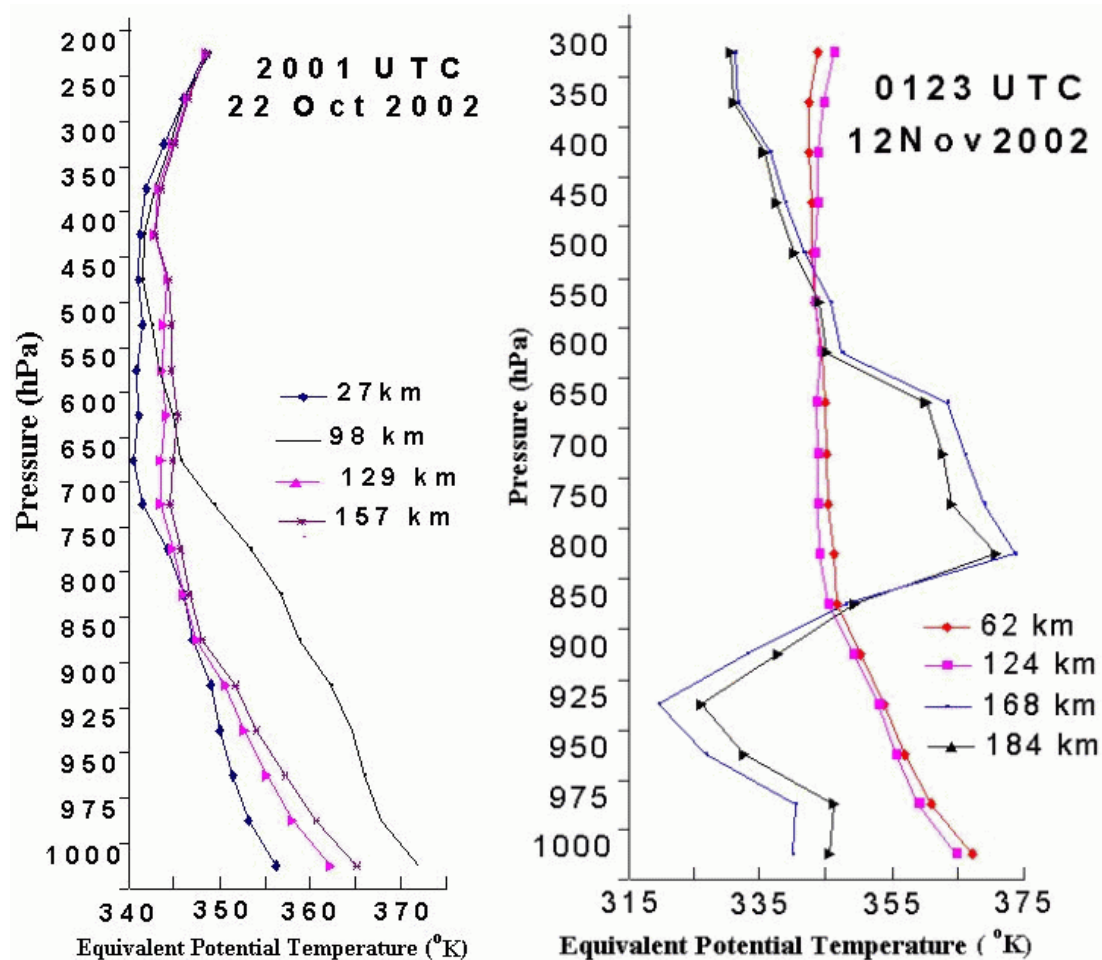
Fig. 19. Equivalent potential temperature profile of the tropical depression on October 22, 2002 and tropical cyclone (Kolkata cyclone) on November 12, 2002.

Fig. 19 shows the $\theta_e$ profile of October 22, 2002 tropical depression and November 12, 2002 tropical cyclone. The $\theta_e$ profile at 0123 UTC of 12th November 2002 with maximum convective instability confined between 975 and 925 hPa and convective stability aloft upto 800hPa over the outer regions (168, 182 km) of tropical cyclone could be the representative of stratiform clouds over these areas as seen by the DWR at Kolkata. This sort of existence of stratiform clouds outside the wall cloud region of a tropical cyclone is not at all uncommon (Asnani, 1993).

