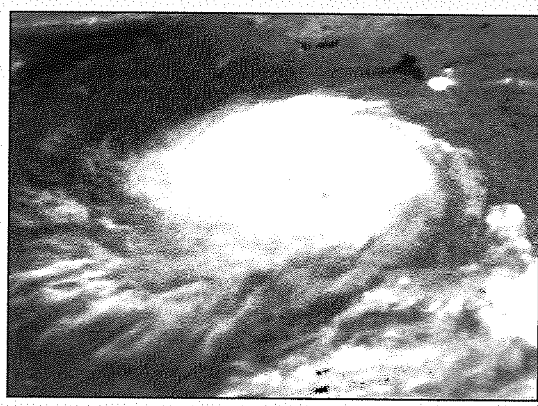
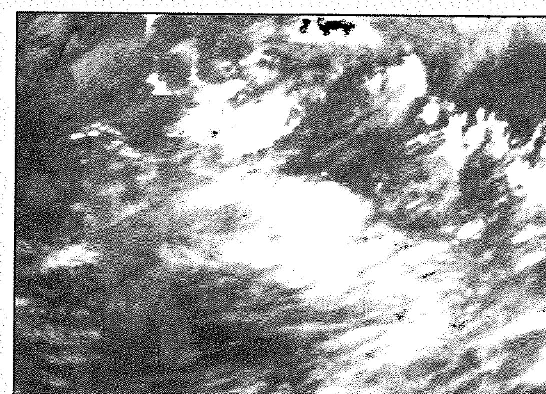
SRR- 1

*Special Research Report*

Indian Institute of Tropical Meteorology
Pune-411 008, India

# INVESTIGATION OF FEATURES OF MONSOON DEPRESSIONS AND TROPICAL CYCLONES BY IRS-P4 MSMR DATA





P. N. MAHAJAN, R. M. KHALADKAR, S. G. NARKHEDKAR and SATHY NAIR
Indian Institute of Tropical Meteorology, Pune – 411 008

P. C. JOSHI and P. K. PAL
Space Applications Centre, Ahmedabad – 380 015

JULY 2003

SRR- 1

***Special Research Report***



**Indian Institute of Tropical Meteorology**
**Pune-411 008, India**

# INVESTIGATION OF FEATURES OF MONSOON DEPRESSIONS AND TROPICAL CYCLONES BY IRS-P4 MSMR DATA

by

**P. N. MAHAJAN, R. M. KHALADKAR, S. G. NARKHEDKAR and SATHY NAIR**
**Indian Institute of Tropical Meteorlogy, Pune – 411 008**

**P. C. JOSHI and P. K. PAL**
**Space Applications center, Ahmedabad – 380 015**

**JULY 2003**

# Acknowledgments

This project is joint effort of Indian Institute of Tropical Meteorology (IITM), Pune and Space Applications Centre (SAC), Ahmedabad. We owe our sincere thanks to the Project Advisory and Monitoring Committee – Indian Space Research Organisation (ISRO), who motivated us to take up this project. The keen interest shown by Dr. R. R. Navalgund, Director, NRSA, Dr. M. S. Narayanan, Head MOG, Dr. Pranav Desai and Dr. Abhijit Sarkar, SAC is greatly acknowledged. We also thank for their valuable suggestions and comments during the periodic review meetings. The support provided by the scientists of SAC viz. Dr. H. I. Andharia, Dr. P. Thapaliyal and Dr. Santanu Chaudhari towards scientific discussions and necessary cooperation is highly appreciated. Thanks are also due to Mrs. U.V. Bhide for reviewing the research report and giving useful suggestions.

We are grateful to Dr. G. B. Pant, Director, IITM for encouraging us to take up this project and providing all help during the course of the project. Thanks are also due to Dr. S. S. Singh, Head, Forecasting Research Division and Dr. (Smt.) P.S. Salvekar, Head, Theoretical Studies Division, IITM for their interest and support for this study. We are benefited by the discussions with several colleagues of the Forecasting Research Division, during the course of this project. We wish to thank them all.

We are thankful to India Meteorological Department (IMD) for providing INSAT imageries, OLR data and other conventional data. Thanks are also due to National Remote Sensing Agency (NRSA), Hyderabad for supply of the MSMR geophysical data (GPD) products.

## Legend of Figures

# Contents

# INVESTIGATION OF FEATURES OF MONSOON DEPRESSIONS AND TROPICAL CYCLONES BY IRS-P4 MSMR DATA

**P. N. MAHAJAN, R. M. KHALADKAR, S. G. NARKHEDKAR and SATHY NAIR**
**Indian Institute of Tropical Meteorology, Pune – 411 008**

**P. C. JOSHI and P. K. PAL**
**Space Applications Centre, Ahmedabad – 380 015**

## Section 1

### Context of present work and scope of the study

IITM and SAC organizations have good research experience in respect of utilization of satellite data for atmospheric studies over the Indian region. Utilizing this asset, a joint effort has been made to evaluate possible use of IRS-P4 MSMR data for better analysis and depiction of important weather systems such as monsoon depressions and cyclonic storms over the Indian region. Hence, a project entitled, ***"Investigation of features of Monsoon depressions and Tropical cyclones by IRS P4 MSMR data"*** is jointly undertaken with due consideration of the following objectives.

i) To study the genesis and structural characteristic features associated with monsoon depressions and tropical cyclones affecting Indian region in the light of geophysical parameters retrieved from IRS-P4.
ii) To compare above results with the conventional observations and the data obtained from DMSP-SSM/I satellite over the same region for similar cases.
iii) To study the variation of the parameters in different stages of the system.
iv) To assess the utility and impact of IRS-P4 data for weather forecasting and other meteorological applications.

In early stages of satellite-remote sensing, few countries were involved in taking observations of earth-atmosphere system since the launch of first meteorological satellite i.e. TIROS-1 on 1st April 1960. It was followed by a number of civilian satellites by various countries, equipped with microwave radiometers to study several environmental parameters. The DMSP (Defense Meteorological Satellite Program) satellite series designed by USA was to provide wide range of earth, atmosphere and environmental data on real time basis for their observations worldwide. A technically advanced microwave radiometer namely Special Sensor Microwave/Imager (SSM/I) was onboard Block 5D-2 flight of DMSP since June 1987. This sensor has given very useful results over the different parts of the globe to various scientists of the world. Hence, in this report a comparison between DMSP and IRS-P4 derived geophysical parameters is made for similar cases of weather systems for getting the status of our data and proper utility for better depiction of important weather systems over the Indian region.

Many types of weather systems viz. lows, depressions, cyclonic storms, offshore vortices, mid-tropospheric cyclones etc. are forming over the Indian region. Out of which monsoon depressions and tropical cyclones are very important weather systems in respect of their disastrous characteristics and widespread rainfall distribution in associated areas. Lack of conventional observations over the oceanic region makes the study or forecasting of these systems very difficult.

MSMR works on the principle of collecting radiation in microwave bands from the earth's surface with the associated advantage of cloud penetration for all weather capacity. Hence, the variation of geophysical parameters in different stages of monsoon depressions and tropical cyclones are studied with respect to MSMR data.

# Section 2

## IRS-P4 MSMR and Geophysical Products

### 2.1 MSMR characteristics

Indian Space Research Organisation launched Oceansat (IRS-P4) satellite in the orbit on May 26, 1999. It is a polar orbiting sun-synchronous satellite at 720 Km altitude covering the globe in two days with equatorial crossing time 1140 hrs (descending) and 2340 hrs (ascending) LST.

Oceansat-I carries two sensors viz. Multifrequency Scanning Microwave Radiometer (MSMR) and an Ocean Colour Monitor (OCM). The project is concerning MSMR data.

MSMR characteristics: MSMR is four-channel sensor with dual polarization. Its frequencies, spatial resolution are given below (Table 1).

**Table 1 : Frequencies and resolutions**

| **Frequencies (GHz)** | 6.6 | 10.65 | 18.0 | 21.0 |
|---|---|---|---|---|
| **Spatial Resolution (km)** | 120 | 75 | 45 | 40 |

### 2.2 Geophysical data (GPD) products from MSMR

Brightness temperature data from MSMR for different channels and polarizations are used to derive various geophysical parameters over the oceanic regions. Gohil et al. (2000) developed suitable algorithms for retrieval of geophysical parameters. The algorithms are based on the general equation

$$G = C_o(s,\theta) + \sum_{i=1}^{N} C_i(s,\theta) \cdot f\left[Tb_i(M,R,\theta)\right]$$

where, G is the parameter to be retrieved, $C_o$, $C_i$ are the retrieval coefficients for the $i^{th}$ channel, i the channel number, $Tb_i$ is corresponding brightness temp, $\theta$ is local incidence angle, N denotes total number of channels used and M is the month of observation. *s* indicates the dependence of coefficients on season and region specific SSTs.

Using different combinations of MSMR frequencies, four geophysical parameters retrieved are considered in the present study.

The parameters retrieved and frequencies used for their derivations are given in Table 2 (Ali et al., 2000).

**Table 2 : Frequencies used for deriving Geophysical Parameters**

| Parameters | Frequencies used (GHz) |
|---|---|
| Sea surface wind speed (SSW) | 6.6, 10.65, 18 & 21 |
| Sea surface temperature (SST) | 6.6, 10.65, 18 & 21 |
| Integrated water vapor (IWV) | 18 & 21 |
| Cloud liquid water content (CLW) | 18 & 21 |

The grid sizes for different parameters and the grid numbers are specified in Table 3

**Table 3 : Resolutions and grid number of different parameters**

| Parameters | Resolutions (km) & Grid Number |
|---|---|
| SST, SSW, IWV, CLW | 150 x 150 (Grid-I) |
| SSW, IWV, CLW | 75 x 75 (Grid-II) |
| IWV & CLW | 50 x 50 (Grid-III) |

Out of the above parameters SSW is derived from both combinations i.e. using 6.6 GHz (8 Channels) & excluding it (6 channels).

The parameters are retrieved over the oceanic regions 200 km away from the coast. They are validated with respect to *in situ* ship and buoy data as well as NWP model analysis (Ali et al., 2000). They are reasonable as compared to DMSP and NOAA satellite data (Varma et al., 2002).

The range of different parameters and their accuracies over the tropical regions are shown in Table 4 (Gohil et al. 2000).

**Table 4 : Range and retrieval accuracy of parameters**

| **Parameter** | **Range** | **Retrieval Accuracy (Approx.)** |
|---|---|---|
| SST (°K) | 281-305 | 1.5 |
| SSW (mps) | 0 – 24 | 1.6 * |
| IWV ($gm/cm^2$) | 0.3 – 8.2 | 0.20 |
| CLW ($mg/cm^2$) | 0 – 132 | 13.0 |

* *In the present study 8 channels are used for wind speed retrieval.*

## 2.3 Importance of geophysical parameters

### i) Sea Surface Wind speed

The kinematics of the atmospheric-oceanic boundary is dominated by the frictional forcing between atmospheric motion and the ocean surface and resulting transfer of energy evolves as the wind stress. Wind stress over the wavy ocean surface is complex and not fully understood. The ocean is recognized as dynamic, energetic and undulating body with random motions that vary both spatially and temporally. Passive microwave emissivity of the ocean surface varies in response to deformation to it caused by wind stress. The ocean surface becomes rougher as the wind speed increases and changes in brightness temperature are expected. MSMR measures the changes in brightness temperature and further it is analyzed to retrieve wind speed over the oceanic region.

The multispectral passive microwave wind speed algorithm is based on surface radiation measurements from satellite footprints. The MSMR views heterogeneous micro scale changes in sea surface emissivities, which are spatially averaged within the largest footprints, so that relative scale of wind speed derived from MSMR can be considered to be within either the mesoscale or synoptic scale domains. These surface wind speeds in specific areas have vital importance for the development/dissipation of the weather systems over the oceanic regions.

### ii) Sea Surface Temperature

Sea surface temperature plays a vital role in many atmospheric processes. Developments of important weather systems depend on crossing of some threshold value of sea surface temperature. Unless we have some typical sea surface temperature over the oceanic region, we cannot get the development of the weather system. Hence, accurate measurements of SST are important. It also helps to recognize warm pool region where the development of more convection is likely to occur.

Accurate measurements of SST are very crucial for many air-sea interaction processes both globally as well as regionally. El Nino-Southern Oscillation (ENSO) phenomena, Ocean circulations, heat transfer to the atmosphere etc. are closely linked with the SST. For development of deep convective systems like tropical cyclones, SST is one of the important parameters. It is also necessary as an input to weather prediction and climate models. MSMR provides SST on global scale. In the present context, it is used to study monsoon depressions and cyclonic storms over Indian region.

### iii) Integrated Water Vapour

During pre-monsoon, monsoon and post monsoon seasons genesis of number of important weather systems such as monsoon depressions and tropical cyclones are caused by transport of large amount of moisture over the Arabian sea and the Bay of Bengal. Hence, quantitative estimates of moisture fields over these oceanic areas play an important role in understanding the mechanism and the dynamics of these systems. The region of high-integrated water vapour gives the idea of development of major convective activity over that region. This gives indication of specific region where more rainfall is likely to occur.

Most of the earlier studies related to the moisture are based on the data from radiosonde stations, which are located over the land areas, with only few island stations over oceans. Therefore, it is not possible to study the distribution of moisture over vast oceanic regions using only conventional means. The satellite data however, make it feasible to study the distribution of moisture over large and remote areas because of their wide and temporal coverage.

With the advent of satellite carrying microwave sensors, the samples of monitoring moisture over oceans have become well established (Grody et al. 1980, Prabhakara et al. 1982, Pandey, 1992). Ruprecht and Gray (1976) have emphasized the importance of moisture fields for the development of weather systems over the oceanic regions. Water vapor values derived from MSMR are thought to be perhaps one of the most accurate MSMR derived parameters, and a number of investigators have proposed retrieval methods that can be utilized globally, regionally and under wide range of atmospheric conditions.

## iv) Cloud Liquid Water Content

The quantitative estimates of CLW are important for improving forecast of rainfall distribution in respect of weather systems crossing the coast of India. The validation of MSMR cloud liquid water content estimates is quite complex and may represent the stiffest challenge of all MSMR retrievals, since it involves uncertainties. Other MSMR meteorological parameters can be more easily related to routine conventional measurements on synoptic basis for calibration and validation. The quantitative validation of cloud liquid water content is difficult. This is because there is lack of conventional ground-truth data since the direct measurements of CLW are extremely difficult. However, our scientists have developed the algorithm but there has been almost no proper work for validation.

Several cloud liquid water algorithms are available based on SSM/I data. The validation of SSM/I CLW estimates is quite complex procedure and faces strong challenge amongst other atmospheric retrievals. At present, there are different approaches for the validation of SSM/I estimates of CLW with each having its merits and demerits. The first includes an upward looking microwave radiometer to view the atmospheric liquid water. Alishouse et al. (1990) selected this technique for their calibration/validation campaign. Kilham and Barrett (1993) explained the limitations of this campaign with respect to wind speed and water vapor. CLW measurements made by aircraft flights through stratiform clouds are associated with second method. The reason is that while generating credible *in situ* data, a very large number of aircraft flights are required to cover the wide range of possible CLW values. The third method is to use humidity values from radiosonde ascent to model the CLW. The algorithm developed by our scientists to find out cloud liquid water content from MSMR has some uncertainties.

# Section 3

## Weather systems considered for the study

### 3.1 Classifications of weather systems

According to India Meteorological Department the weather systems over Indian region are classified according to the surface wind speeds. Specifications are given below.

| | |
|---|---|
| Less than 8.5 mps | Low |
| 8.5 - 13.5 mps | Depression **(D)** |
| 14.0 - 16.5 mps | Deep Depression **(DD)** |
| 17.0 – 23.5 mps | Cyclonic Storm **(CS)** |
| 24.0 – 31.5 mps | Severe cyclonic storm **(SCS)** |
| 32.0 – 59.5 mps | Very severe cyclonic storm **(VSCS)** |
| 60.0 mps and above | Super cyclonic storm **(Sup CS)** |

WML – *Well Marked Low - a stage between low and depression*

During the period 1999-2001, four cases of monsoon depression and eight cases of cyclonic storms formed over India region. They are studied with respect to MSMR derived geophysical parameters. The cases are as below.

### 3.2 Monsoon Depressions

1. Deep depression formed on 17 June 1999
2. Deep depression formed on 27 July 1999
3. Depression formed on 23 August 2000
4. Depression formed on 12 June 2001

### 3.3 Tropical Cyclones

1. Very severe cyclonic storm formed during 16-18 October1999
2. Super cyclonic storm formed during 28-30 October 1999
3. Cyclonic storm formed on 30 March 2000
4. Cyclonic storm formed on 17 October 2000
5. Cyclonic storm formed on 27 October 2000
6. Very severe cyclonic storm formed during 27-29 November 2000
7. Very severe cyclonic storm formed during 25-27 December 2000
8. Very severe cyclonic storm formed during 21- 28 May 2001

Break up of above depressions and storms with respect to the period, location etc. are given in the text.

Out of above cases two cases of monsoon depressions (June 1999 and August 2000) and two cases of cyclonic storms (October 1999 and May 2001) are discussed in detail in Sections 4 and 5 respectively.

Specifications of MSMR derived products in various stages and tracks of the systems for all the above cases are provided in Appendix (a-l).

## 3.4 Data used for the project

Along with the MSMR data, daily weather summaries obtained from India Meteorological Department are used for selecting proper synoptic situations over the Indian region involving the complete life cycle of monsoon depressions and tropical cyclones. INSAT and METEOSAT satellite imageries are used to locate and mark the advancement of the depressions and tropical cyclones. Surface and upper air charts obtained from India Meteorological Department are used to identify the surface pattern and upper air circulations associated with monsoon depressions and tropical cyclones. INSAT-OLR (Outgoing Long wave Radiation) data obtained from IMD at 06 UTC matching with descending node of IRS-P4 satellite are utilized for finding the aerial coverage and movement of major convective activity in the region of above weather events. Cloud Motion Vectors (CMVs) and Water Vapor Wind Vectors (WVWVs) obtained from METEOSAT-5 satellite are used for finding dynamical aspects of these systems during their genesis, development and dissipation over the Indian region. Domain of the study : Lat 0° – 30°N and Long 40°E – 90°E.

In general, both descending and ascending nodes of IRS-P4 are combined to get daily MSMR parameters. Grid-I data corresponding to 150 km resolution are considered. The data are plotted with GrADs software developed by COLA, Department of meteorology, University of Maryland, USA.

# Section 4

## Monsoon Depressions with respect to MSMR data

## 4.1 Introduction

### Monsoon Depressions

Monsoon depressions are important synoptic scale weather systems that form over the Indian region during the southwest monsoon season (June-September). Eliot (1884), Rao (1976), Sikka (1977), Sarkar and Chowdary (1988), Asnani (1993) etc. have presented various aspects of monsoon depression e.g. life history, structure, movements, thermal and moisture patterns etc.

Monsoon depressions account for large amount of the monsoon rains over the Indian region. They are described as low pressure areas with two or three closed isobars at two hPa intervals, covering an area of about five degree square. They mostly form over north Bay of Bengal and move west/northwestward at least to the central part of India.

On the basis of the statistics of 80 years of data (1891-1970) average frequency of formation of monsoon depression is four to five over the Bay of Bengal during monsoon season. Only about one or less than one system formed over the Arabian sea for the above period. The typical life time of monsoon depression is of the order of three to five days.

