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Satellite meteorology in India—An overview

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Received 11 April 1994

The growth of satellite meteorology in India during the last thirty years, beginning with the establishment of ground equipment to receive the automatic picture transmissions by the US polar orbiting satellites, is traced. The impact of India's own satellite, INSAT, on operational meteorology in recent times and the complex nature of satellite data processing are discussed in detail. The usefulness of INSAT imagery and derived quantitative products, particularly over data-sparse oceanic regions, is described. The successful exploitation of INSAT's communication capabilities for meteorological data dissemination, collection of data from remote platforms and disaster warnings to coastal areas are also reviewed. Finally, the research applications of INSAT data in areas of monsoon variability, climate studies, physical initialization of numerical models, etc. are dealt with.

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1 Introduction

April 1, 1960 marked the beginning of the era of weather satellites with the launch of TIROS-1 (Television and Infra-Red Observation Satellite) by the United States. In 1964, on the TIROS-8 satellite, a new facility called APT (Automatic Picture Transmission) was introduced. This enabled reception of cloud imagery from the polar-orbiting satellites on real-time with the help of inexpensive ground equipment. The India Meteorological Department (IMD) established its first APT station at Bombay in 1965 which gave Indian meteorologists a direct access to cloud imagery of the Indian subcontinent and adjoining sea areas, as viewed by the orbiting satellites. This was the real beginning of satellite meteorology in India.

In the seventies, six more stations were added to the APT network of IMD, thus providing the field forecasters with satellite input routinely. The APT pictures had to be subjectively interpreted as there was no quantitative data available and they were received only twice a day. Even then, they became important to the meteorologists as they covered the Arabian Sea, the Bay of Bengal and inaccessible land areas over which little synoptic data were available. The satellite thus became a valuable tool for (i) tracking tropical cyclones and estimating their intensity, (ii) following the migration of systems like monsoon depressions and western disturbances, and (iii) monitoring the advance of the southwest monsoon over the country.

Satellite meteorology in India, however, may be said to have come of age only in 1982 when India acquired the unique distinction of becoming the first developing country in the world to operate its own communications-cum-meteorological geostationary satellite, INSAT-1A. This paper reviews the recent and upcoming developments in the area of satellite meteorology in India and it discusses how INSAT is being used to support operational meteorology, atmospheric research, climate studies, and disaster warning.

2 INSAT system concept

INSAT is a domestic satellite system set up to bring in satellite-based services in as many fields as possible in the quickest possible time¹. The multi-purpose concept of INSAT led to the realization of the full potential of the geostationary satellite system at one stroke. Thus, while other countries had dedicated satellites for different usages, INSAT-1A, launched in April 1982, ushered in a new era in communications, television and radio broadcasting, and meteorology at the same time. The multi-user utilization of INSAT has continued to gain acceptance and so far there have been four satellites in the INSAT-1 series, followed by INSAT-2A and INSAT-2B which were fabricated indigenously.

The basic meteorological payload on INSAT is the Very High Resolution Radiometer (VHRR) which measures the radiance in two narrow spectral windows, viz. 0.55-0.75 μm in the visible channel and 10.5-12.5 μm in the thermal infrared

band. The former is a measure of the solar radiance reflected from the earth's surface and cloud tops, i.e. the brightness of these surfaces, whereas the thermal infrared measurement gives an indication of the temperature of the earth's surface and cloud tops assuming them to be acting as black bodies. In the case of INSAT-2, the spatial resolution at the sub-satellite point is 2 km for the visible channel, and 8 km for the infrared channel².

The INSAT-2 VHRR scans the earth's disc from a height of 36 000 km in three different modes which require different periods to complete. These are (i) full frame mode of $20^\circ \times 20^\circ$ in 33 min, (ii) normal frame mode of 14° N-S \times 20° E-W in 23 min, and (iii) sector mode of 4.5° N-S \times 20° E-W in 7 min for rapid repetitive coverage. The VHRR data are transmitted from the satellite in real-time for reception by IMD at the INSAT Meteorological Data Processing System (IMDPS), New Delhi. The INSAT-2 data are received directly here through IMD's own earth station, while INSAT-1 data are received by DoT's earth station at Sikandrabad and sent to IMDPS over a dedicated microwave link.

The INSAT satellites also carry a payload named Data Relay Transponder (DRT) specially for relay of meteorological data from remote locations. This is described later in this paper.

3 INSAT meteorological data processing

To process the data from the INSAT's VHRR and DRT, IMD established in 1982 a Meteorological Data Utilisation Centre (MDUC) at New Delhi. This system was integrated around a set of four PDP 11/34 and two PDP 11/70 computers and was basically designed to meet the requirements of (i) real-time processing of VHRR and data collection platform (DCP) data, (ii) production of hard copies of INSAT imagery, (iii) interactive image analysis, (iv) archival, and (v) transmission of analogue imagery to field locations.

While these primary functions of MDUC continued to be carried on, a considerable amount of software development effort was made in the eighties to fully exploit the system capabilities for derivation of quantitative meteorological products for the digital VHRR data. In 1992, therefore, a new computer system, called INSAT Meteorological Data Processing System (IMDPS), was set up at IMD, New Delhi, with vastly enhanced computing power and resources and its own earth station. This synchronized with the launch of the second-generation INSAT satellite, INSAT-2A, which had a better resolution of 2 km in the visi-

ble and 8 km in the infrared against 2.75 and 11 km for INSAT-1 series³. A schematic diagram of the IMDPS hardware is given in Fig. 1. The system is configured around eight VAX 3400 computers. A key feature of the IMDPS configuration is its advanced, distributed architecture aimed at providing maximum uptime, improved overall reliability, built-in redundancy and allocation of optimum computing power to various processing jobs. While reception and raw data processing is done by dedicated computers, complex applications are passed on to high-speed array processors. The eight VAX machines are interlinked through an Ethernet LAN and 4 gb disk cluster storage. Four interactive work stations enable meteorologists to analyse imagery and perform operations like zooming, pseudocolouring, gray scale enhancements, and other applications. Hard copies can be taken on black-and-white as well as colour thermal recorders and on roll-and-sheet-type laser photowriters. IMDPS can process data in real-time from INSAT-1, INSAT-2 and NOAA orbiting satellites simultaneously. Vertical temperature profiles can be retrieved from NOAA's TOVS (TIROS Operational Vertical Sounder) data. The system is also connected to Global Telecommunications System (GTS) for reception as well as transmission of coded data.