The $\theta_e$ profile of the Machilipatnam cyclone on 13th and 14th December 2003 is in total agreement with Barnes et al (1983) to the fact that the convectively unstable air entering the rain band develops into towering cumulus and manifests the almost constancy of $\theta_e$. However, during its depression stage at 0828 UTC on 12th December (see Fig. 20), the convective instability ($\approx 3.7\ ^{\circ}\mathrm{K}$ /km) was not more marked as in the case of the other depression on October 22, 2002 ($\approx 6.7\ ^{\circ}\mathrm{K}$ /km) at a range of 158 km and 157 km respectively Perhaps due to close proximity to the coast and in view of high convective instability, the depression on October 22, 2002 might have rained out before intensifying into a cyclonic storm. On the contrary, in view of excessive lower tropospheric warmness, large sea travel and relatively weak convective instability in the lower troposphere, the depression at 0828 UTC on December 12, 2003 had intensified into a cyclonic storm. The reason for the

varying processes of the atmosphere in each case of tropical disturbance is yet to be fully understood with more case studies.
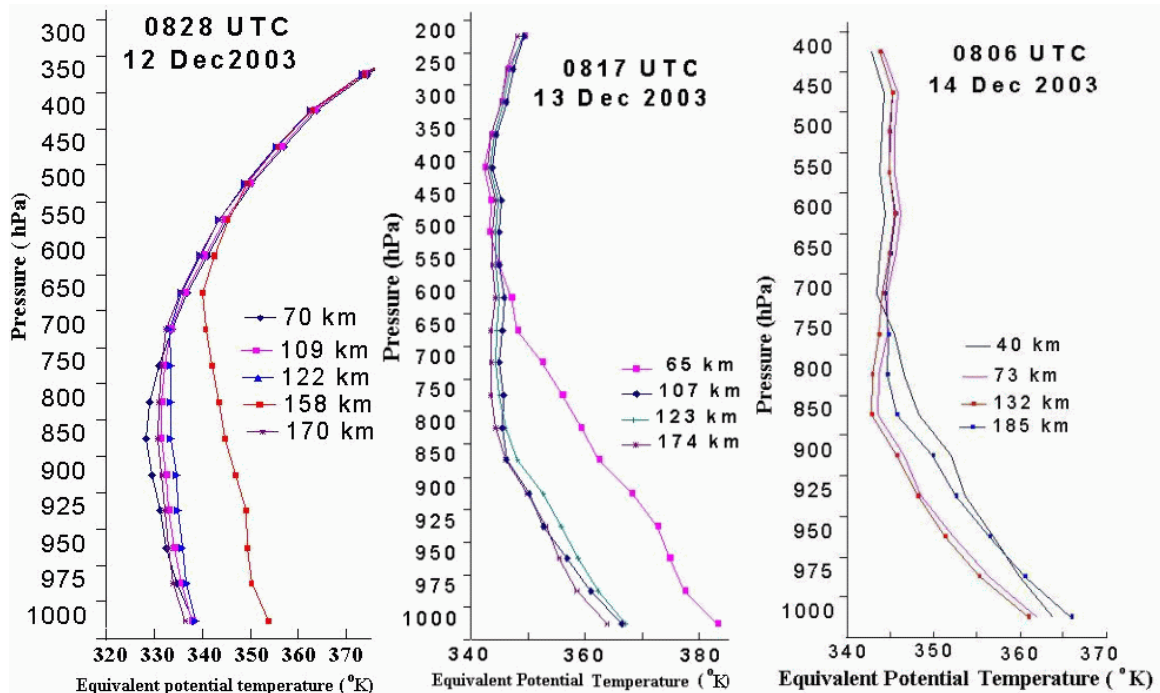


Fig. 20. Equivalent Potential Temperature profile of Machilipatnam cyclone, 12 – 14 December 2003.

## 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.

➤ 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.

➤ 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.

➤ 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).

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 geostationary satellites, it is hoped that the temporal resolution as well the ' data gap' problem would be solved.

## Summary and conclusions

The method outlined in this paper, viz., protrusion of warm tongue in the mid-tropospheric layer (700-400 hPa) ahead of the storm as a pre-cursor to the storm's movement, can be tried initially as a parallel forecasting tool till such time the forecaster is satisfied

with the suitability of the technique in comparison to the other cyclone track forecasting methods such as climatology, persistency, climatology and persistency (CLIPER) and numerical methods. The method can easily be made operational, if found suitable, thanks to the rapid advancement in computing technology. The thermal structure of the tropical disturbances over Bay of Bengal and Arabian Sea can be better understood by analyzing the ATOVS data with more number of storms in the years to come since in this paper we had analysed a very limited sample of ATOVS data.

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