Out of the total number of depressions formed during SW monsoon seasons 80% form over the Bay of Bengal and 10% over Arabian Sea and the rest over the land. In general, zone of formation of depression is over head Bay of Bengal during July and August and over Central Bay during June and September. Average number of depressions, which form in each of the four months, varies from 2 to 2.5, although the scatter for individual year is large. It is noticed that in general, certain conditions are favorable for formation of depression. One of the conditions is that SST should be more than 29°C (Sikka, 1977).

Monsoon depression has horizontal wavelength about 2000 km. In its most intense stage it extends upto 10-12 km in the vertical. It is cold core in the lower troposphere. These depressions seldom acquire very strong intensity presumably due to large vertical wind shear and short travel over the seas. Nevertheless, they have high probability of intensification during September when the vertical wind shear weakens.

Monsoon depression is very important so far as distribution of rainfall in space and time over the region of its influence. Generally, 24 hr accumulated rainfall is 10-20 cm and isolated falls can exceed 30 cm in 24 hours. On any particular morning heavy rainfall exceeding 7.5 cm extends to about 500 km ahead and 500 km in the rear of the depression center and this area has a width of 400 km lying entirely to south of the track. The preferential rainfall is in the SW Sector. Contribution of total depression associated rainfall is 11 to 16% in the left sector along the track (Mooley, 1973).

A clear understanding of variations in geophysical parameters for the complete life cycle of monsoon depression is yet to emerge in detail. This is due to lack of observational data over ocean. Uses of DMSP-SSM/I derived geophysical parameters (SSW, IWV) are highlighted by Mahajan (2001,2002) for diagnostic study of monsoon depression formed during July 1992. For better understanding of large-scale structural features of monsoon depressions, it is necessary to utilize our IRS-P4 satellite data to comprehend more clearly its diagnostic and prognostic potentialities. Therefore MSMR data have been used to study four cases of monsoon depression formed over the Indian region during 1999 to 2001.

Characteristic features associated with the complete life cycle of this depression have been brought out in the following section in the light of MSMR data. Details viz. locations, track , variations of GPD products of the systems are given in Appendix (a-d).

## 4.2 Variation of MSMR derived parameters during the life cycles of the monsoon depressions

The day-to-day variations in the geophysical parameters derived from MSMR is studied in the vicinity of the depressions during their life cycles. Two cases are described below.

### I Depression during 13-18 June 1999

The low was reported on 15$^{th}$. It became well marked low on 16$^{th}$. Then it developed into a depression and further to deep depression on 17$^{th}$. Its position was 19°N and 85°E. The case is studied from the date 4 days prior to the formation of the depression. The day to day variations in the MSMR GPD products are described below.

**SSW** : On 13$^{th}$ June SSW of the order 12-13 mps were noticed over Northwest Bay. Next day, the areal extent of strong winds of 12-15 mps was increased. On 15$^{th}$ when the low pressure area formed, the winds of the order of 12-14 mps towards south and 8-10 mps towards northeast of the low were observed. On 16$^{th}$ winds of 15-18 mps with strong gradient were noticed on northeast of the system and on southern side speeds of 13-14 mps were seen. When the depression formed on 12th, the winds of the order 12-14 mps were observed around the system. The system intensified to deep depression on the same day at 19°N/85°E. It crossed the Orissa coast on 18$^{th}$ with reduction in the surrounding winds to 10-12 mps. During the formative stage of the depression the SSW which were of the order of 10 mps on 13$^{th}$ and 14$^{th}$ got strengthened to 12-15 mps when the system was located on land on 18$^{th}$ June.

**SST** : On 13$^{th}$ June most of the area of Bay showed SST of about 30-31°C. Same condition prevailed on 14$^{th}$ and 15$^{th}$June. On15$^{th}$ the low was reported. The low became WML on 16$^{th}$. SST was around 29-30°C showing reduction in temperature by 1-2°C. The low developed into depression and further to deep depression with position at 19°N/85°E on 17$^{th}$. On this day SST was around 30-31°C with isotherms showing semi circular shape around the depression. The system crossed the land on 18$^{th}$ when SST of 30-31°C got split up into different cells to northeast and southwest side with central portion showing temperature of the order of 28-29°C.

**IWV :** Integrated water vapor was of the order of 5-6 gm/cm$^2$ on 13$^{th}$ June over the Bay. It increased to about 7.5 gm/cm$^2$ over west central Bay (low pressure area). On 15$^{th}$ the maximum amount remained about 7.5 gm/cm$^2$ but concentrated at 15°N/85°E with gradual decrease symmetrically around the maximum. The amount was reduced on 16$^{th}$ which was around 5-6 gm/cm$^2$. On 17$^{th}$ i.e. day of formation of depression at 19°N / 85°E, the isolines of IWV are aligned around the depression with values about 6-6.5 gm/cm$^2$. The area of the depression is clearly noticed. The system also got intensified to deep depression on the same day and weakened to the depression on 18$^{th}$. It crossed the land with IWV about 6 gm/cm$^2$. Then gradient of IWV got reduced over the Bay. The maximum IWV during the life cycle of the depression was observed about 7.5 gm/cm$^2$. Over the Arabian Sea the values were around 5-6 gm/cm$^2$ during most of the period. The concentration over Arabian Sea shot up to about 7 gm/cm$^2$ on 18$^{th}$ June that could be due to the existence of the depression over the land.

**CLW** : On 13$^{th}$ June the value of CLW was about 0- 20 mg/cm$^2$ (i.e.0.2 kg/m$^2$) over most of the area over Bay of Bengal. It increased to 20- 50 mg/cm$^2$ over west central Bay with steep gradient on 14$^{th}$. When the low-pressure area was observed on 15$^{th}$, the concentration of CLW increased with maximum 10 mg/cm$^2$. The isolines are well aligned in a circular way with steep gradient with CLW values varying from 10 to 100 mg/cm$^2$. This gives the indication of some system located over this region. On the next day i.e. on 16$^{th}$ the CLW gradient got weakened and split up into two cells 50 – 60 mg/cm$^2$ at the center and 30 - 40 mg/cm$^2$ on northern and southern side of this maximum value. When depression was formed on 17$^{th}$ the values of CLW aligned according to the isobars but with the amount of 20 – 40 mg/cm$^2$. Deep depression formed on the same day. When the depression moved over the land on 18$^{th}$ the CLW values drastically reduced to 0-30 mg/cm$^2$ over the Bay, while they have increased considerably to 60-70 mg/cm$^2$ over the Arabian Sea. Some times IWV and CLW data are available over the area where SST and SSW are not available.

The maximum values of the MSMR derived parameters during the case of depression are as follows (range): SST 29-31°C, Wind speeds 14-18 mps with steep gradient at well marked low stage, Integrated water vapor 6-7.5 gm/cm$^2$ and CLW 80- 100 mg/cm$^2$.

Maximum wind speeds are observed 1 day before the formation of depression whereas other parameters show maximum values 2 days before the formation of depression i.e. during the low-pressure system is located.

Although, CLW values numerically do not match with the values of other satellites or NWP model analysis (Varma et al., 2002), they qualitatively give the region of maximum concentration and alignment of the values around the system 1-2 days before giving prior signatures of the system formation over the oceanic region.

## 4.3 Utilization of the data from other sources along with MSMR derived parameters

A case of monsoon depression that formed on 23 August 2000 at Bay of Bengal is studied using data from other sources along with MSMR derived parameters. Details are described below.

Surface pressure charts and INSAT visible imagery during the life cycle of this depression are shown in Figs. 1 and 2.

Geophysical parameters obtained from IRS-P4 were used to get daily composite pictures. Area covered by monsoon depression has given more importance to acknowledge the changes observed in development / dissipation stages. METEOSAT-5 derived CMVs and WVWVs were used for monitoring the dynamical changes at different stages of monsoon depression. For this purpose, CMVs and WVWVs were compared with conventional winds reported by radiosonde observations of Minicoy and Port Blair island stations over the Arabian Sea and the Bay of Bengal respectively. Linear regression equations between Meteosat-derived winds at 850 hPa and radiosonde winds at 850 hPa were developed. Similar procedure was applied for 200 hPa.

Statistical relationship between conventional winds and satellite-derived winds at 850 and 200 hPa (Mahajan, 2002) obtained for independent data set is as follows:

| Level (hPa) | n | Regression relation | r | SD |
|---|---|---|---|---|
| 850 | 105 | Yu(850) = 3.51 + 0.97 X1 | 0.79 | 4.11 |
| 850 | 105 | Yv(850) = - 1.76 + 0.95X2 | 0.74 | 3.59 |
| 200 | 160 | Yu(200) = -3.71 + 0.83 X3 | 0.53 | 8.51 |
| 200 | 160 | Yv(200) = 1.23 + 0.76 X4 | 0.48 | 7.62 |

where Yu(850) and Yv(850) are estimated winds for u and v components at 850 hPa. Similarly, Yu(200) and Yv(200) are estimated u and v components at 200 hPa. X1 and X2 are u and v components of CMVs at 850 hPa. X3 and X4 are u and v components of WVWVs at 200 hPa. r and SD denotes correlation coefficient and standard deviation respectively.

Above regression equations were used to modify the wind fields of METEOSAT-5 during the life period of the monsoon depression. National Centre for Environmental Prediction (NCEP) daily wind field analysis during life period of monsoon depression i.e. 19-24 August 2000 is used for performing objective analysis (OI) of the wind field at 850 and 200 hPa by including non-conventional winds obtained from METEOSAT-5. These satellite-derived winds at 850 and 200 hPa were modified by regression equations. These modified winds were used in objective analysis of the wind field for the complete life period of monsoon depression over the Bay of Bengal. Later, using these objectively analysed wind fields, vorticity fields at 850 and 200 hPa were computed. Special emphasis was given to monitor the vorticity fields in the region of monsoon depression activity. It was then compared with the cloudiness pattern and OLR field. MSMR derived daily geophysical parameters were compared with the intense convective activity in the area of depression.

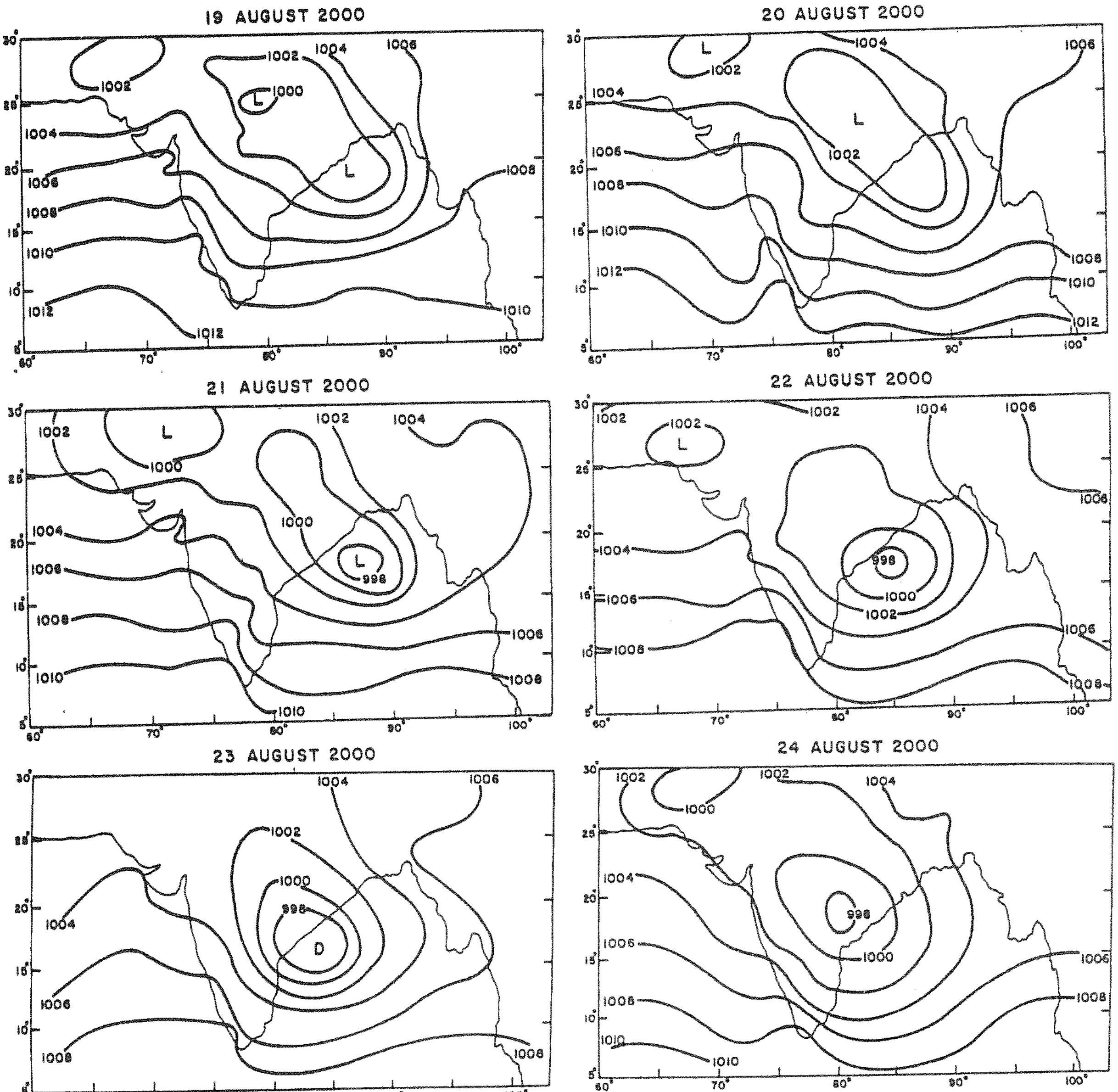



**Fig. 1 : Surface Pressure pattern 19-24 August 2000, depression**

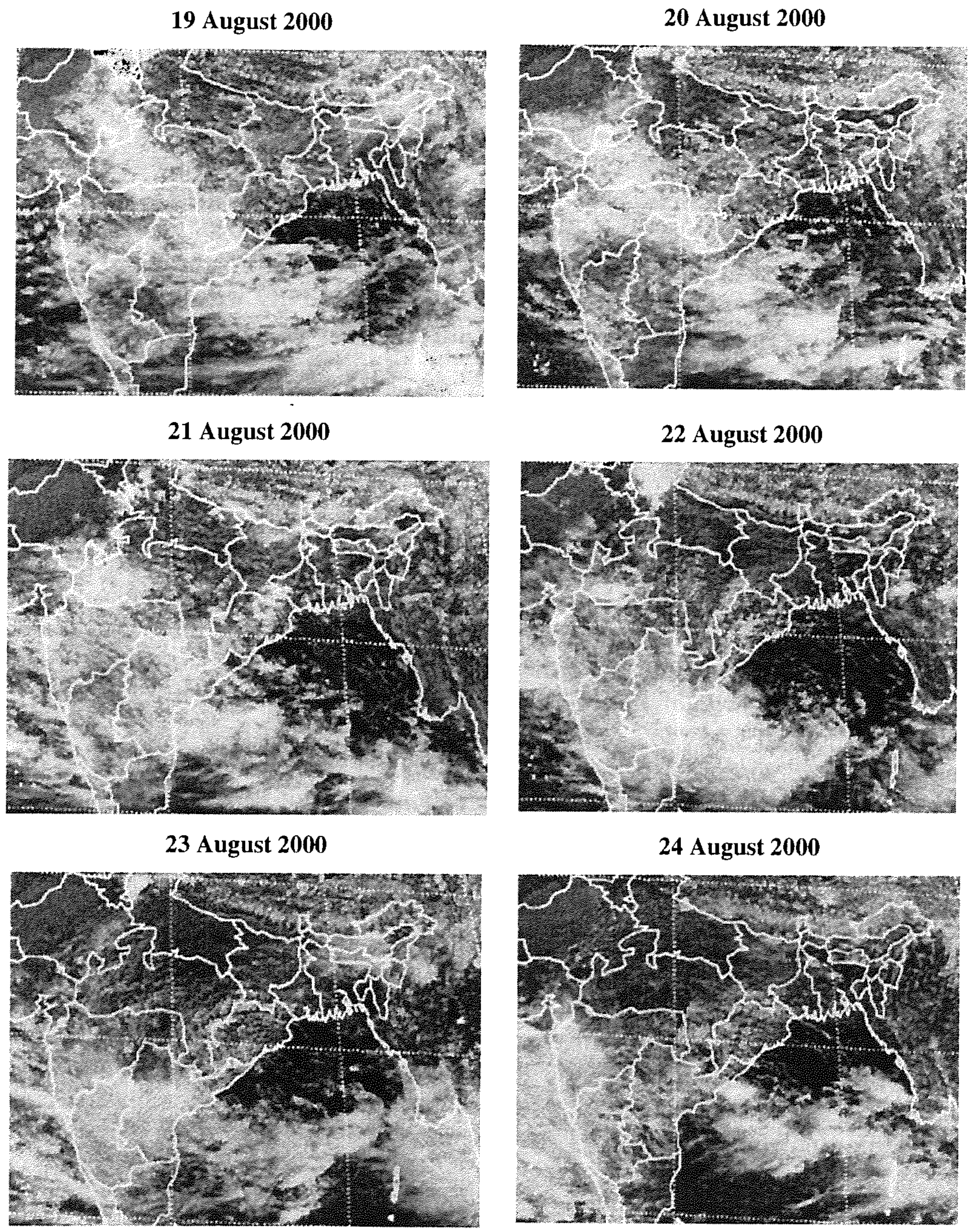



**Fig. 2 : INSAT imageries for 19-24 August 2000, depression**

The following are the major results of the study

i) Sea surface wind speed to the south of low pressure area increased gradually from 12 to 16 mps during 19 to 22 August and it was maximum just one day before the formation of depression (Fig. 3).

ii) Sea surface temperature 30° - 32° C was maintained during the life period of monsoon depression (Fig. 4).

iii) Maximum integrated water vapour of the order of 6-8 gm/cm$^2$ was observed in the region of monsoon depression during 21 to 24 August (Fig. 5).

iv) Maximum value of cloud liquid water content (70-80 mg/cm$^2$) was noticed in major convective region of monsoon depression on 22 August(Fig. 6).

v) Based on visible and infrared imageries of INSAT, METEOSAT-5 and OLR (INSAT) data at matching time (06 UTC) with descending mode of IRS-P4, it was found that the existence of intense convective activity with low OLR values (120 W/m$^2$) was in the southwest sector of the monsoon depression (Fig. 7).

vi) Maximum value of convergence (-2.5 x 10$^{-5}$/s) at 850 hPa (Fig.8) and maximum value of divergence (2.5 x 10$^{-5}$/s) at 200 hPa (Fig.9) were observed in the same region of low-pressure area on 22 August, just one day before the formation of monsoon depression.