4 Qualitative interpretation of satellite imagery

In the pre-INSAT age, only qualitative use could be made of satellite pictures. However, even now the INSAT digital data is converted by gray scale transformation into picture products which can be conveniently and quickly viewed in conjunction with synoptic weather maps for routine operational weather forecasting. Such pictures are also shown in television newscasts every day for the general public.

Basically, six characteristic features of satellite pictures are helpful in extracting information⁴:

(1) Brightness: In visible pictures, highly reflecting surfaces like cumulonimbus tops and snow appear pure white, whereas the sea looks black. Other clouds and land appear in varying degrees of grayness. In infrared images, warm land surfaces appear very dark, while cold ones are white (e.g. cumulonimbus tops, thick cirrus, snow). Lower level clouds and thin cirrus appear gray.

(2) Pattern: Cloud elements are seen to be organised into distinctly identifiable patterns like lines, bands, waves, etc.

(3) Structure: Shadows and highlights are indicative of a mixture of clouds of different heights and thicknesses.

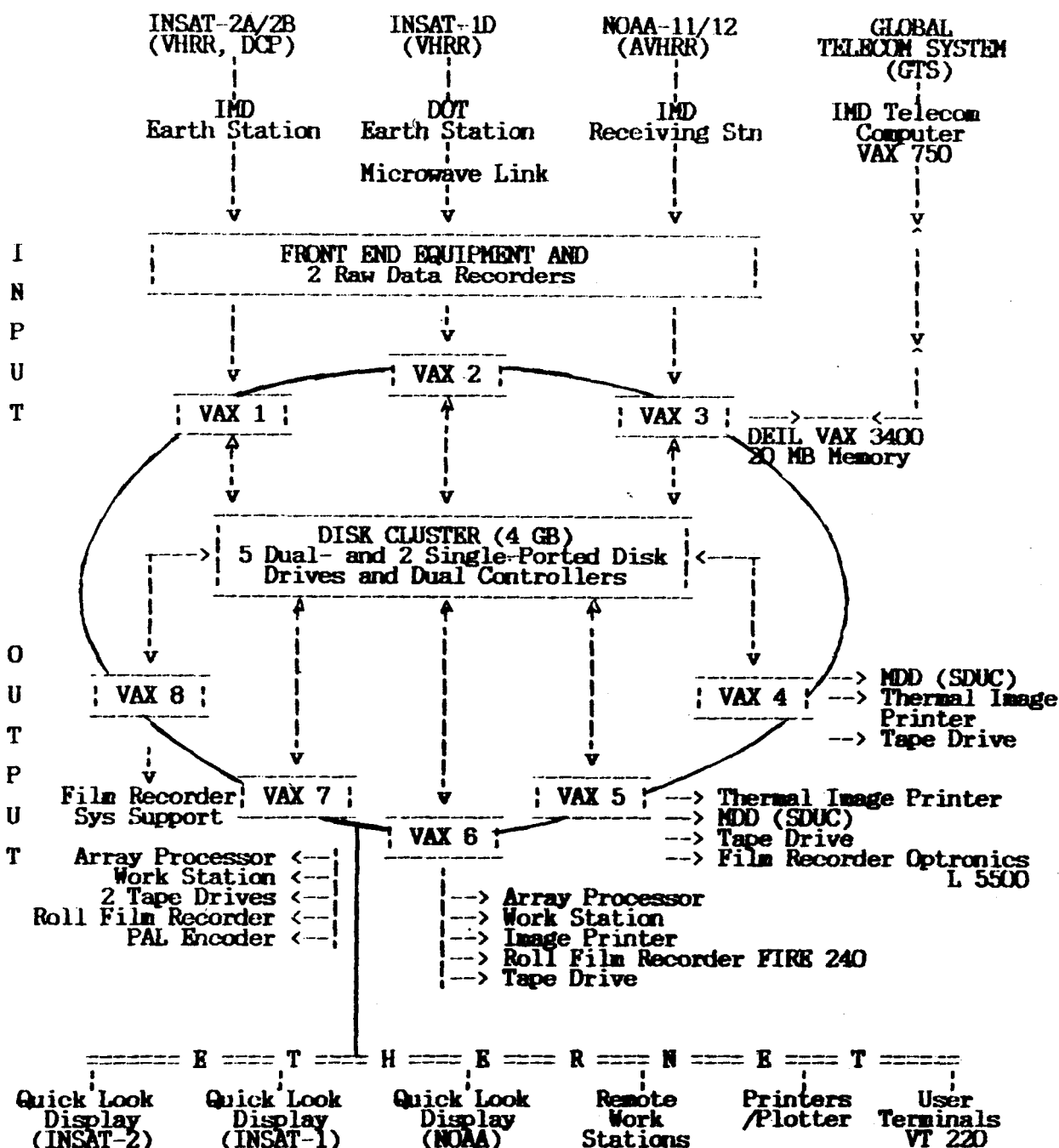


Fig. 1—Hardware configuration of the INSAT-2 Meteorological Data Processing System (IMDPS) at IMD, New Delhi.