Sea surface temperature through IRS-P4 was found varying from 30°-32°C throughout the life period of monsoon depression and it was suitable temperature for the development of monsoon depression. Sea surface wind speed started intensifying to the south of low pressure area giving indication that cyclonic vorticity must have increased and that was good indication for the development of low into depression. Considering this situation vorticity fields at 850 hPa was computed for whole life period of monsoon depression. This vorticity field was computed with input of CMVs in objective analysis of the wind field and it was noticed that the value of cyclonic vorticity was maximum just one day before the formation of depression. Similarly, vorticity field at 200 hPa was computed with input of WVWVs in objective analysis of wind field and noticed similar characteristics features such as the value of anticyclonic vorticity was maximum, that too one day before the formation of depression. Thus, cyclonic vorticity and anticyclonic vorticity were maximum and matching at the location of formation of depression giving a signal for the development of depression. Accordingly, the depression was formed on 23 August 2000. Low values of OLR (120 W/m$^2$) were noticed in the major convective region of the depression and it was mainly concentrated in the southwest sector of the depression. It is consistent with the results of the earlier researchers. On the same background the maximum values of integrated water vapour and cloud liquid water content were maximum in the region of major convective activity and it is appropriate as per the structural features of the depression. Cloud liquid water content values are not of expected accuracy as compared to other remote sensing satellites and NWP model estimates (Varma et al, 2002). It is observed that cloud liquid water content values increase systematically from the day of formation of a low and are maximum just before the formation of depression.

Depiction of proper variations in geophysical parameters through IRS-P4 satellite and analysis of vorticity, convergence and divergence based on modified CMVs and WVWVs in objective analysis of the wind field at 850 and 200 hPa gave a signal of development of monsoon depression over the Bay of Bengal during 19-24 August 2000.