(4) Texture: Some cloud surfaces are uniform and smooth, while others are ragged.

(5) Shape: Clouds assume variety of shapes.

(6) Size: Size of individual clouds in a pattern and size of the pattern itself indicate the scale of the weather systems.

By applying feature classification schemes, the different types of clouds and cloud systems can be identified from a satellite picture. Expert analysts can usually do so intuitively.

INSAT being a geostationary satellite, repetitive coverage of a given area is available. This helps in two ways: (i) to watch *in situ* growth of weather phenomena like cumulonimbus cells, fog, etc. or their decay, and (ii) to track the movements of migrating systems like tropical cyclones, monsoon depressions, western disturbances, etc. INSAT images have been of great help to the forecasters in identifying and locating primary synoptic systems like surface lows, troughs and ridges, jet streams,

regions of intense convective activity, inter-tropical convergence zones (ITCZs), etc. INSAT pictures are most useful at the time of the onset of the southwest monsoon over Kerala and for subsequently monitoring its advance into the country. In particular, the movement of monsoon depressions, forming in the north Bay of Bengal and moving inland, can be tracked by INSAT. All this has greatly enhanced the forecasters' ability to predict weather accurately as the INSAT information is available every 3 h or more frequently and conventional data are just absent over many vital areas.

One major thrust area of INSAT which can be singled out is the tropical cyclone forecasting. INSAT allows us to detect the genesis of tropical cyclones far out at sea in the Bay of Bengal and the Arabian Sea. Their further intensification and movement towards land is followed carefully and advance warnings can be given to the coastal areas likely to be affected. Dvorak's technique⁵ for estimating the intensity of tropical cyclones from the satellite pictures is used in India as is done elsewhere. Tropical cyclones have their distinctive patterns in INSAT imagery depending upon their stage of development⁶. In the more mature and destructive cyclones, the so-called "eye" is seen (Fig. 2). Infrared pictures of INSAT are further analysed for determining the temperature of the coldest cloud band and the warmest area of the centre or eye to obtain a measure of the storm intensity.

Satellite pictures in the absence of clouds also reveal features like snow cover, dust-storms, etc. depending upon the season and area.

5 Quantitative product derivation

The need for quantitative meteorological data on a global scale has been increasingly felt over the last decade or so for initialization purposes in numerical weather prediction. Such a demand, particularly over data-sparse areas like the Indian Ocean, can be met only through derivation of results indirectly from satellite data which are the only source of observation here. While satellites basically measure the radiance reaching them from the earth's surface and cloud tops, by making such measurements in appropriate wavelength channels and applying physical and/or statistical techniques, it is possible to compute a host of derived products⁷.

The most successful of such INSAT-based products are the cloud motion vectors (CMVs) which are the only source of upper wind data over the Indian Ocean barring a few island stations. The

principle here is to use two or three successive half-hourly INSAT images and to track the movement of clouds over them. This essentially involves a detailed pattern matching process which has to be done automatically if it is to be completed in time. If the position of a cloud or cloud pattern in an image at time T_1 is known and if the same can be identified in the successive images at time T_2 and T_3 , the displacement of the cloud indicates the speed and direction of the upper air flow at the cloud level. INSAT-based CMVs are derived thrice a day and the data for 0000 and 1200 hrs UT are globally disseminated within three hours to enable them to be assimilated by NWP Forecast Centres and other services the world over. A typical INSAT-2B-based CMV product is shown in Fig. 3.

CMVs are known to have many errors and uncertainties and therefore have to be subjected to a rigorous quality control procedure for ensuring time consistency (two-image pairs are used), spatial consistency (gradient should not be large), agreement with broadly known climatological features and compatibility with prevailing synoptic patterns (they should be comparable within limits to the forecast field). Even after automatic elimination of winds which fail to qualify the above tests, they are subjected to manual editing before they are cleared for dissemination on GTS.

INSAT-based CMVs are very useful in the analysis of upper winds during the monsoon season to study the formation of eddies, cross-equatorial flow, approach of the monsoon towards the west coast of India, off-shore vortices, and activity of two separate branches of the monsoon⁸.

Satellite radiance measurements in the infrared thermal window can be worked back upon using physical principles to obtain the surface temperature. This is easily done in the case of tops of thick clouds, giving an idea of the degree of convection. In the absence of clouds, the radiance can be attributed to the earth's surface and if the emissivity is known (= 1 in case of sea surface), the temperature can be obtained. However, a major anomaly in the satellite-derived sea surface temperatures (SSTs) is the attenuation of the radiation by moisture in the lower atmosphere. By suitably parameterizing this attenuation⁹, which can never be perfectly accomplished, SSTs can be derived over the Indian Ocean by using INSAT thermal infrared data. A typical SST chart is shown in Fig. 4. Retrieval of SST is badly affected during the monsoon season by heavy clouding, but it can be derived regularly in other seasons.

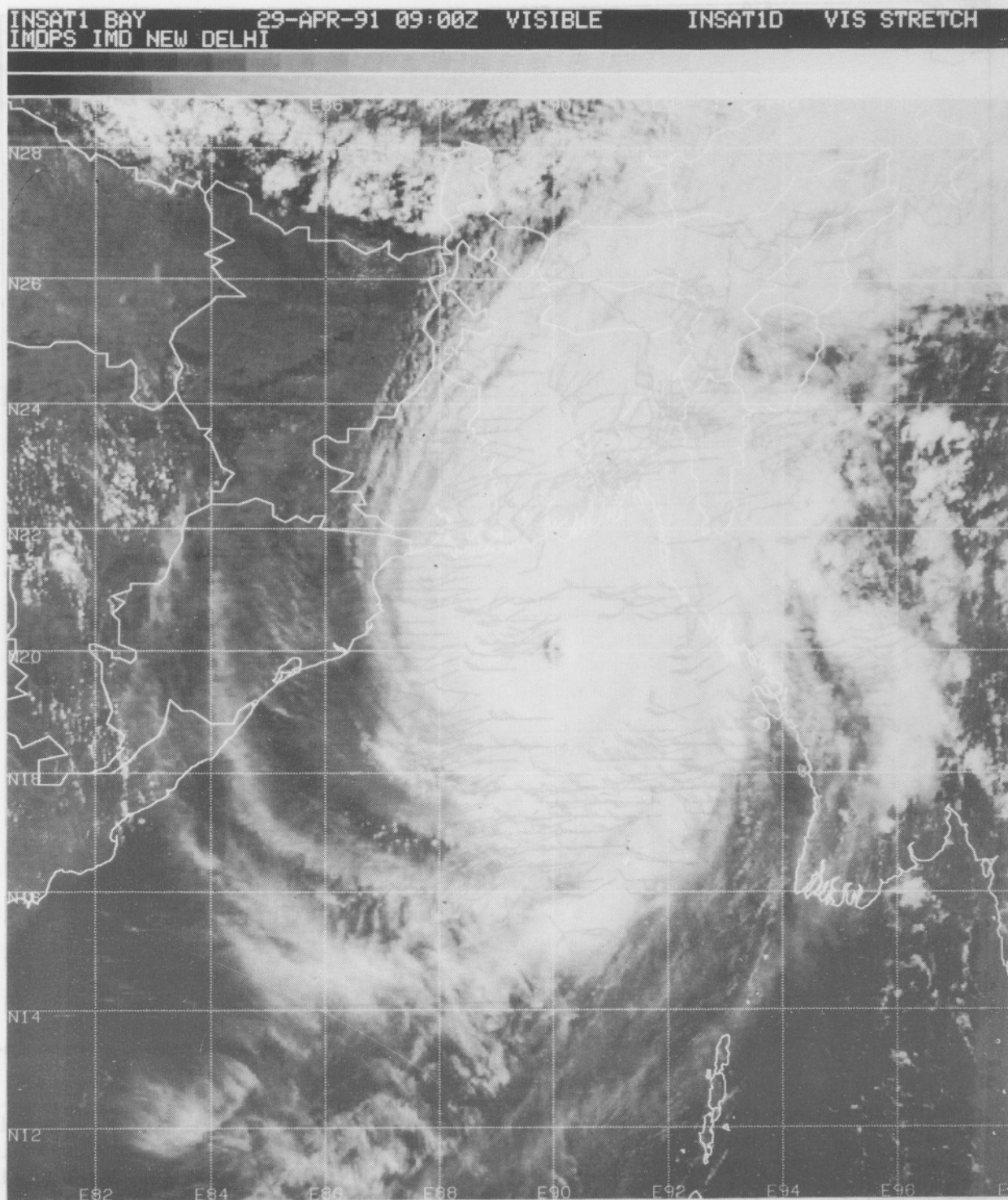


Fig. 2—Severe cyclonic storm over the Bay of Bengal as viewed by INSAT-1D on 29 Apr. 1991 at 0900 hrs UT.

The outgoing flux of longwave radiation at the top of the atmosphere is an important parameter in the earth-atmosphere radiation budget. This parameter can be derived by physical/statistical algorithms from the narrow band ($10.5\text{--}12.5\ \mu\text{m}$) measurements of INSAT made every 3 h. The

outgoing longwave radiation (OLR) is derived using the 3-hourly data on a daily/weekly/monthly scale over $2.5^\circ \times 2.5^\circ$ lat./long. boxes over the INSAT disc. Regular OLR derivations from INSAT have been in progress since June 1986 (Ref. 10). The spatial and seasonal variations of OLR reflect