SSW(m/s) Grid1-(150X150) Both Passes

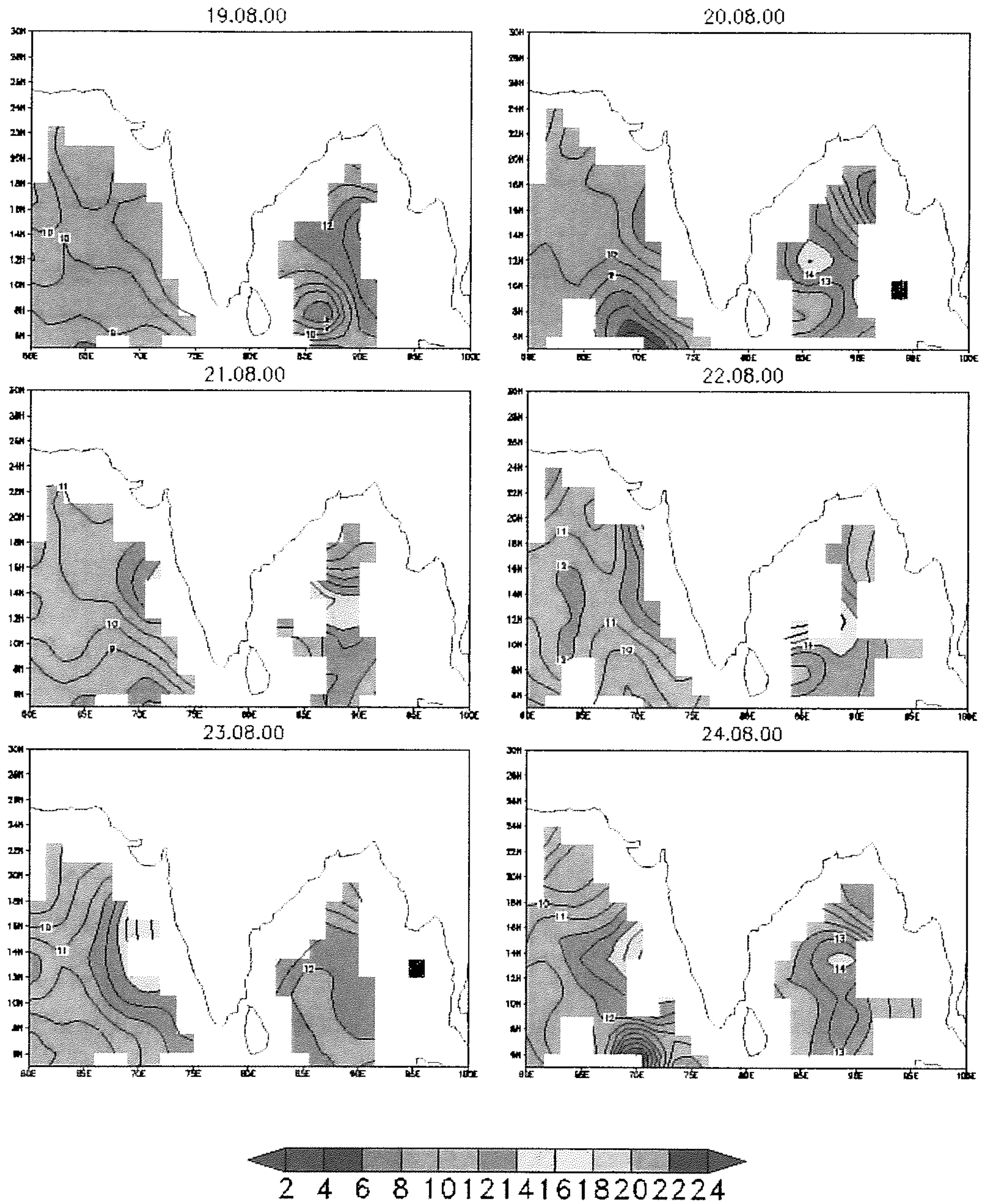



**Fig. 3 : SSW values for 19-24 August 2000, depression**

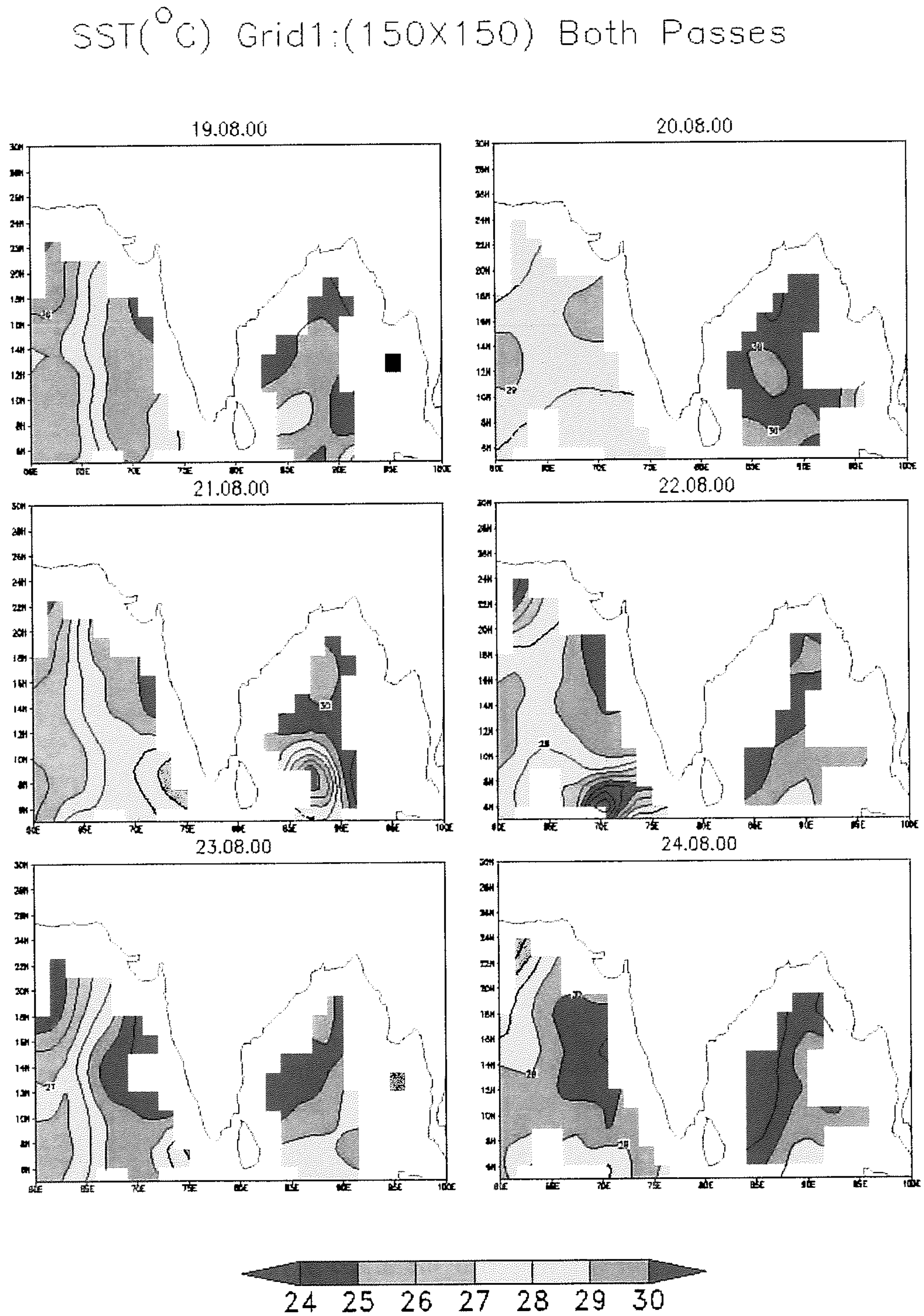



**Fig. 4 : SST values for 19-24 August 2000, depression**

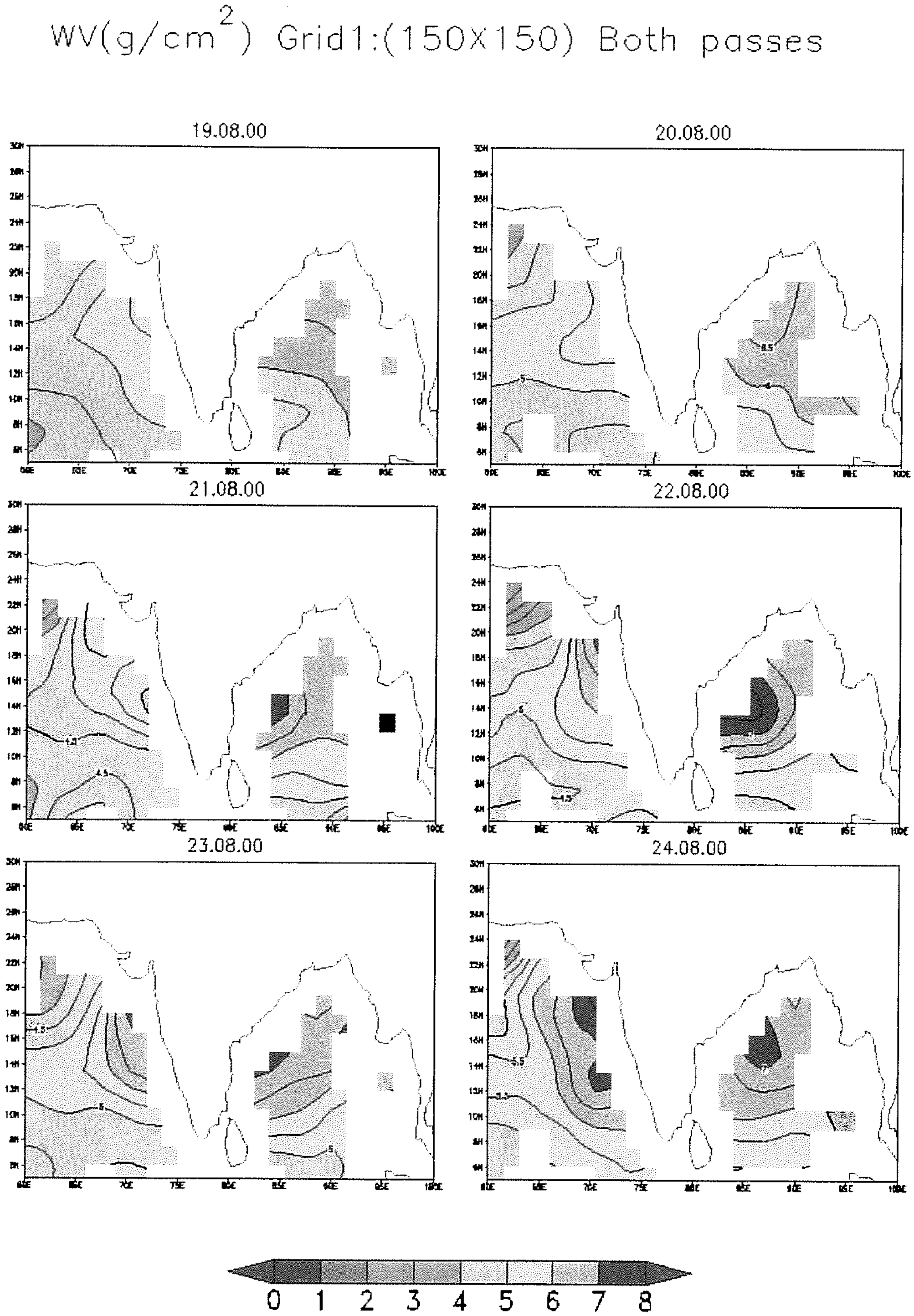



**Fig. 5 : IWV values for 19-24 August 2000, depression**

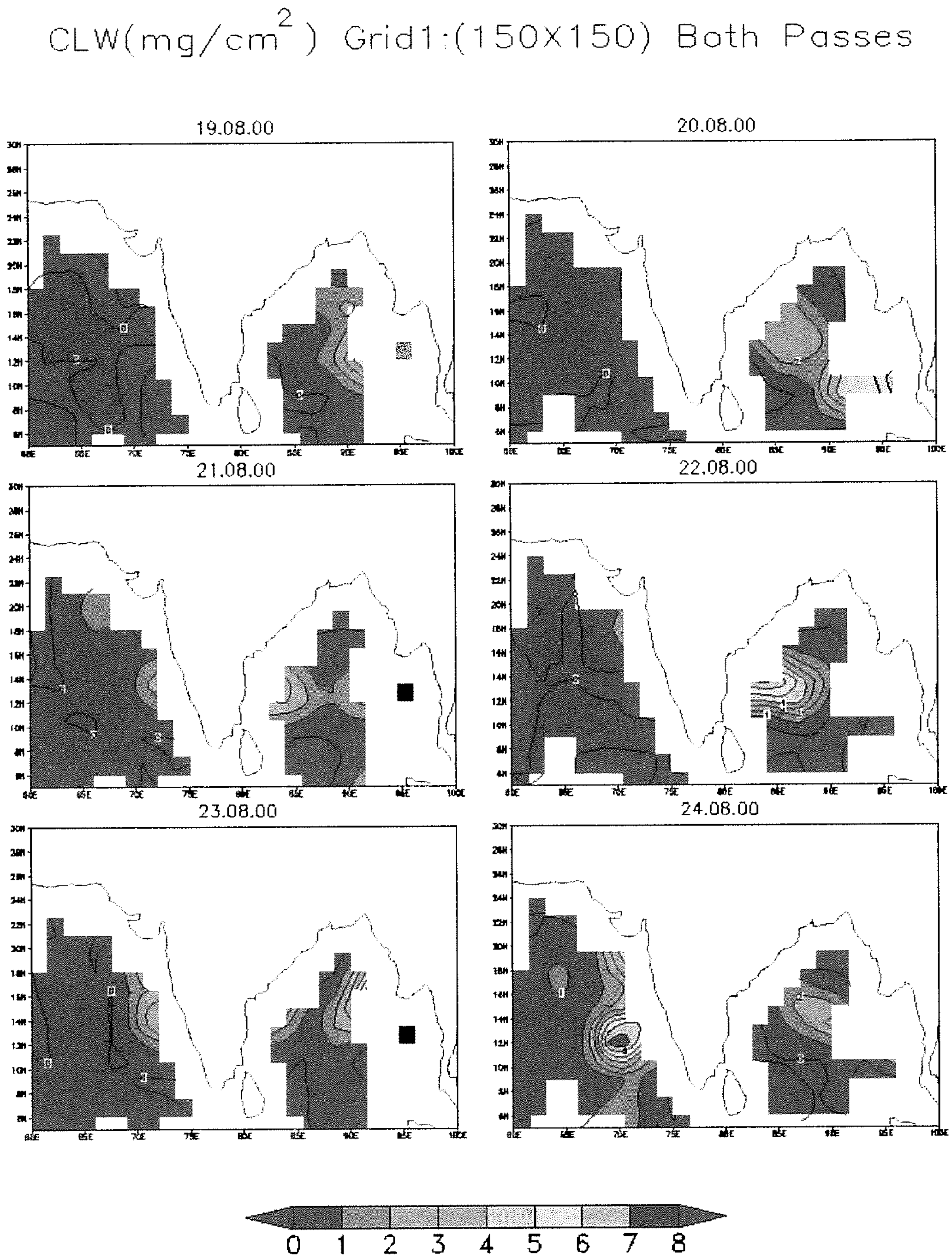



**Fig. 6 : CLW values for 19-24 August 2000, depression**

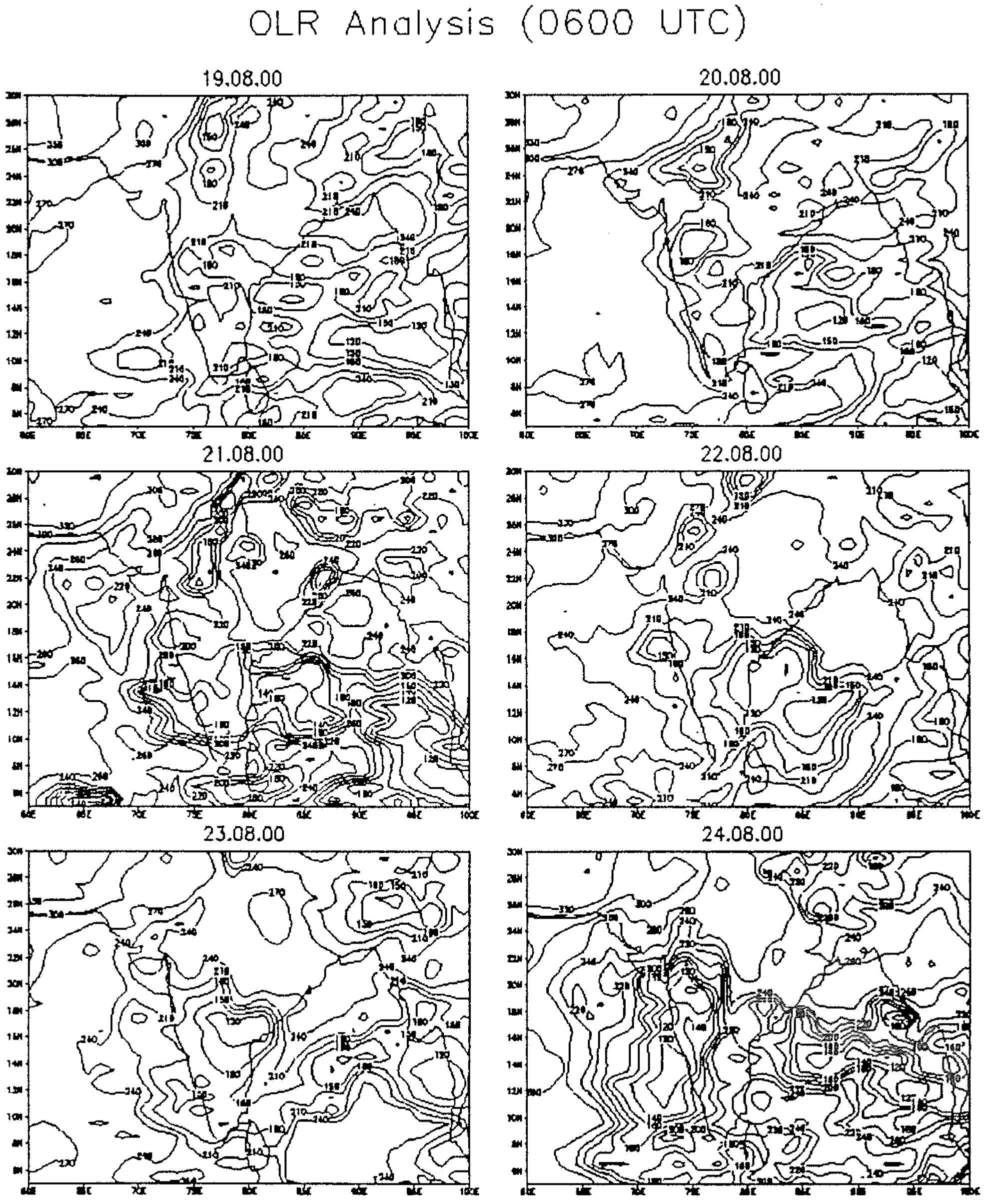



**Fig. 7 : OLR analyses for 19 –24 August 2000, depression**

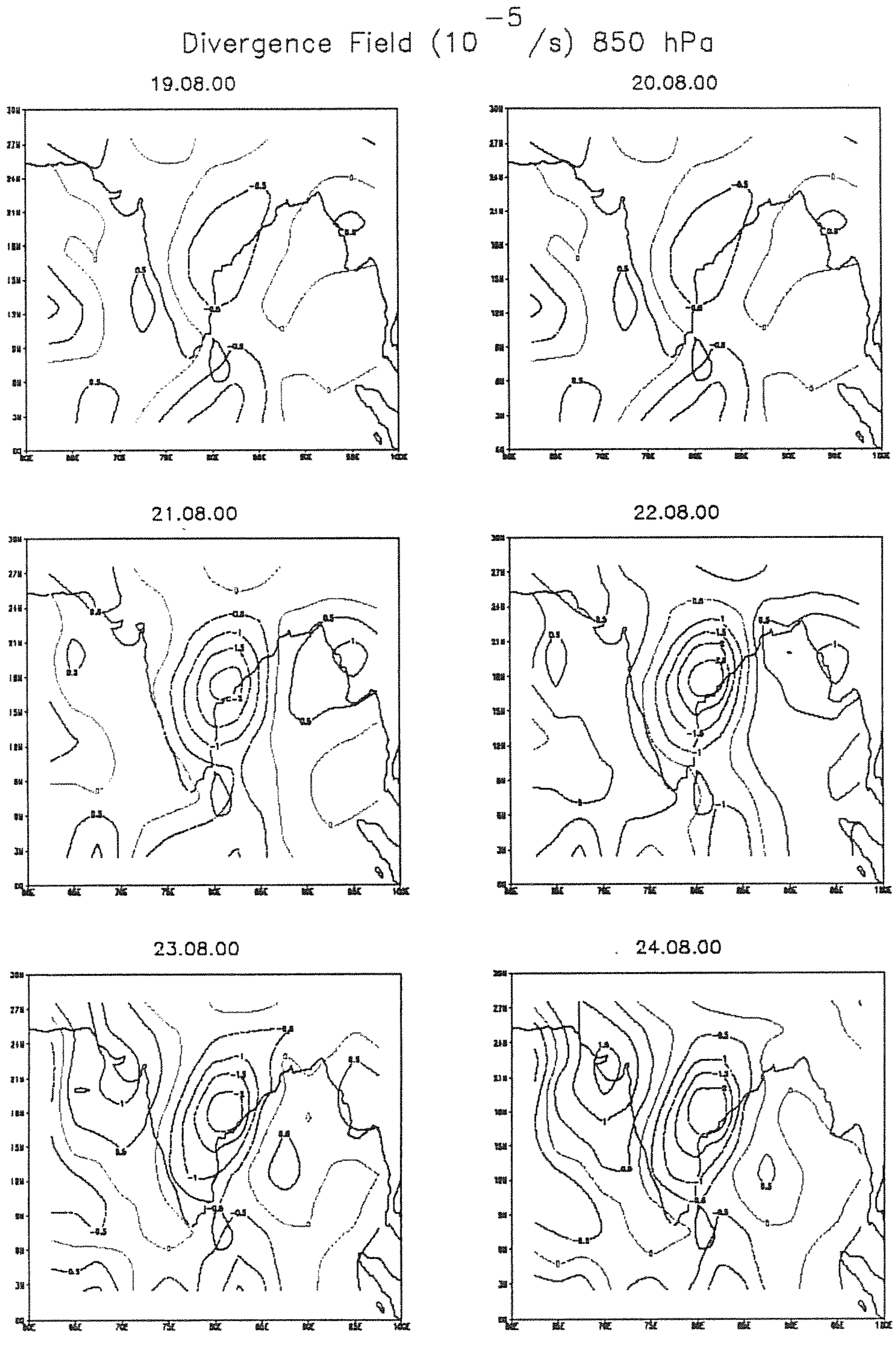



**Fig.8 : Divergence analyses at 850 hPa for 19-24 August 2000, depression**

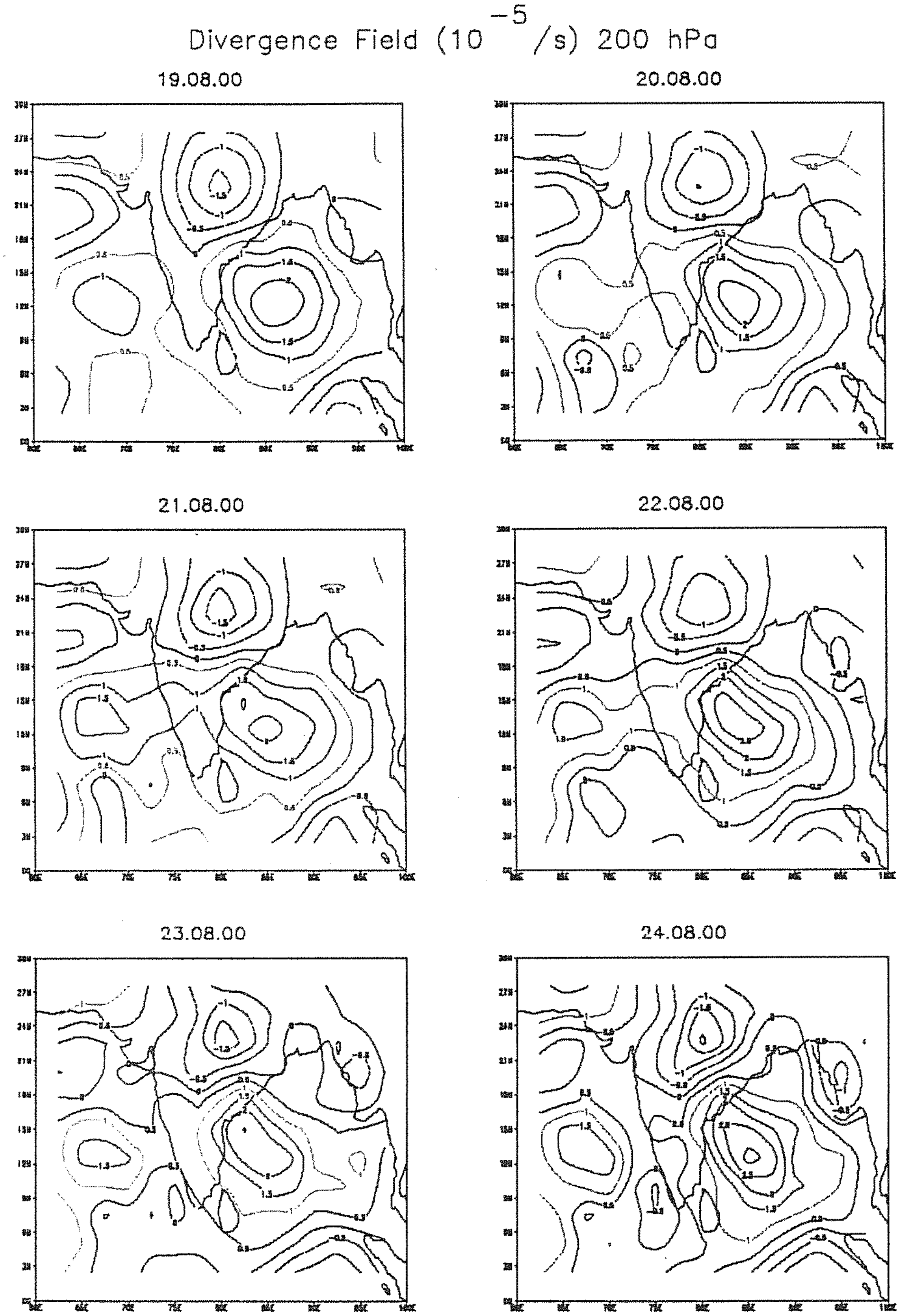



**Fig.9 : Divergence analyses at 200 hPa for 19-24 August 2000, depression**

## 4.4 General Observations about MSMR parameters in different stages of the monsoon depressions

Based on the study carried out of four depressions studied following conclusions are inferred so far as MSMR derived parameters are concerned.

i) SSW: During the stage of WML, steep gradient of wind speeds about 8-14 mps is noticed on NE, SE or southern sector.

ii) SST: The SST value around 29°C is found over the large area of Bay of Bengal before formation of depression.

iii) IWV: values are > 7.0 gm/cm$^2$ one or two days before the formation of the depression. At this location formation of depression is expected.
In some cases (IWV and CLW), these data are available even if SST or SSW data are not available over a particular area.

iv) CLW: WML or the depression is formed at the locations where there is steep gradient of CLW with maximum value of 50-70 mg/cm$^2$. Some times the isolines of CLW are aligned in a circular way with maximum value at the center. Numerically these values may not be correct, but the pattern may be appropriate.

## 4.5 Comparison of MSMR data with DMSP- SSM/I satellite data

Daily variation of DMSP-SSM/I derived geophysical parameters for a case of monsoon depression formed over the Bay of Bengal during 22-27 July 1992 was studied, Mahajan (2003). Following observations were noticed during the life cycle of the depression.

SSW : Initial winds of 6-10 ms$^{-1}$ increased to 12-15 ms$^{-1}$ to the south of the low pressure area.

IWV : Highest values of IWV were 6.0 to 7.0 gm/cm$^2$.

CLW : Highest values of CLW were 180-220 mg/cm$^2$.

Above features are similar with respect to the MSMR derived geophysical parameters during the cases of monsoon depressions studied in the present report.

The MSMR derived parameters will provide necessary indications or signatures 1-2 days before formation of major synoptic system over the oceanic regions and its probable location. This information and the data from other satellites and the conventional observations are helpful for forecasting the formation and location of such weather systems.

# Section 5

## Tropical Cyclones with respect to MSMR data

## 5.1 Introduction

### Tropical Cyclones

The tropical cyclones (TCs) are the most fascinating weather events of the tropics. They have got significant impact on the weather and climate of the tropical countries. These cyclones cause considerable loss of life and property in the region with their ferocious wind and heavy rainfall. The formation, intensification and movement of these devastative events (TCs) particularly over the Indian Ocean (Bay of Bengal and Arabian Sea) have been studied by various researchers in detail viz. Neumann et al. (1981), Rajeevan (1989), Mandal G. S. (1991), Kelkar (1997), Dube et al. (1997), Singh et al. (2001). A global view of TCs is provided in an international workshop on TCs ( Elsberry et al., 1985).

TCs form from an initial convective disturbances known as cloud clusters or mesoscale convective complexes. As they evolve from a loosely organized state into mature, intense storms they pass through several characteristic stages. TC is the intense low pressure systems having associated wind speed more than 33 knots. It is a warm core system. The pressure departure from the normal at the center of the low pressure system is of the order of 7 hPa. After its landfall, there occurs a rise of sea level and rush of sea water inland. This storm surge is the cause of devastating damage to coastal property and also loss of life along the coast. The horizontal diameter of TC over Indian seas in the Pre-monsoon months is about 800 kms whereas the diameter in the Post-monsoon season is about 1200 to 1400 kms. The maximum pressure gradient associated with TC is of the order of 0.5 hPa/km. The vertical extent of the system generally is up to 200 hPa (approx. 12 km). Average life span of TC is 5 to 6 days. Value of Sea Surface Temperatures (SSTs) more than 27°C is one of the pre-requisites for the formation of TC.

During pre-monsoon and post monsoon seasons most of the TCs form over the Bay of Bengal and to a certain extent over Arabian sea. As per IMD report (1979) in the month of May most of the Bay storms originate between 10°N and 15°N. They move initially in a northwesterly or northerly direction and then recurve towards the northeast. The storms during this month make landfall either at the eastern coast of India, the coastal areas of Bangla Desh or the Arakan coast of Mynmar. The storms in the Arabian Sea move northwest, towards the coast of Arabia. A few of them move in a northerly direction towards the Maharashtra-Gujrat coast. In October, the Bay storms form over the area between 8°N and 14°N. Initially they move in a northwesterly direction and then recurve towards northeast. The storms in this month make landfall at Tamil Nadu and Andhra coasts of India and the Bangla Desh coast. The storms, which cross Indian coast south of 15° N, enter the Arabian Sea and reintensify. In the month of October in the Arabian Sea, the direction of movement of the storms is generally westerly.

The advent of meteorological satellites has contributed greatly to tropical cyclone detection, analysis and forecasting throughout the globes. The human causalities in India have decreased considerably during the recent years. The Dvorak (1984) technique for estimating intensity of tropical cyclones based on satellite imagery is used globally. In many cases, the satellite is the only available method for estimating intensity.

The most basic problem for the tropical cyclone forecaster and researcher is to make optimum use of a variety of data sources. The forecaster does not have sufficient observations to define accurately the structure of the tropical cyclone and adjacent synoptic features. New observational tools and strategies are being developed that have a potential for improving analyses of tropical cyclones. In view of the above points, tropical cyclones have been considered for the study with respect to MSMR data in the following sub-sections.

## 5.2 Cases of the cyclones studied

Using IRS-P4 geophysical parameters viz. SST, SSW, IWV & CLW, eight cases of the cyclonic storms during 1999-2001 (section 3.3) are studied. The area of the storm formation, storm track, day to day variations of MSMR parameters are given Appendix (e-l).

Classifications of the cyclones, according to region of genesis, year, month and severity are given below.

**The storms studied are as below**

Out of eight cyclonic storms, first seven are Bay of Bengal cyclones and last one i.e. during 21-28 May 2001 is Arabian Sea cyclone.

**Types of cyclones considered**

Cyclonic storms: 3
Very severe cyclonic storms: 4
Super cyclone: 1

**Year wise break-up is as below.**

1999: 2
2000: 5
2001: 1

**Month-wise classification is as follows**

March: 1
May: 1
Oct: 4
Nov: 1
Dec: 1

It is noticed from above that, for the period under study, October has maximum cyclonic storms i.e. 4, while March, May, November and December have one each.

During the intense stages of TCs viz. severe, very severe cyclonic storms and super cyclone cases, these winds are not estimated by MSMR because maximum wind speed derived by the sensor is 24 mps. Similarly, during rainy conditions, the geophysical parameters are not retrieved because brightness temperature values are erroneous due to contaminated signals. Therefore, the observations are not available over the main system, but they are available in the vicinity of the system.

## I Very Severe Cyclonic Storm formed during 21-28 May 2001 over Arabian Sea

**Life History:**

On 21 May 2001, a low was observed in the morning on southern part of the Arabian sea and developed to a depression in the evening. Next day, it concentrated into deep depression and further intensified into a cyclonic storm centred near 14.0°N/71.0°E about 350 kms westsouthwest of Panjim. On 23 morning, it reached severe cyclonic storm and very severe cyclonic storm stages at 15°N/71°E about 350 kms southwest of Ratnagiri and moved in northwesterly direction. It remained stationary at 17°N/68°E on $25^{th}$ On $26^{th}$ it weakened to a severe cyclonic storm and then to a cyclonic storm on $28^{th}$ at 003 UTC. Same day at 21 hrs UTC it further weakened to depression and then well marked low over north eastern Arabian sea.

The synoptic features with the center of the system are depicted in surface pressure charts (Fig.10) and the track of the cyclone is shown in Appendix (l). The INSAT imagery also depicts the synoptic situation. Dense cloud patches were seen over the area of the TC genesis. They were seen to move in the west northwestward direction, Fig. 11.

MSMR derived parameters associated with different stages of this cyclone are described below.