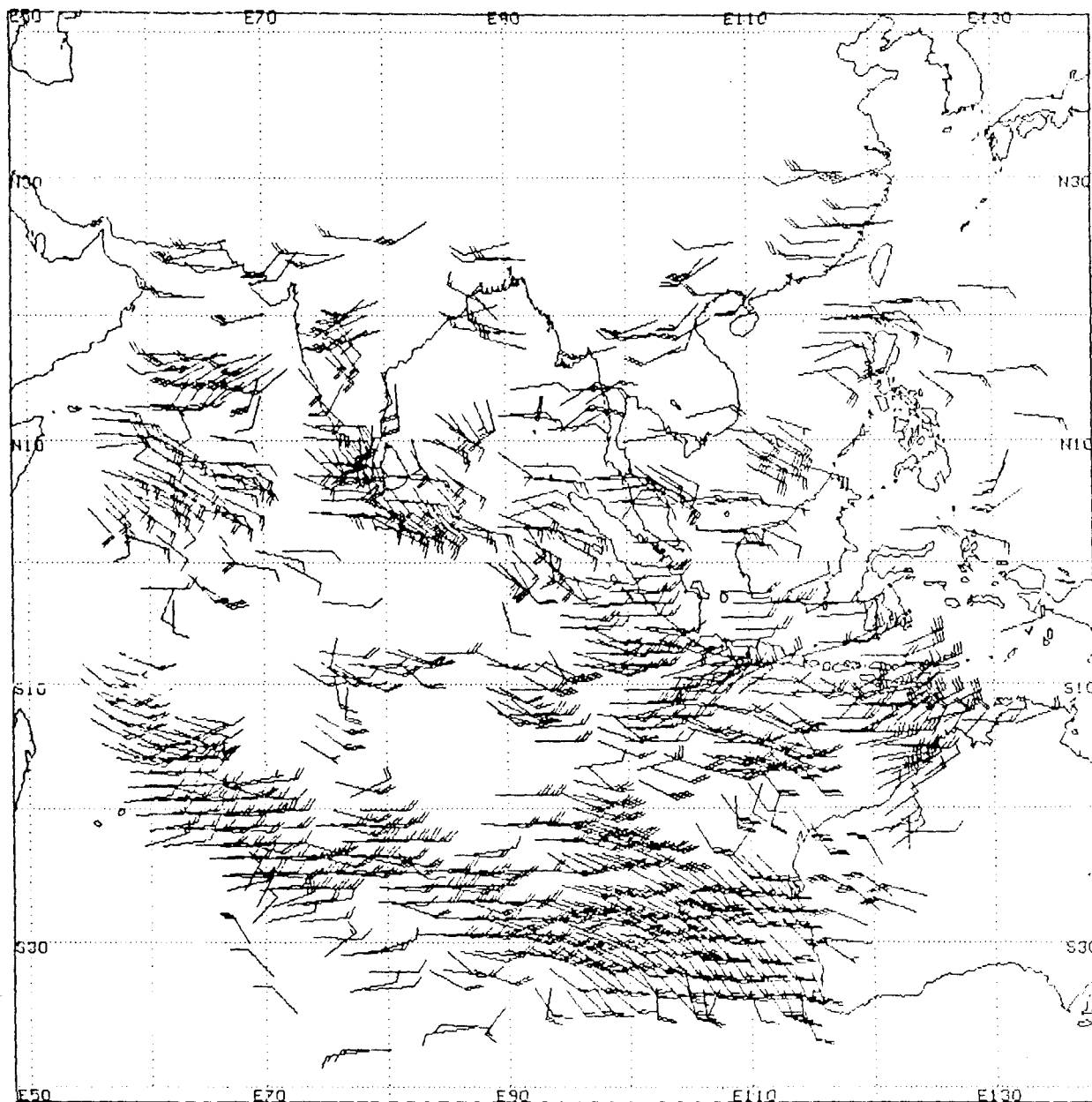


Fig. 3—Cloud motion vectors derived from INSAT-2B imagery around 0000 hrs UT of 4 Apr. 1994, showing low-level atmospheric flow patterns.

the patterns of convective activity and their seasonal shifts. In recent years OLR has come to be regarded as a proxy parameter for convective activity in many research applications.

While the OLR is a good indicator of convective activity in the tropics, it is also possible to directly estimate the precipitation by accumulating 3-hourly cloud top temperature data over $2.5^\circ \times 2.5^\circ$ lat./long. boxes. In the method used with INSAT and other geostationary satellites¹¹, cloud pixels colder than 235 K are considered to be raining pixels and by measuring the number of

such pixels in a box over a week, the rainfall amount is estimated using a statistical regression. The results are good basically over the tropical ocean and meet the needs of NWP initialization, but over land orographic effects lead to uncertainties. Nevertheless for large-scale estimation, satellite-derived values have the potential for giving a fairly reliable value of large-scale rainfall. Monthly means of outgoing longwave radiation and large-scale precipitation estimates derived from 3-hourly INSAT data for the monsoon month of August 1993 are shown in Figs 5 and 6 respectively. Re-