**SSW**: Fig. 12 shows SSW from 21 to 28 May 2001 on different stages. On $21^{st}$ May when the low was noticed, the SSW were about 12-14 mps on the southern and western side whereas on northern and northwestern side, they were about 14-18 mps with steep gradient. Next day, during severe cyclonic storm stage, winds on southern side strengthened to 14-16 mps with increase in area. The gradient and speed on northwestern side was reduced. On 23, 24 and 25 i.e. during very severe cyclonic storm stage, strong winds further increased and the

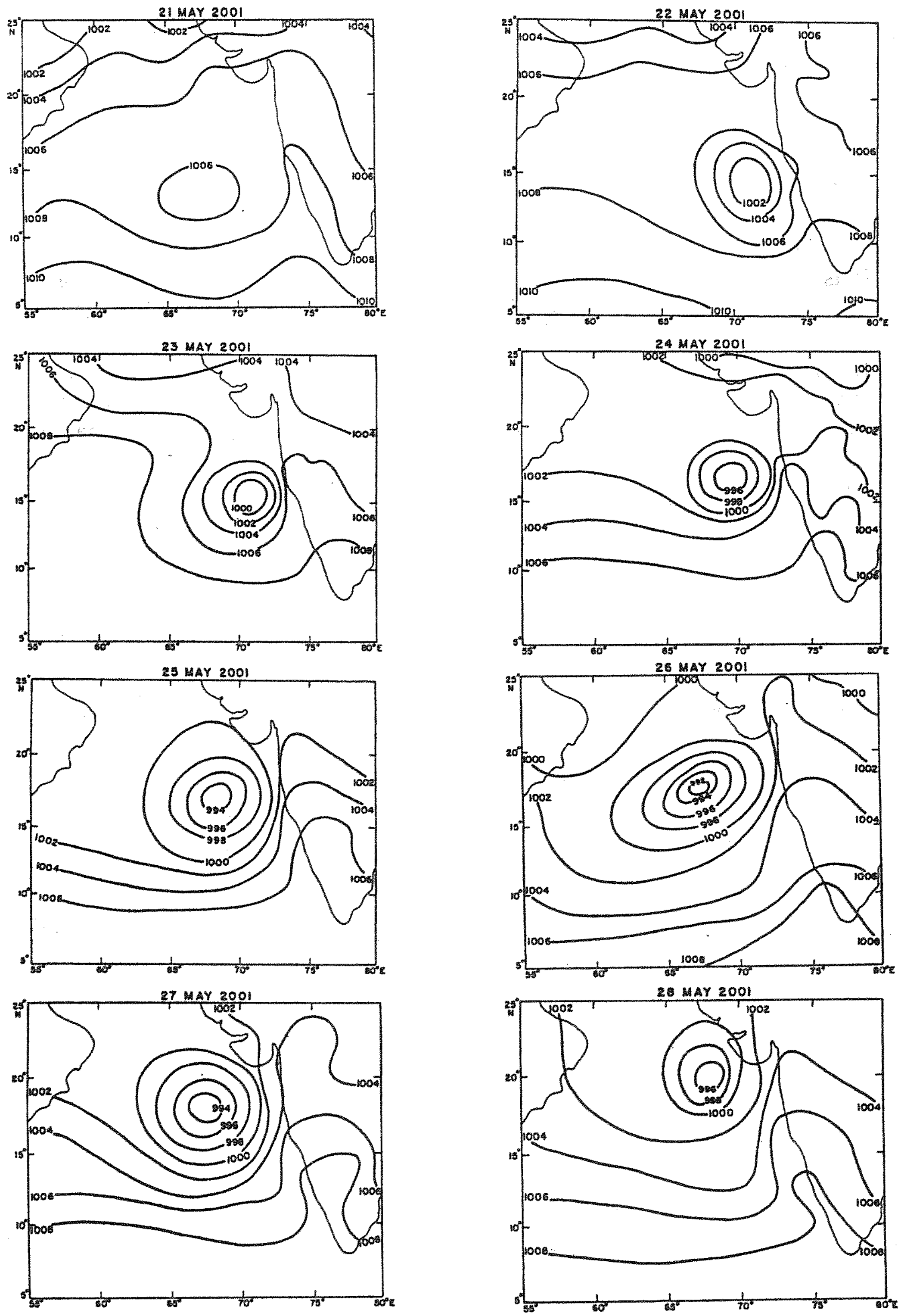



**Fig. 10 : Surface Pressure pattern for 21-28 May 2001, tropical cyclone**

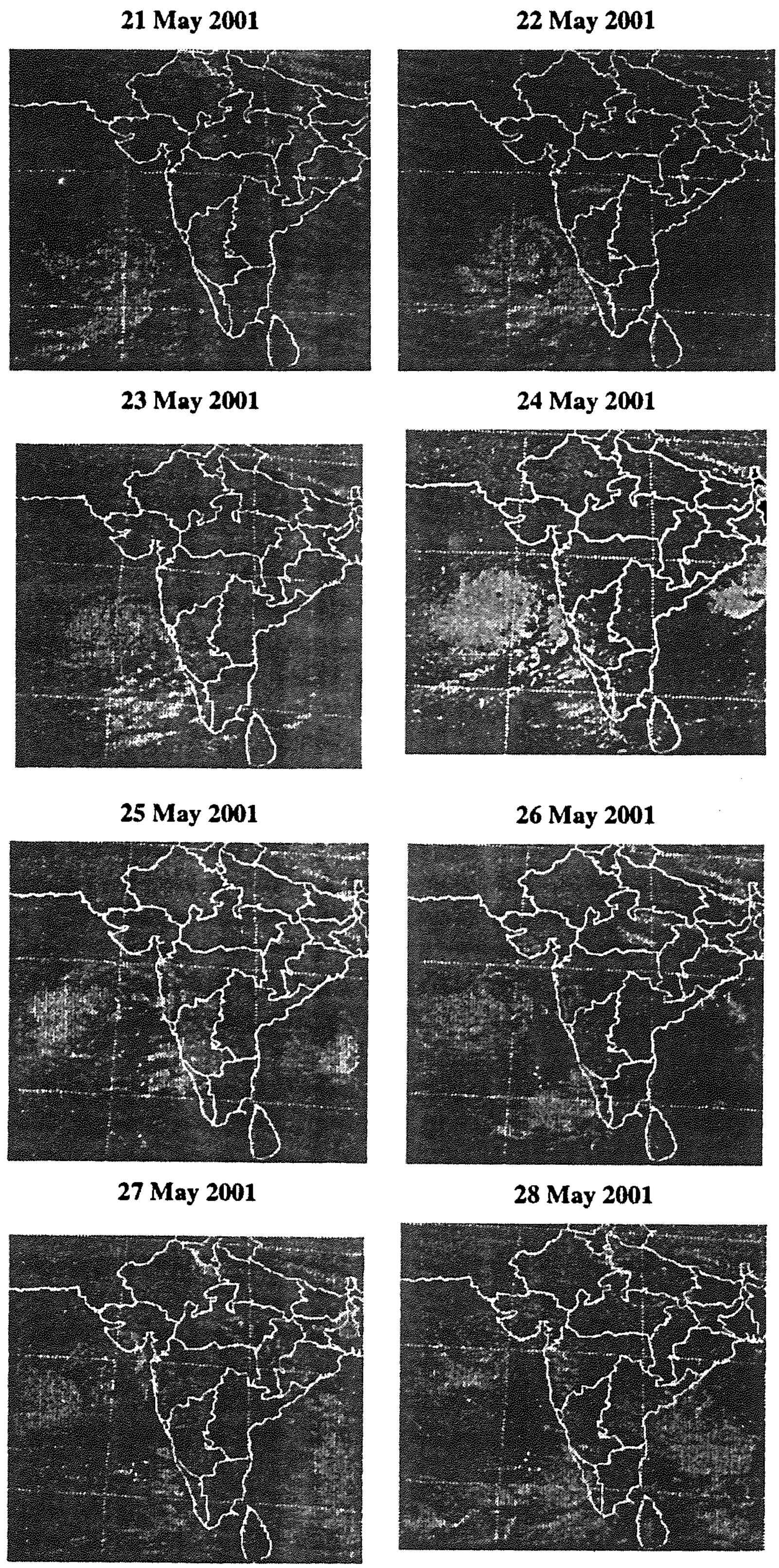



**Fig. 11 : INSAT imageries for 21-28 May 2001, tropical cyclone**

reduction of wind speed over northern sector was noticed to about 8-10 mps. When the system started weakening to severe cyclonic storm and cyclonic storm stages, winds surrounding the system gradually weakened from 15 to 10-12 mps.

**SST**: Fig. 13 gives SST from 21 to 28 May 2001. It is noticed that on 21$^{st}$ and 22$^{nd}$ May, the SST over Arabian Sea were around 29-31°C in the vicinity of the system. During the weakening stage i.e. on 27$^{th}$ and 28$^{th}$ the area of SST above 30°C is reduced. The gradient on northwestern side increased showing SST about 26-27°C.

**IWV**: Fig.14 shows IWV values during different stages of the cyclone. In the vicinity of the system IWV is found to vary from 5 to 6.5 gm/cm$^2$ at the time of formation of a low on 21 May 2001. Next day, i.e. during severe cyclonic storm stage IWV reached its maximum value of 7.5 gm/cm$^2$. During very severe cyclonic storm stage it remained so and then reduced during weakening stage. On 26$^{th}$ i.e. at severe cyclonic storm stage the area of IWV more than 7 gm/cm$^2$ increased and then got drastically reduced to 6 to 6.5 gm/cm$^2$. Maximum value is seen near the central portion of the system.

**CLW**: Fig. 15 shows CLW values. At the low stage maximum CLW varies from 10 to 50 mg/cm$^2$ in the vicinity of the low. The circular pattern remained so till severe cyclonic storm, very severe cyclonic storm stage with maximum value more than 70-80 mg/cm$^2$ on 23$^{rd}$. Isolines are aligned according to the cyclonic storm in circular way with values increasing towards southwest of the storm center.

IRS-P4 MSMR derived geophysical parameters during the development of different stages of tropical cyclone (21-28 May 2001) have given the indication that it is likely to intensify into super cyclonic storm. However, instead of developing into super cyclonic storm it started dissipating from very severe cyclonic storm to well marked low from 25 May – 29 May 2001. These unique features of tropical cyclone were thoroughly examined by computing vorticity fields at 850 and 200 hPa using METEOSAT-5 derived low level winds (CMVs) and upper level water vapour winds (WVWVs) in the objective analysis (OI) of the wind field.

On 21$^{st}$ May 2001, when low was noticed the OLR values over the system were 120 w/m$^2$ (Fig. 16). It remained so on 22$^{nd}$ during severe cyclonic storm stage. Next four days i.e. from 23 to 27 May, OLR values reduced to 90 w/m$^2$ during very severe cyclonic storm stage. When the cyclone started weakening i.e. on 28$^{th}$ OLR values again rose to 120 w/m$^2$. As seen from the GPD products, the maximum values of IWV and CLW match with minimum OLR. Minimum OLR values are towards south of the system during weakening stage.

Cyclonic vorticity at 850 hPa (Fig. 17) in the region of tropical cyclone started increasing from 22 May onwards and it was gradually more on the following days upto 28 May 2001. It was developed from 3 to 5 x $10^{-5}$ /s during 23-28 May 2001. This was a positive sign for the development of tropical cyclone possibly into its peak intensity. But it did not develop into a severe cyclonic storm.

In the similar manner, vorticity fields at 200 hPa (Fig. 18) were examined to know the further progress of development of tropical cyclone. Area of small anticyclonic vorticity was