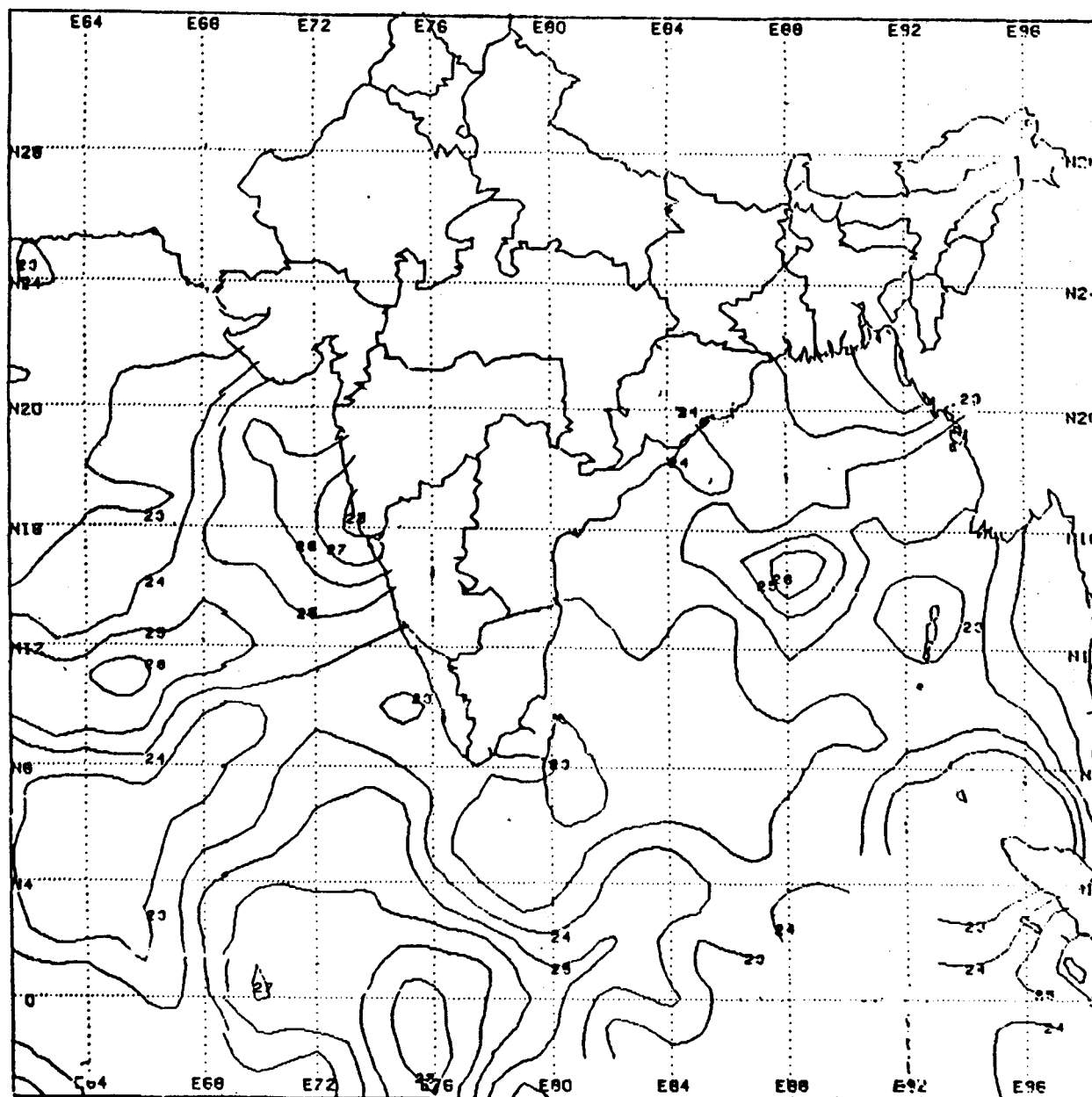


Fig. 4—INSAT-derived sea surface temperature ($^{\circ}\text{C}$) over the Indian Ocean for 15 Jan. 1994.

gions of low OLR have high precipitation and vice versa as seen from Figs 5 and 6.

6 Use of INSAT communication capabilities for meteorology

Since the INSAT satellites have multi-purpose application, it is possible to exploit their communications capabilities for serving meteorological interests¹². One example of such a dual application is the meteorological data dissemination (MDD) scheme under which INSAT is used to disseminate (i) processed INSAT imagery, (ii) ana-

lysed weather charts, and (iii) five streams of coded meteorological data. These three types of information are multiplexed and uplinked to INSAT-1D/2B on one of the C-band RN carriers and the TV transponder of the satellite rebroadcasts them in the S-band for reception anywhere in India with the aid of a 3.6 m diameter dish antenna and low cost receiving equipments. The MDD scheme eliminates the dependence on terrestrial links and provides more reliable service as terrestrial links are prone to breakdowns. The MDD scheme, though originally planned for serving IMD's field offices at 25 locations, is now be

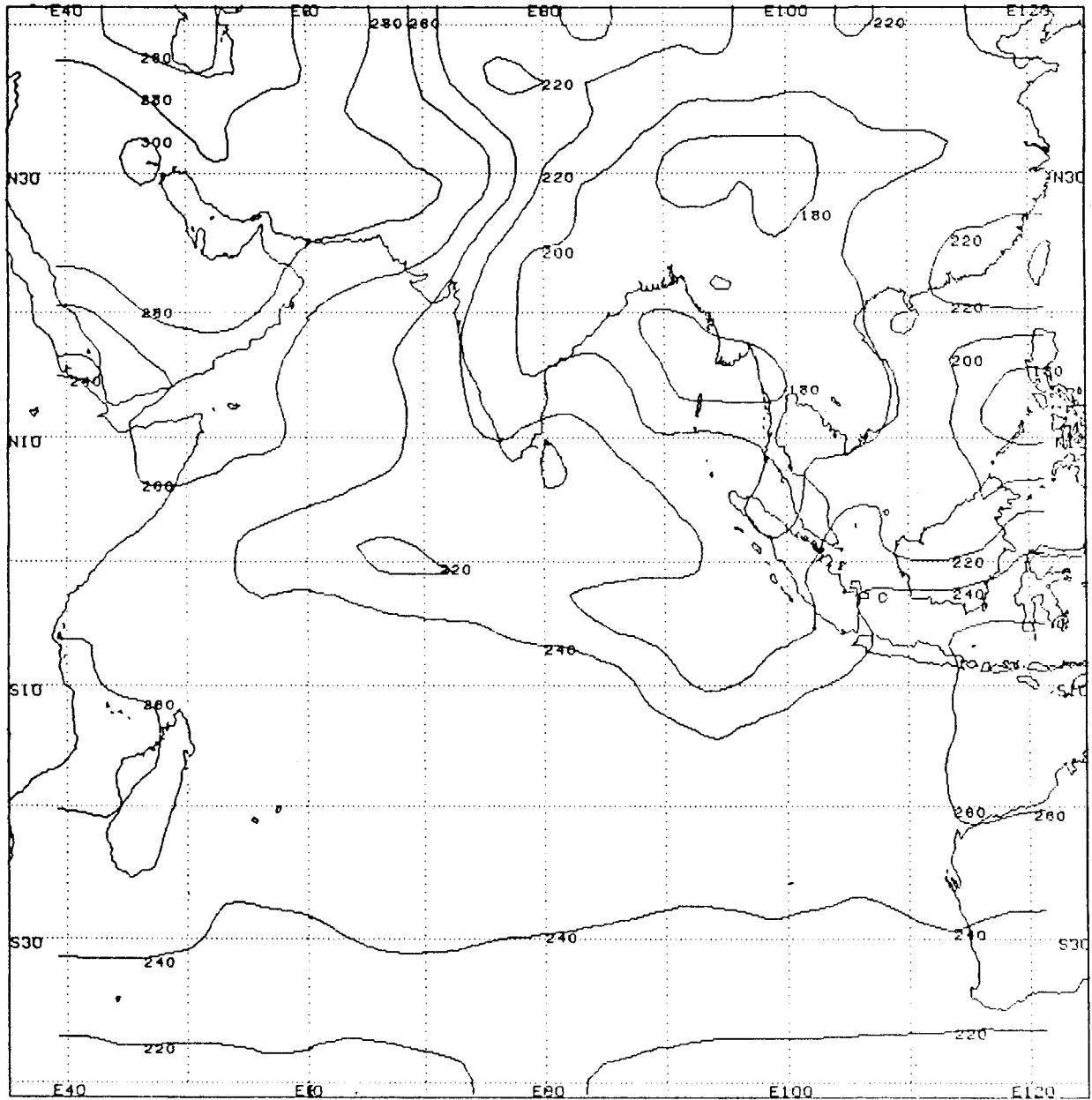


Fig. 5—Monthly mean of outgoing longwave radiation (Wm^{-2}) derived from 3-hourly INSAT data for the monsoon month of August 1993.

ing used by other users requiring meteorological information in near real-time.

INSAT Satellites have a facility for relaying meteorological data recorded by unmanned instruments at remote and inaccessible locations to the central processing system at New Delhi. The INSAT data collection system (DCS) has three components: (i) data collection platforms (DCPs) at the remote sites, (ii) data relay transponder (DRT) on board the satellite, and (iii) facility for receiving the DCP data on ground, and for processing and disseminating it to the users. The

DCP itself consists of (i) meteorological sensors, (ii) signal conditioner, (iii) data conversion, storage and transmission subsystem (DCSTS) and (iv) power supply. There is a provision for 7 analogue sensors and 3 digital sensors. Among the parameters which can be measured are dry bulb temperature, relative humidity, instantaneous wind speed and direction, accumulated rainfall, sunshine duration, and atmospheric pressure. It is not possible to record observations like cloud amount and type, etc. which have to be made visually by an observer. The analogue outputs vary from 0 to

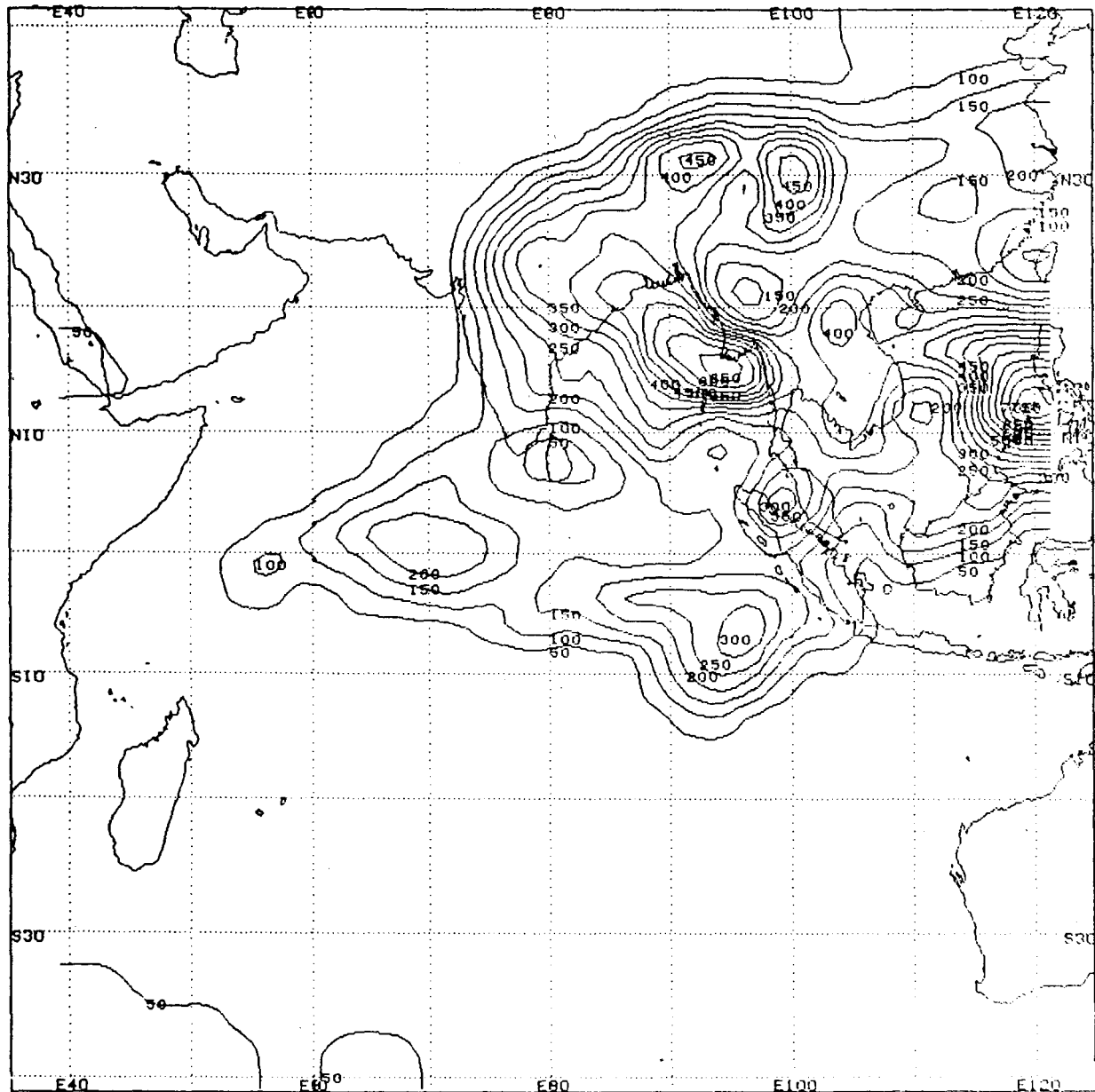


Fig. 6—Monthly mean of large-scale precipitation estimates (mm/month) derived from 3-hourly INSAT data for the monsoon month of August 1993.