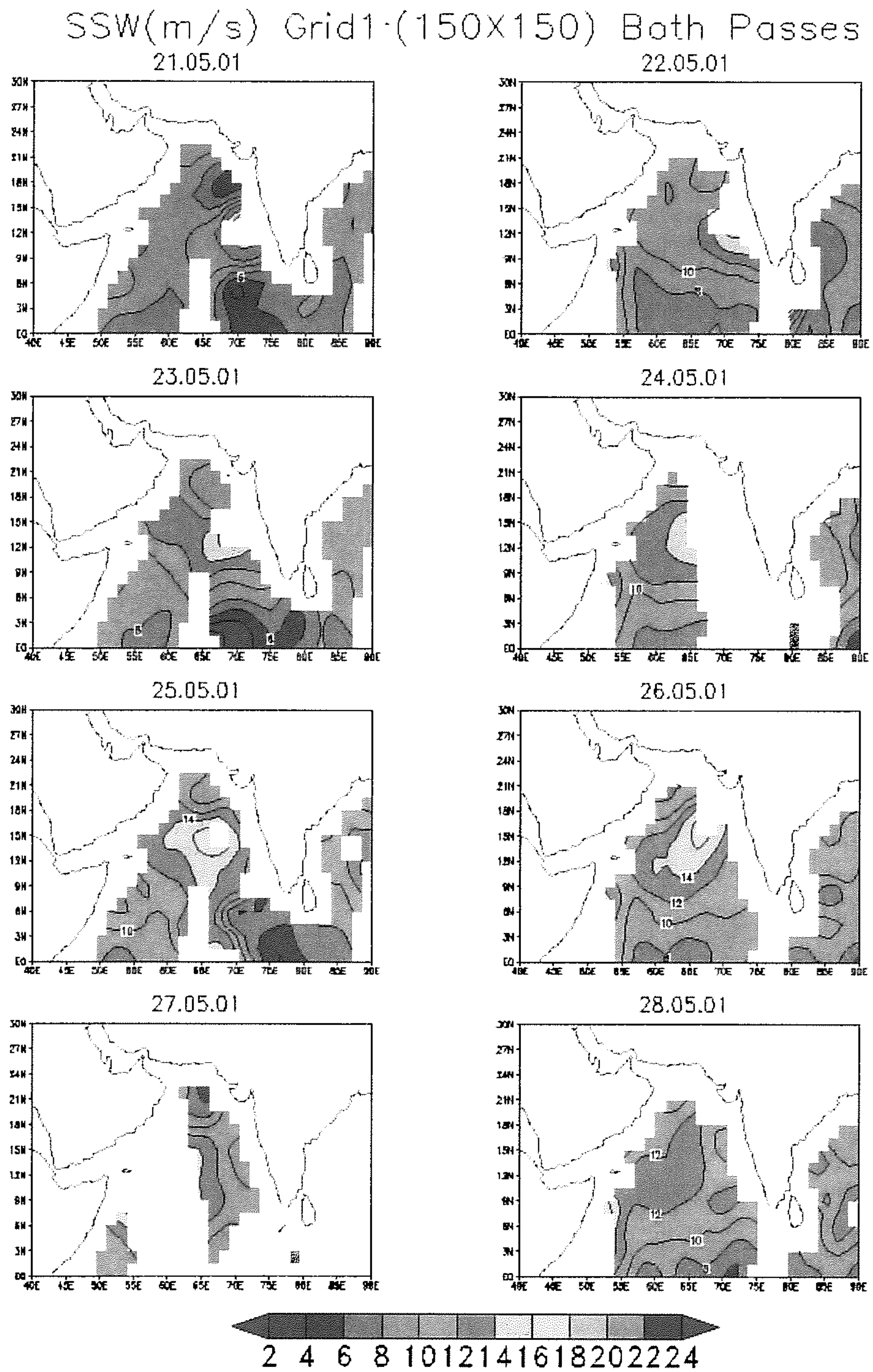



**Fig. 12 : SSW values for 21-28 May 2001, tropical cyclone**

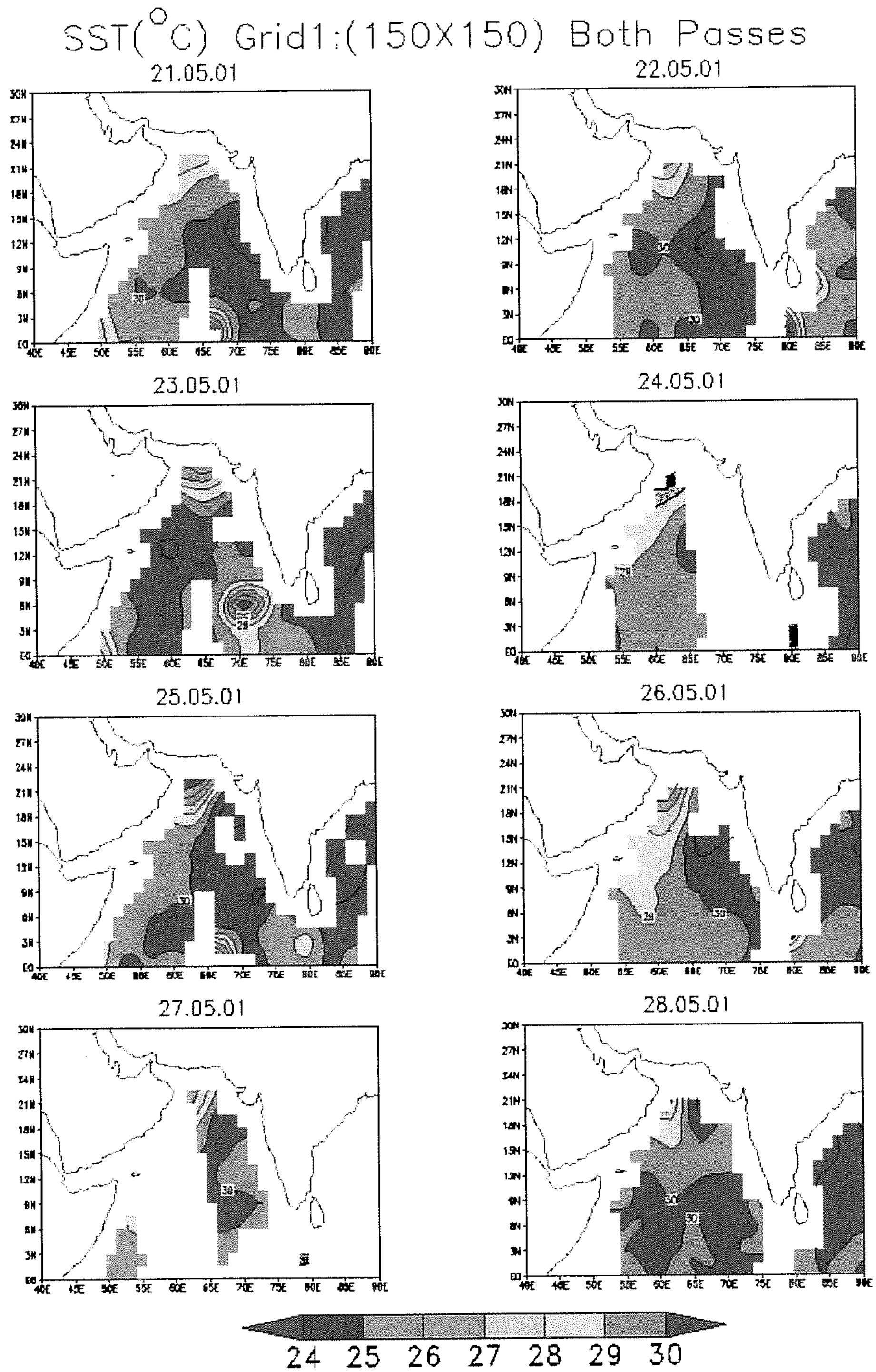



**Fig. 13 : SST values for 21-28 May 2001, tropical cyclone**

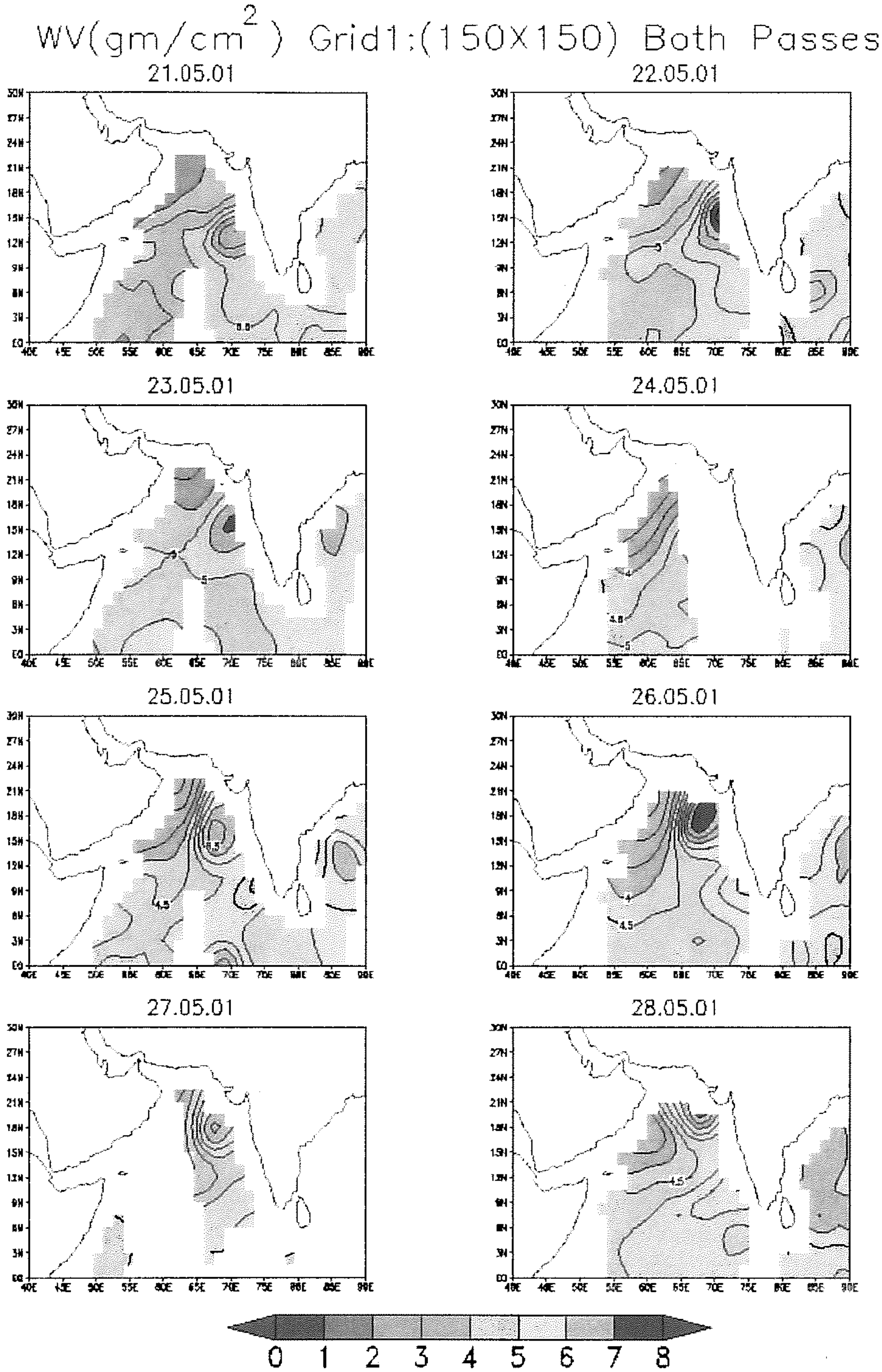



**Fig. 14 : IWV values for 21-28 May 2001, tropical cyclone**

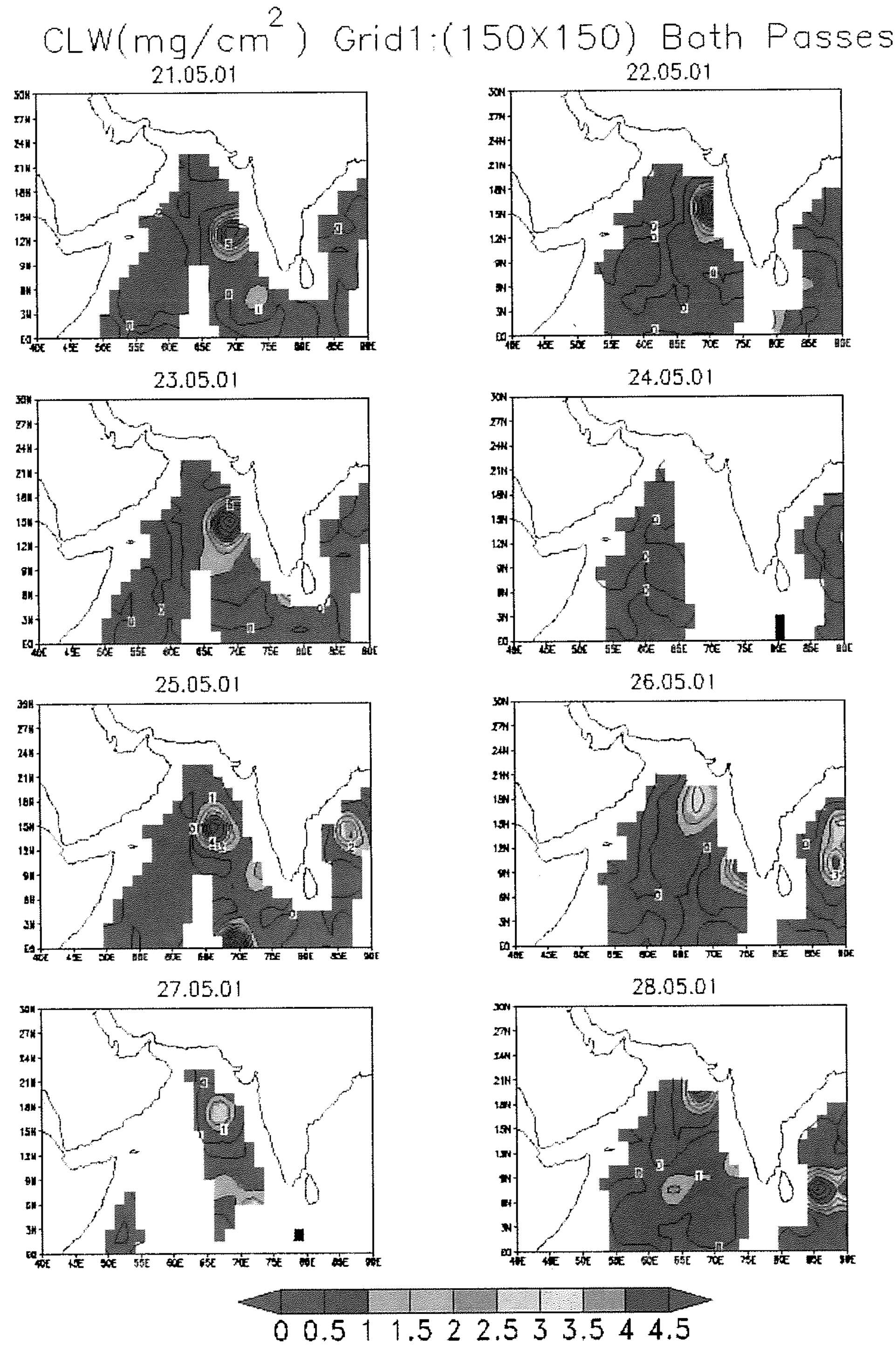



**Fig. 15 : CLW values for 21-28 May 2001, tropical cyclone**

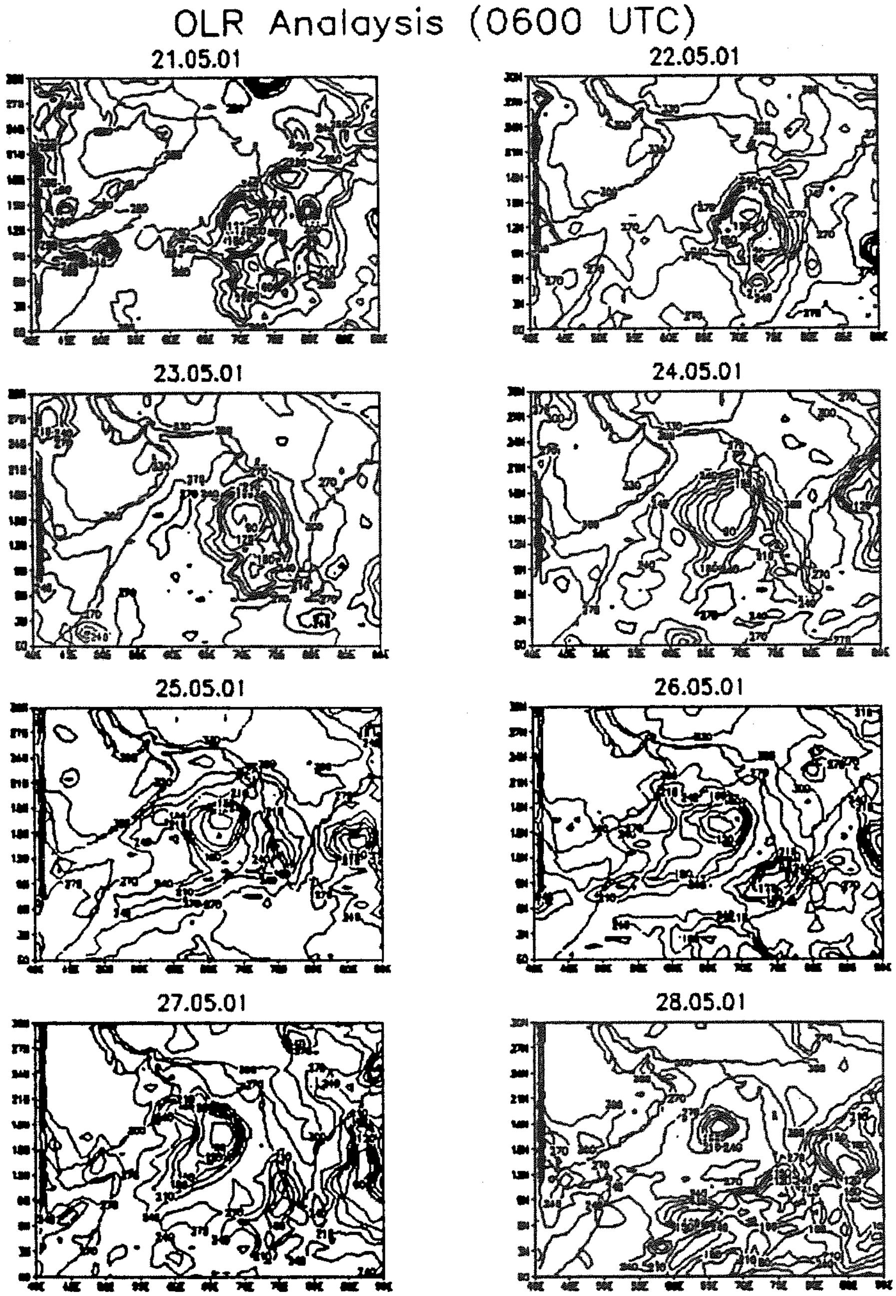



**Fig. 16 : OLR analyses for 21-28 May 2001, tropical cyclone**

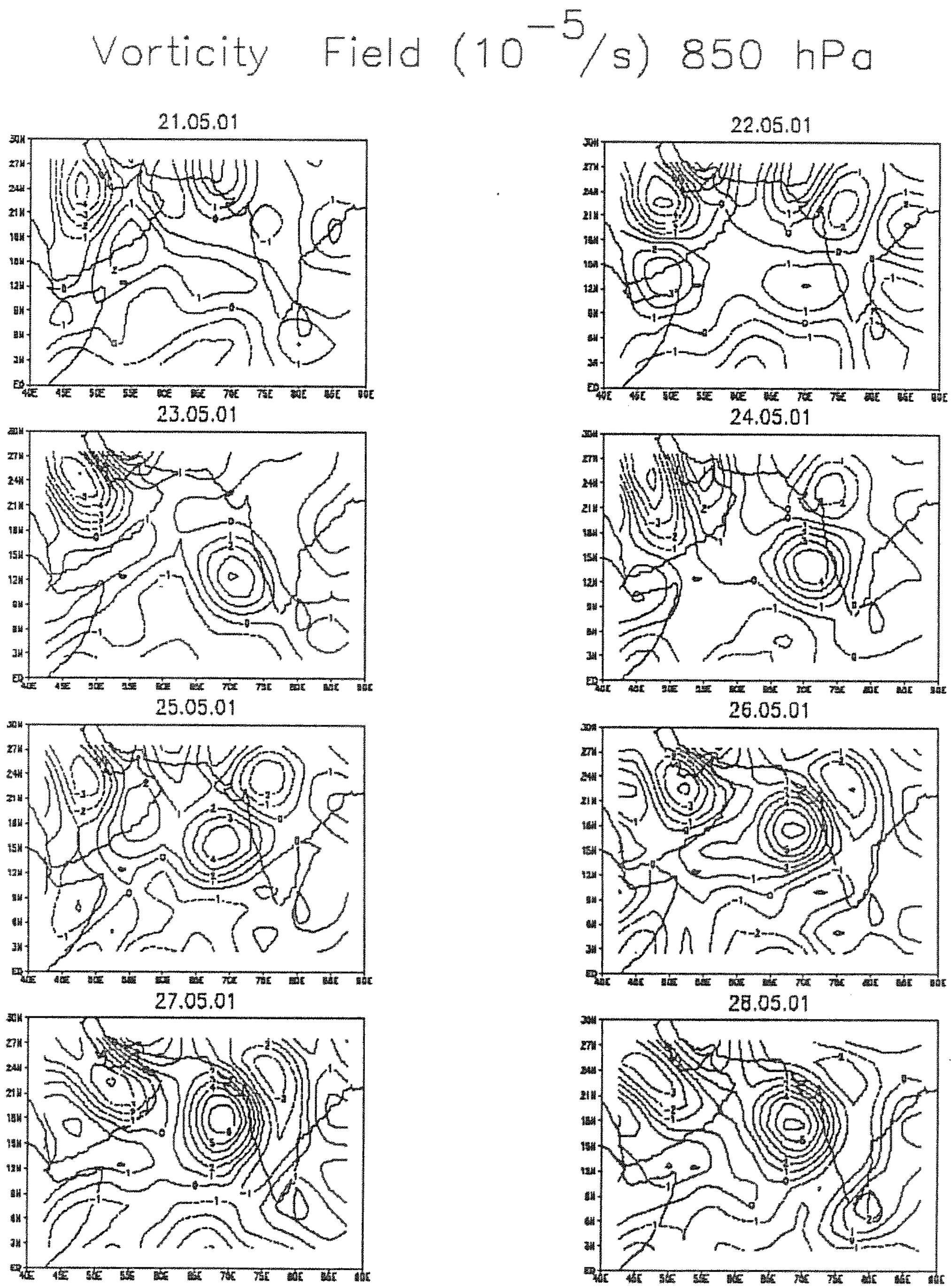



**Fig. 17 : Vorticity analyses at 850 hPa level for 21-28 May 2001, tropical cyclone**

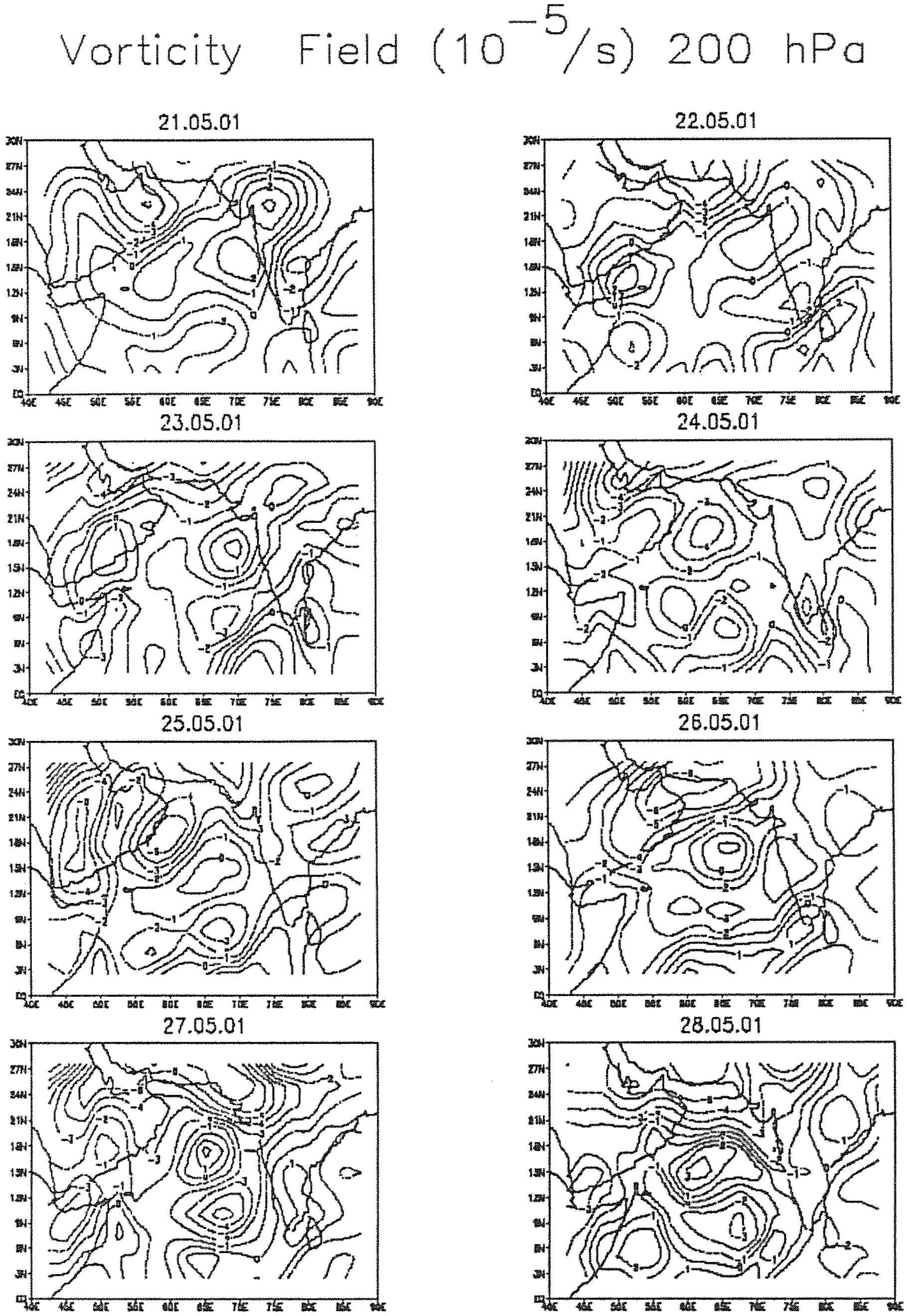



**Fig. 18 : Vorticity analyses at 200 hPa level for 21-28 May 2001, tropical cyclone**

further developed to more anticyclonic vorticity field ($-4x10^5s^{-1}$) in the region of tropical cyclone during 21-24 May 2001. This has shown the proper development of tropical cyclone with eye features, central dense overcast region and banding features and these were well marked on 24$^{th}$ May. Thereafter, non-cyclonic/anticyclonic area was developed in the region close to the center of tropical cyclone on 25$^{th}$ and 26$^{th}$ May. Further cyclonic vorticity was developed over larger area on 27$^{th}$ and 28$^{th}$ May giving signal of dissipation of tropical cyclone. It dissipated into well-marked low-pressure area on 29$^{th}$ May 2001 and hit the Gujarat Coast.

## II Super Cyclone formed during 24-31 October 1999 over Bay of Bengal

The case of super cyclone, which formed during 24-31 October 1999 over Bay of Bengal is studied. It was the most intense cyclone in last 114 years for the state of Orissa. It produced fierce and very strong winds along with huge storm surge and catastrophic floods causing severe damage in districts of Orissa and West Bengal.

**Life History:**

A well-marked low-pressure area lay over Gulf of Siam and neighborhood on 24 October 1999. Associated cyclonic circulation extended upto lower tropospheric levels. Moving westwards, it concentrated into a depression over North Andaman Sea and neighborhood at 1200 UTC of 25 and lay near 12.5°N/ 98.0°E. It further moved in a west northwesterly direction and intensified into a cyclonic storm and lay centred at 0300 UTC of 26 near 13.5°N/95.5°E, about 350 km northeast of Port Blair, and at 1200 UTC of 26 near 14.5°N/94.0°E. It further intensified into a severe cyclonic storm at 0300 UTC of 27 and lay centred near 16.0°N/92.0°E, about 750 kms southeast of Paradip. It moved in a northwesterly direction and lay at 1200 UTC of 27 near 17.2°N/90.3°E. At 0300 UTC of 28, it was centred near Lat. 18.0°N/ 88.0°E. It became a Super Cyclonic storm at 1800 UTC of 28 near 19.3°N/ 87.2°E. At 0300 UTC of 29, it was near 19.9°N/86.7°E. The cyclone crossed Orissa coast near Paradip on 29 between 0400 and 0530 UTC. After crossing the coast, it weakened into a very severe cyclonic storm and lay centred at 1200 UTC of 29 near 20.5°N/86.0°E, about 30 km northeast of Bhubaneswar. It remained practically stationary and further weakened into cyclonic storm and lay centred at 0300 UTC of 30 near 20.5°N/86.0°E, very close to Bhubaneswar. It, then, weakened into a depression at 0300 UTC of 31 near 21.0°N/87.0°E, when it was very close to Chandbali. Moving in a southeasterly direction, it again entred into the sea and weakened into a well-marked low pressure area over northwest Bay and adjoining parts of north Orissa-West Bengal coast in the evening of 31$^{st}$ October (IMD report).