5 V depending on the value of the parameter, while the digital sensors count the number of pulses. The DCSTS controls the various operations and transmits the data to the satellite at 402.75 MHz frequency in a burst mode every hour in a pre-assigned 10-min window.

7 INSAT-based disaster warning system

The tropical cyclones which develop over the Bay of Bengal and the Arabian Sea, particularly in the pre-monsoon and post-monsoon months, have a very high destructive potential and lead to

heavy losses of life and property when they cross the coast. The INSAT imaging capability has greatly improved the detection and tracking of the cyclonic storms while they are far out at sea. As they approach the land, they also come within the range of the cyclone detection radars. However, by terrestrial communication links it is difficult to reach public and government officials during such impending disasters so that they can take preventive measures. This is particularly so because the passage of cyclonic storms is usually accompanied by a disruption or a total breakdown of terrestrial

communication links because of dislocation of power supply, waterlogging of cables, uprooting of telephone poles, etc. To bypass difficulties of this nature, the S-band broadcast capability of INSAT has been exploited for an effective and targeted dissemination of cyclone warnings under what has come to be known as the disaster warning system (DWS). The working of the DWS is similar to that of the MDD service described earlier in that the cyclone warning messages are uplinked to INSAT in the C-band and re-broadcast in the S-band. However, the unique feature of the DWS is its ability to activate the receiver sets in the affected regions which can be selectively addressed. Thus weather warnings in local languages pertinent to the area threatened by disaster or under its influence can be issued by the weather forecaster directly to the affected population or concerned authorities.

The DWS transmission consists of the area code in digital form of the receivers to be activated, followed by weather warnings in voice form. This message is multiplexed with TV and other RN carriers for uplink from the INSAT earth station in the C-band. The receiving station receives the signal through a 3.6 m diameter chicken mesh antenna. The DWS receiver consists of a code detector, siren, loud speaker, and power supply. After the code is detected, the siren is sounded for 1 min to draw public attention. Then the audio amplifier gets switched on for the rest 9 min for relaying the warning message through the loud speaker.

The DWS service, which began as an experimental measure in 1986, has been highly effective in north Tamil Nadu and south Andhra Pradesh areas during the cyclones of recent years. Its working and usefulness has been acclaimed by the press, public and relief agencies alike. The network of 100 DWS receivers operative in north Tamil Nadu/south Andhra Pradesh areas are serviced through the Madras earth station. Another 50 receivers have recently been added to the network in West Bengal, Orissa, north Andhra Pradesh and Gujarat coasts, and two more satellite uplinks at Calcutta and Bombay have been provided. Very shortly, the set-up will be further augmented by 100 more receivers, after which the entire coastline of the country will be covered by the DWS scheme.

8 Research applications of satellite data

While the paper has so far summarized the utilization of INSAT data in operational meteorology, it must be mentioned that the availability of

satellite data has triggered a number of research investigations which could not have been attempted or pursued in the absence of such data¹³.

A major thrust area is the derivation of moisture profiles and diabatic heating for physical initialization purposes in NWP models¹⁴. This is being done through the use of OLR, fractional clouding, large-scale precipitation estimates, and similar parameters. The OLR particularly is gaining popularity among researchers because of its availability over a long period and also because it is simple to use. One example of its many applications is in the computation of divergent wind component¹⁵. The intra-seasonal variations of the monsoon, the modes of low-frequency oscillations, movement of the maximum cloud zone, and the southern hemispheric equatorial trough have been the subject of many recent satellite-based investigations¹⁶⁻¹⁹.

Other important applications of satellite data are the study of the core structure of tropical cyclones²⁰, computation of aerosol concentrations in the atmosphere²¹, study of oceanic eddies and gyres²², identification of atmospheric waves of different types and mountain waves, etc.

9 Future scenario

The next two satellites of the INSAT-2 series, viz. INSAT-2C and INSAT-2D, are scheduled for launch in the middle of 1995 and 1996. Unlike their predecessors, these spacecrafts will not be carrying a meteorological component, but they will have a substantially augmented communications payload including three Ku-band transponders. The meteorological instruments will be reinstated on board INSAT-2E, which is likely to be launched in 1997-98 as a replacement for the currently operational INSAT-1D satellite. For the INSAT-2E satellite, it is necessary to arrive at an acceptable compromise among the long-standing demands of meteorologists, spacecraft constraints, and the magnitude of efforts involved in the indigenous development of payloads. It is likely that INSAT-2E will have a 3-channel VHRR with visible, infrared and an additional water vapour band and a 3-channel CCD camera providing 1 km resolution imagery in visible and near infrared wavelengths.

Imaging in the water vapour band (5.7-7.1 μm) will provide a deeper insight into the middle tropospheric circulation as the moisture patterns can be observed and tracked. The 1 km resolution CCD imagery will enhance the meteorologists' capability to isolate the finer features of cloud

systems related to phenomena such as mountain waves, mesoscale developments, overshooting cloud tops, intense convection, etc.

Another significant area of future efforts is the application of remote sensing technology to oceanography²³. The availability of data from satellites of other countries having microwave sensors has demonstrated the utility of such information in the understanding of ocean conditions and the observation of dynamic ocean parameters like surface winds, wave height, etc. If plans towards having an indigenous ocean satellite fructify, the vast amount of ocean data that would become available would have a many spin-off benefits to meteorology, particularly for numerical weather prediction and climate studies.

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