Track of the cyclone and day to day variations of different parameters are described in Appendix (f).

Details of the variations in GPD products are discussed below in brief (figures are not shown).

**SST:** It is seen that SSTs were above 27°C on 24 and 25 October 1999 during the stages of the low and depression respectively. On and after 26 (Cyclonic storm stage) up to the landfall; the sea was warmer and the values were above 27°C and sometimes more than 30°C. On 29$^{th}$ the cyclone crossed the coast and started weakening. After 29$^{th}$ there was decrease in the SSTs. It is a well known fact that the post monsoon cyclones over Indian subcontinent have 1200 to 1400 km diameter areal coverage. SSTs were found to be consistent with this fact.

**SSW:** The increase in SSW is noticed as system intensified from the low to super cyclone stage. The values of sea surface winds range from 4 to 12 m/s on 24 and 25$^{th}$ Oct.'99. From 26 onwards the values started increasing when the system was intensifying. The SSWs reached up to 18 m/s on 29. Although, it was super cyclone and has reached to the maximum wind intensity up to 140 kt (as per IMD's report), the MSMR was not able to catch them as it has its own range limitations and was able to depict the maximum wind speed up to 24 m/s (50 kt).

**IWV:** It is seen that there was over all increase in the water vapor over the region where cyclone has formed. The values range from 4 to 8 gm/cm$^2$. It is indicative that there was advection of moisture over the disturbed area due to strong winds.

**CLW:** Similar features were observed in the case of CLW. Throughout the system period, the values were in the range 20 to 45 mg/cm$^2$. The presence of the moisture can be confirmed with the help of INSAT imageries where dense clouds are seen and also by the chief rainfall amounts within 24 hours reported by IMD over the area.

Quantitative as well as qualitative analyses of these geophysical parameters have shown the usefulness of remotely sensed data over the oceanic region, which is otherwise data sparse region. It has also helped in tracking the systems.

In order to verify the upper air anticyclonic features of this cyclone, analyses of METEOSAT Water Vapour Winds (WVWVs) at 200 hPa level are also carried out. WVWVs for 00 and 12 GMT obtained from METEOSAT satellite at 151-250 hPa and 251-350 hPa layers have been compared with the coincidental radiosonde upper tropospheric winds reported by Port Blair station. Linear regression of the from $y = a+b*x$ was developed between satellite derived moisture winds ($y$) and radiosonde winds ($x$). The regression constants $a$ and $b$ were determined. Using these constants, the METEOSAT winds were modified. These modified winds were used as observations and NCEP/NCAR reanalysis data was used as first guess to perform the analysis. The analysis was carried out over the domain of the study. The grid resolution was 2.5°. It was clearly seen from the analyses that there was positive impact of METEOSAT winds on the NCEP/NCAR reanalysis. The analyses produced in this manner were able to depict the synoptic situation.

IRS-P4 geophysical parameters over the disturbed area are consistent with the synoptic situation. It is revealed from our study that such remote sensing satellite data can be used as a tool to predict the intensity, movement and strength of intense weather systems. The study of this cyclone proves the importance of IRS-P4 data for better tracking of the devastative events over the Indian region.

## 5.3 General Observations about MSMR parameters in different stages of the cyclones

The cyclonic storms considered above are studied from its genesis i.e. from LOW or depression stage to intensification and then to their weakening stages. Although, case to case variation is noticed, following observations are recorded during the life cycles of the cyclonic storms for different MSMR derived GPD parameters. Ranges or maximum values are given below at different stages.

i) SSW: During the stage of low and depression the wind speeds are about 8-14 mps and in the cyclonic storm stage they are 10-22 mps.

ii) SST: The SST values around 28°- 31°C are found over the large area of Bay of Bengal. They are reduced during weakening stage and are 27°-30°C.

iii) IWV: values are 5.0 - 7.5 gm/cm$^2$ during low/depression stage and during cyclonic storm stage they are in the range 5-8 gm/cm$^2$ . During weakening stage they are 4 to 6.5 gm/cm$^2$

iv) CLW: The values for CLW during low/depression stage are between 30-80 mg/cm$^2$ while they become 40-70 mg/cm$^2$ at the cyclonic storm stage. In the weakening stage they are between 0-70 mg/cm$^2$.

# Conclusions

In order to investigate features of monsoon depressions and tropical cyclones by IRS-P4 MSMR data, four cases of monsoon depression and eight cases of tropical cyclone formed over Indian oceanic area are considered in the present work. These systems formed during 1999-2001 are studied with respect to MSMR derived geophysical parameters viz. sea surface temperature, sea surface winds, integrated water vapour and cloud liquid water content. All these parameters are retrieved at 150 X 150 km resolution.

Variation of the geophysical parameters during various stages of the monsoon depressions and tropical cyclones right from their genesis to the dissipation or landfall is studied on day to day basis combining data of the both ascending and descending nodes of IRS-P4. The analysis of the data corresponding the swath of the satellite of 1360 km is presented using GrADS software.

In general the values increase systematically from the stage of formation of a low pressure area and they become maximum one or two day before the peak intensity of the system. The CLW and IWV are aligned in a circular or elliptical shape with maximum values close to center. In order to justify the presence of higher values of CLW and IWV in convective areas of the system, NCEP wind analyses at 850 and 200 hPa are modified by objective anlaysis of wind field (OI scheme) with the inclusion of CMVs and WVWVs obtained from METEOSAT-5 on daily basis for the complete life cycles of some cases of monsoon depressions and tropical cyclones over the Indian sea. Maximum values of convergence and divergence at 850 and 200 hPa are observed through above modified analysis in the region of major convective activity giving full justification for the presence of higher values of CLW and IWV in that region.

The study shows that MSMR data provides information of very important meteorological parameters over the oceanic region to carry out diagnostic and prognostic work concerning monsoon depressions and tropical cyclones over Indian region.

# References


Ali M M and Collaborators 2000 Validation of Multifrequency scanning microwave radiometer geophysical data products; *Pacific Ocean Remote Sensing Conference (PORSEC-2000)* 182-191

Alishouse J C, Snider J B, Vongsathorn J and Ferraro R R 1990 Determination of oceanic Precipitable water from SSM/I, *IEEE Transaction of Geoscience and Remote Sensing*, 28, 811-816

Asnani G C 1993 *Tropical Meteorology, Vol. I*, pp 603

Dube S K, Rao A D, Sinha P C, Murty T S and Bahulayan N, 1997 Storm surge in the Bay of Bengal and Arabian Sea: The problem and its prediction, *Mausam*, Vol. 48, No.2, 283-304

Dvorak V F, 1984 Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS, 11, 47 pp

Eliot J 1884 Accounts of southwest monsoon storms generated in the Bay of Bengal during 1877-188; *Mem. India Met. Dept.* 2 217-448

Elsberry R L, Frank W M, Holland G J, Jarrell J D and Southern R L 1985 *A Global view of tropical cyclones* pp 185

Gohil B S, Mathur A K and Varma A K 2000 Geophysical parameter retrieval over global oceans from IRS-P4 MSMR; *Pacific Ocean Remote Sensing Conference (PROSEC-2000)* 207-211

Grody N C, Gruber A and Shen W 1980 Atmospheric water content over Pacific derived from Nimbus 6 scanning microwave spectrometer, *Journal of Applied Meteorology*, 19, 986-996

India Meteorological Department, 1979 Tracks of storms and depressions in the Bay of Bengal and Arabian Sea, 1877-1970

Kelkar R R 1997 Satellite–based monitoring and prediction of tropical cyclone intensity and movement, *Mausam*, Vol. 48, No.2, 157-168.

Kilham D A and Barrette E C 1993 SSM/I study in the Norwegian Sea, *Progress report to the Defence Research Agency, Contract No. CB/FRN/914/2034/118/A*, Remote Sensing Unit, University of Bristol, U.K.

Mahajan P N 2001 Utility of DMSP-SSM/I for integrated water vapour over the Indian seas; *Proc. Ind. Aca. Sci. (Earth and Planet. Sc.)* 110 225-229

Mahajan P N 2002 DMSP-SSM/I retrieval of proper surface winds during monsoon depression; *Mausam*, 53 367-373

Mahajan P N 2002 Signal of weakening of tropical cyclone through multiple satellite approach; Tropmet 2002 (submitted for publication)

Mahajan P N 2003 Satellite data for diagnostics of monsoon disturbances; *Mausam*, 54, 1 165-172

Mandal G S 1991 Tropical cyclones and their forecasting and warming systems in the north Indian Ocean, *WMO/TD No. 430, TCP, Rep. TCP-28*, WMO, Geneva

Mooley D A 1973 Some aspects of Indian monsoon depressions and associated rainfall; *Mon. Weath. Rev.* 101 271-280

Neumann C J, 1981 Trends in forecasting the tracks of Atlantic tropical cyclones. *Bull. Amer. Meteor. Soc.* 26, 1473-1485

Pandey P C 1992 Linear retrieval and global measurement of Precipitable water from Seasat-SMMR data, *Journal of Meteorology and Atmospheric Physics*, 47(2-4), 165-195

Prabhakara C, Cheng H D and Cheng A T C, 1982 Remote sensing of the Precipitable water over the oceans from Nimbus 7 microwave measurements. *Journal of Applied Meteorology*, 21, 59-68

Rajeevan M 1989 Post monsoon tropical cyclone activity in the north Indian ocean in relation to the El-Nino/Southern Oscillation phenomena, *Mausam*, 41, 43-46

Rao Y P 1976 Southwest Monsoon, *India Meteorological department Monograph, Synoptic Meteorology, No. 1/1976* Delhi, 367

Ruprecht E and Gay W M 1976 Analysis of satellite observed cloud clusters ; Part II Thermal, moisture and precipitation, *Tellus*, 23, 414-425

Singh O P 2001 Long term trends in the frequency of monsoonal cyclonic disturbances over the north Indian ocean, *Mausam*, 52, 4, 655-658

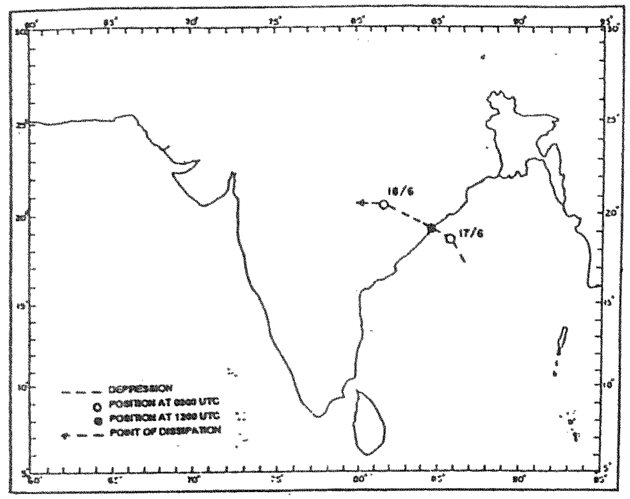
Sarkar R P and Chowdhary A 1988 A diagnostic structure of monsoon depressions; *Mausam*, 39 9-18

Sikka D R 1977 Some aspects of life history, structure and movement of monsoon depression; *Pure and Appl. Geophys. Basel* 115 1501-1529

Varma A K, Gairola R M Mathur A K Gohil B S and Agarwal V K 2002 Intercomparison of IRS-P4 MSMR derived geophysical products; *Proc. Ind. Aca. Sci.*, 111 247-255

Appendix-a

## Track of the Deep Depression – June 99

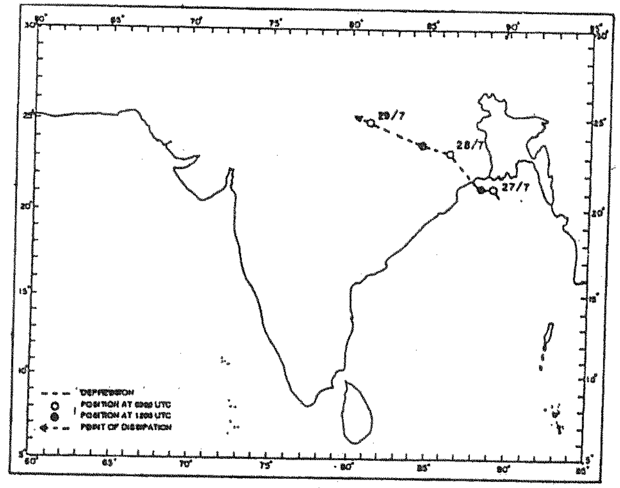



## Daily variation of geophysical parameters for complete life cycle of the above Deep Depression

| Date | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|
| Stage | - | - | Low | WML | D/DD | D/WML |
| Location Lat(°N)/Lon.(°E) | - | - | NW Bay | Orissa Coast | 18.5/86.0 19.0/85.0 | 20.5/82 |
| SSW (m/s) | 10-12 | 12-14 | 12-14 | 14-18 | 12-14 | 13-14 |
| SST (°C) | 30-31 | 30-31 | 31 | 30-29 | 30-31 | 28-29-30 |
| IWV ($gm/cm^2$) | 5.0-6.0 | 6.0-7.0 | 6.0-7.5 | 5.5-6.0 | 6.0-6.5 | 6.0-6.5 |
| CLW ($mg/cm^2$) | 0-10 | 10-40 | 70-90 | 40-50 | 30-40 | 10-30 |

Appendix-b

## Track of the Deep Depression – July 99

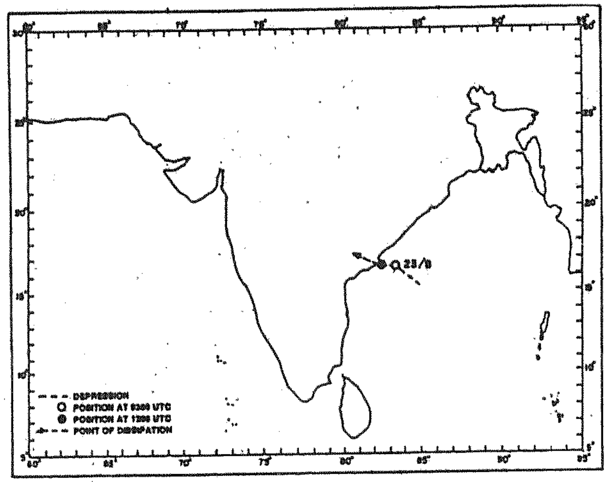



## Daily variation of geophysical parameters for Complete life cycle of the above Deep Depression

| Date | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|
| Stage | - | Low | Low | WML | D/DD | DD/D | D/WML |
| Location Lat.(°N)/Lon.(°E) | - | NW Bay | NW Bay | NW Bay | 21.0/89.0 21.0/88.5 | 23.0/84.5 crossed Orissa | 24.5/81.0 NW M.P |
| SSW (m/s) | 12-13 | 8-10 | 12-14 | 8-11 | 13-14 | 12-13 | - |
| SST (°C) | 29-30 | 29-30 | 30 1 | 29-30 | 30 | 26-30 | - |
| IWV ($gm/cm^2$) | 5.0-6.0 | 6.5-8.0 | 7.0-8.0 | 6.5-8.0 | 7.0-8.0 | 6.0 | - |
| CLW ($mg/cm^2$) | 20 | 50-80 | 45-65 | 30-80 | 30-40 | 0-10 | - |

Appendix-c

## Track of the Depression – August 2000

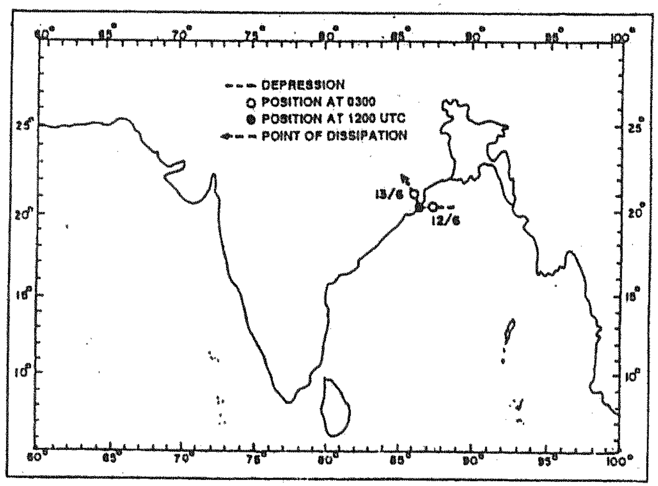



## Daily variation of geophysical parameters for complete life cycle of the above Depression

| Date | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|
| Stage | WML | WML | WML | WML | D | - |
| Location Lat.(°N)/Lon.(°E) | N.Bay | N.Bay | W.C. Bay N. Andhra | W.C.Bay N.A/Orissa | 16.5/83.5 | - |
| SSW (m/s) | 8-10 | 12-14 | 12-14 | 14-16 | 10-12 | 12-14 |
| SST (°C) | 29-30 | 29-30 | 29-30 | 30 | 29-30 | 31 |
| IWV ($gm/cm^2$) | 5.0-6.5 | 6.0-6.5 | 6.5-7.0 | 7.0-7.5 | 6.5-7.0 | 6.0-7.0 |
| CLW ($mg/cm^2$) | 10-30 | 20-30 | 30-40 | 50-60 | 30-50 | 10-20 |

Appendix-d

## Track of the Depression – June 01

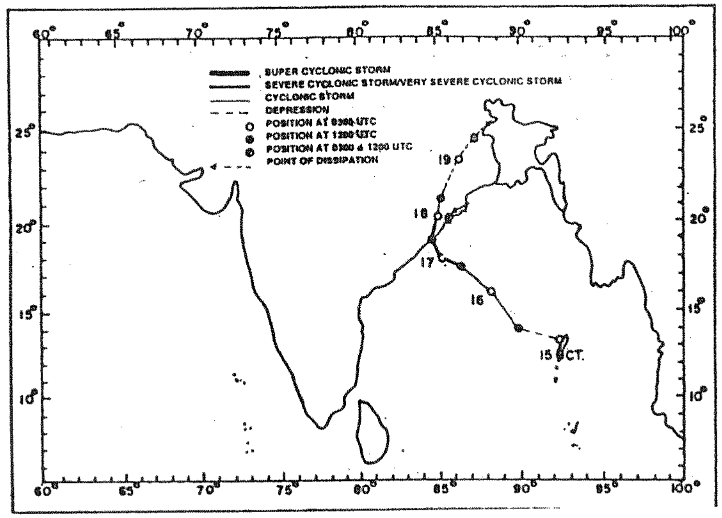



**Daily variation of geophysical parameters for complete life cycle of the above Depression**

| Date | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|
| Stage | - | Low | WML | D | D | WML |
| Location Lat.(°N)/Lon.(°E) | - | - | - | 20.0/87.0 | 21.0/86.0 | M.P. Chattisgadh |
| SSW (m/s) | 8-12 | 12-14 | 12-14 | 14-16 | 16-18 | 13-15 |
| SST (°C) | 30-31 | 30-31 | 29-31 | 30-31 | 27-30-31 | 30-31 |
| IWV ($gm/cm^2$) | 6-7 | 6.5-7.5 | 5-6 | 6.5-7 | 6-6.5 | 5.5-6 |
| CLW ($mg/cm^2$) | 30-40 | 40-50 | 20-30 | 20-30 | 20-30 | 40-45 |

Appendix -e

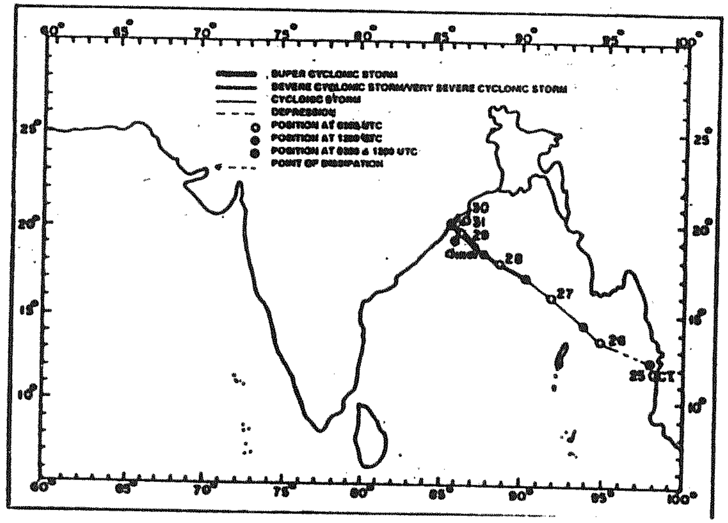
## Track of the Very Severe Cyclonic Storm – October 1999




## Daily variation of geophysical parameters for complete life cycle of the above Storm

| Date | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|
| Stage | - | - | D | CS/SCS | VSCS | CS Crossed coast | Low | - |
| Location Lat (°N)/Long (°E) | - | - | 13.5/92.5 | 16.0/88.5 | 18.6/86.0 | 20.5/85 | 23.5/86.5 | - |
| SSW (m/s) | 6-8 | 8-10 | 10-12 | 12-22 | 12-14 | 12-18 | 8-10 | 12-14 |
| SST (°C) | 29-30 | 26-29 | 29-30 | 25-29 | 29-30 | 26-28 | 28-29 | 25-28 |
| IWV (gm/cm$^2$) | 5.5-6 | 5-5.5 | 6.5-7.5 | 5.5-6 | 5.5 | 4-5 | 4.5-5 | 5.5 |
| CLW (mg/cm$^2$) | 5-45 | 5-15 | 15-40 | 20-45 | 15-45 | 5-15 | 15-35 | 0-5 |

## Track of the Super Cyclonic Storm - October 1999

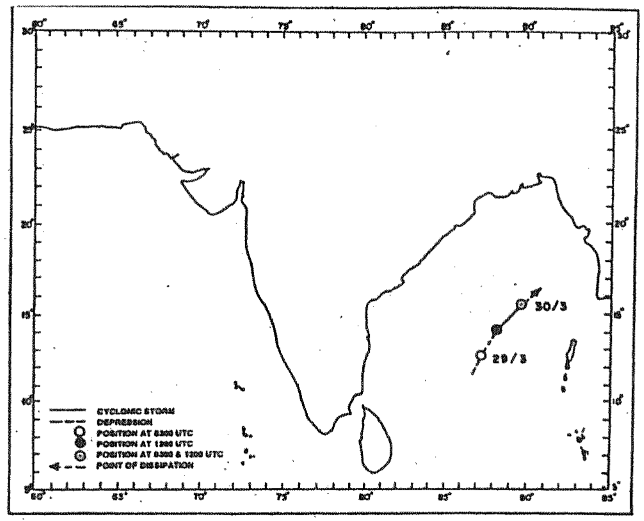


## Daily variation of geophysical parameters for complete life cycle of the above Storm

| Date | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
|---|---|---|---|---|---|---|---|---|
| Stage | - | WML | D | SCS | VSCS | SupCS | VSCS | D |
| Location Lat(°N)/Long(°E) | - | Gulf of Siam | 13.5/95.0 14.5/94 | 16.0/92.0 17.0/90.0 | 18.0/89.0 18.5/88.0 | 19.9/86.7 | 20.5/86 | 20.5/87.0 Land |
| SSW (m/s) | 4-10 | 6-10 | 6-12 | 12-20 | 10-14 | 12-18 | 12-14 | 12-16 |
| SST (°K) | 28-29 | 29-30 | 26-29 | 28-30 | 28 | 29-30 | 28-30 | 26-28 |
| IWV (gm/cm$^2$) | 5-6 | 5-6 | 5-6 | 6-7 | 5-7 | 4-5.5 | 4.5-6 | 4-5.5 |
| CLW (mg/ cm$^2$) | 0-5 | 20-45 | 35-45 | 45 | 20-35 | 10-30 | 20-30 | 15-20 |

Appendix-g

## Track of the Cyclonic Storm – March 2000

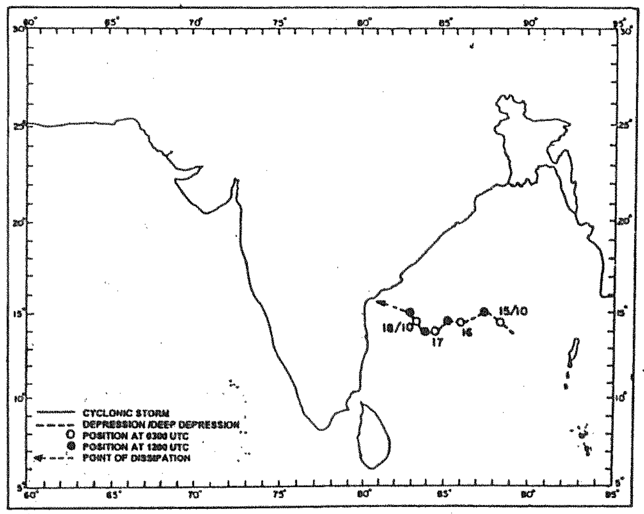



## Daily variation of geophysical parameters for Complete life cycle of the above Storm

| Date | 26-3 | 27-3 | 28-3 | 29-3 | 30-3 | 31-3 | 1-4 | 2-4 |
|---|---|---|---|---|---|---|---|---|
| Stage | - | - | D | D/DD | C.S | L | - | - |
| Location Lat.(°N)/Lon(°E) | - | - | 12.5/87.5 | 15.5/90.0 | EC Bay | - | - | - |
| SSW (m/s) | 6-10 | 12-18 | 10-14 | 10-12 | 10-12 | 12-16 | 8-10 | No Data |
| SST (°C) | 29-30 | 29-30 | 26-30 | 29-30 | 26-29 | 24-29 | 26-29 | No Data |
| IWV (gm/cm$^2$) | 5-6 | 6-7 | 3-7 | 3-6.5 | 3-6 | 4-6 | 3-5 | No Data |
| CLW (mg/cm$^2$) | 0-5 | 50-80 | 25-45 | 25-45 | 10-30 | 0-10 | 0-5 | No Data |

Appendix -h

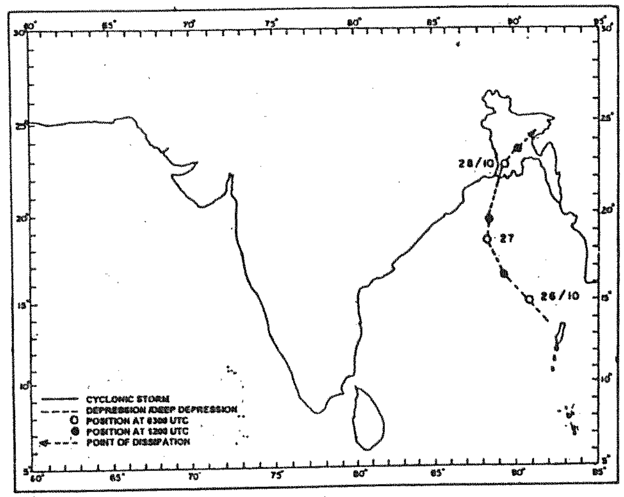
## Track of the Cyclonic Storm – October 2000




## Daily variation of geophysical parameters for complete life cycle of the above Storm

| Date | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|
| Stage | - | - | D | DD | CS | DD | D | low | - |
| Location Lat.(°N)/Lon(°E) | - | - | 14.5/88.5 | 14.5/86.5 | 14.0/84.5 | 14.0/83.5 | 14.5/82.5 | - | - |
| SSW (m/s) | 12-14 | 12 | - | 12 | 12-14 | 8-10 | 8-10 | 6-8 | 6-8 |
| SST (°C) | 30 | - | - | 29-30 | 29-30 | 27 | 30 | 28 | 30 |
| IWV ($gm/cm^2$) | 7-8 | 7-8 | - | 7-8 | 6-7 | 6-7 | 6 | 4-6 | 3-5 |
| CLW ($mg/cm^2$) | 24 - 40 | - | - | 15-45 | 0-5 | 0-5 | 35-45 | 0 | 20 |

## Track of the Cyclonic Storm – October 2000

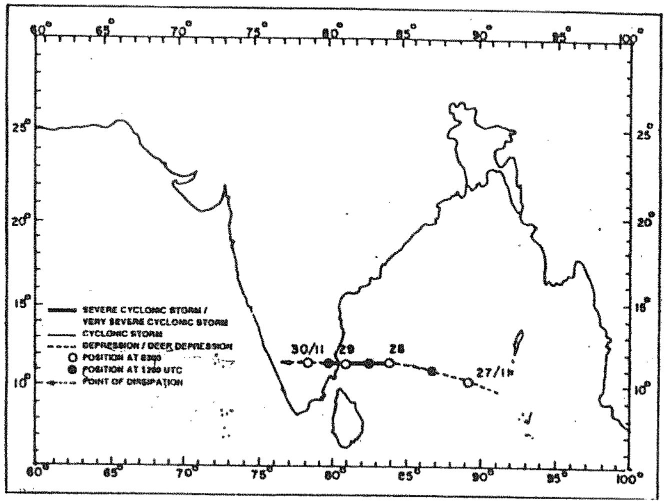



## Daily variation of geophysical parameters for complete life cycle of the above Storm

| Date | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|
| Stage | - | Low | D | D | DD/CS | DD/D | Low |
| Location Lat.(°N)/Lon(°E) | - | Andaman Sea | 13.5/93.0 | 15.0/90.0 | 18/88.5 20/88.5 | 22.5/89 23.5/90.5 | - |
| SSW (m/s) | 10-12 | 8-10 | 8-9 | 8-12 | 10-12 | - | 5-6 |
| SST (°C) | 30 | 29-30 | 27-28 | 29-30 | 29-30 | - | 28-29 |
| IWV (gm/cm$^2$) | 6-6.5 | 6-7.0 | 6-7 | 6-7.5 | 5-6 | - | 3-4 |
| CLW (mg/cm$^2$) | 30-60 | 60-80 | 60-70 | 60-80 | 10-20 | - | 0 |

Appendix-j

## Track of the Very Severe Cyclonic Storm – November 2000

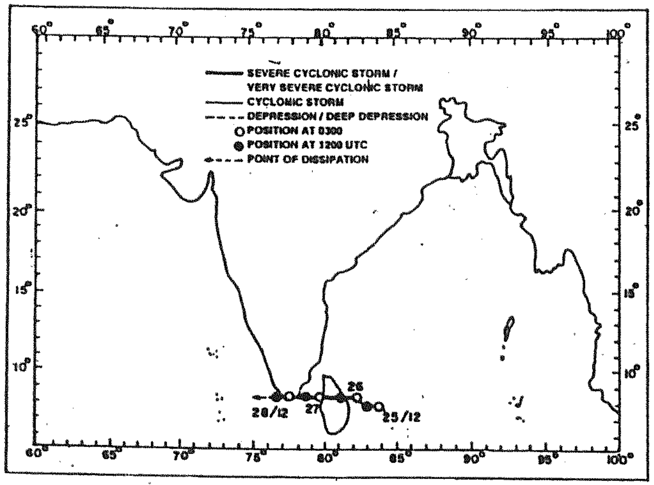



## Daily variation of geophysical parameters for complete life cycle of the above Storm

| Date | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|
| Stage | - | Low/D/DD | CS | SCS VSCS | VSCS SCS/CS | DD/D |
| Location Lat.(°N)/Lon(°E) | - | Andaman Sea 8.5/91.5 10.0/90.0 | 11.0/86.5 | 11.5/84.0 11.5/83.0 | 11.5/80.0 11.0/78.5 | 11.5/78.0 11.5/77.0 |
| SSW (m/s) | 6-9 | 12-16 | 12-13 | 8-9 | 7-8 | 8-10 |
| SST (°C) | 22-27 | 30-29 | 29-31 | 30-31 | 28-29 | 27-28 |
| IWV ($gm/cm^2$) | 3-4 | 5-6.5 | 7-8 | 5-6 | 4-5.5 | 4.5-5 |
| CLW ($mg/cm^2$) | 20-40 | 40-60 | 50-70 | 10-20 | 10-30 | 0-10 |

Appendix-k

## Track of the Very Severe Cyclonic Storm – December 2000

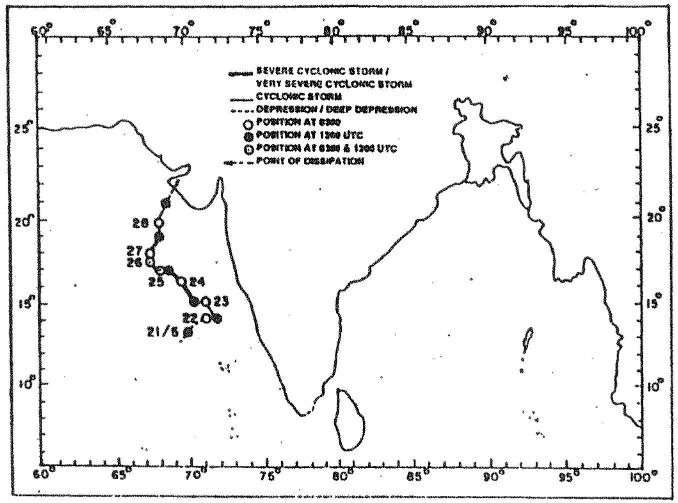



## Daily variation of geophysical parameters for Complete life cycle of the above Storm

| Date | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|
| Stage | Low/D | DD | CS/SCS | VSCS | SCS/CS | DD/D | Low | - |
| Location Lat.(°N)/Lon(°E) | SC Bay 8.0/86.0 | 8.0/84.0 | 8.5/83.0 | 8.5/82.5 | 8.5/78.5 8.5/78.0 | 8.5/77.0 9.0/76.5 | East Arabian Sea | - |
| SSW (m/s) | 14 | 12 | 12 | 12-14 | 10 | 10-14 | 8-10 | 8-10 |
| SST (°C) | 28-30 | 29-30 | 28-29 | 30 | 29 | 27 | 27-28 | 28-29 |
| IWV (gm/cm$^2$) | 6-7 | 6.5-7.5 | No Data | 4-5 | 4.5 | 4 –4.5 | 4.5 - 5 | 3.5 |
| CLW (mg/cm$^2$) | 40-45 | 60-70 | No Data | 5-15 | 5-15 | 0-5 | 0-5 | 0-5 |

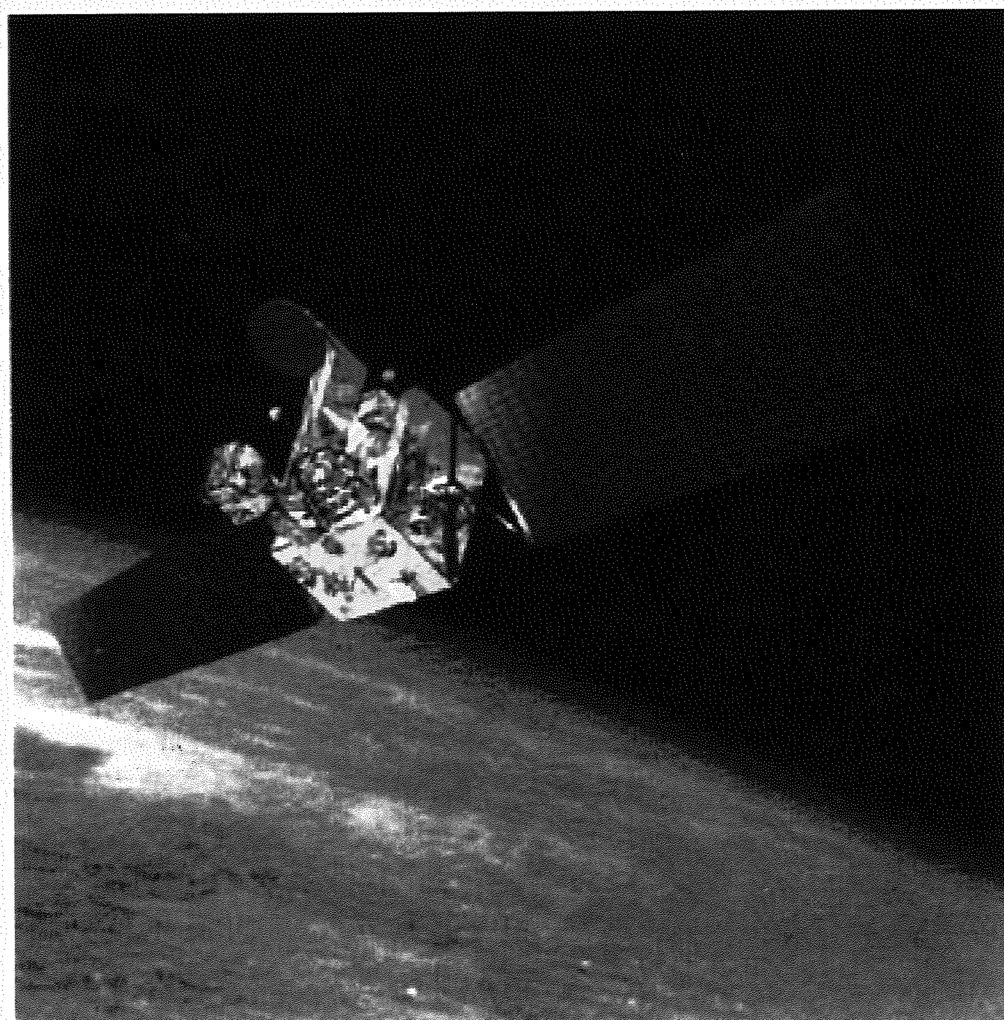
**Appendix-I**

## Track of the Very Severe Cyclonic Storm – May 01




## Daily variation of geophysical parameters for complete life cycle of the above Storm

| Date | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
|---|---|---|---|---|---|---|---|---|
| Stage | Low | SCS | VSCS | VSCS | VSCS | SCS | SCS/CS | CS |
| Location Lat.(°N)/Lon(°E) | - | - | 15.0/71.0 | 16.0/69.0 | 17.0/68.0°E | 17.5/67.0 | 18.0/67.5 | 20.0/68.0 |
| SSW (m/s) | 12-14 | 12-16 | 12-16 | 12-15 | 14-17 | 14-16 | 10-14 | 11-13 |
| SST (°C) | 30-31 | 30-31 | 29-30 | 29-30 | 30-31 | 30-31 | 29-30 | 29-30 |
| IWV ($gm/cm^2$) | 6.5 | 6-7.5 | 6.5-7 | 3-4 | 6.5 | 7 | 6 | 6.5 |
| CLW ($mg/cm^2$) | 50 | 40-50 | 65 | - | 45 | 30-35 | 10-25 | 50-60 |



IRS-P4 (OCEANSAT-1)