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Satellite meteorology in India: Its beginning, growth and future

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सार – सैटेलाइट भारत में उपग्रह मौसम विज्ञान की शुरूआत 1965 में हुई। इसकी शुरूआत मुंबई में तब हुई जब यू.एस. उपग्रह से बिम्ब चित्र प्राप्त करने की सुविधा पहली बार मिली। बाद में इस प्रकार के स्टेशन और भी स्थापित किए गए। फील्ड मौसम विज्ञानियों ने उपग्रह बिम्ब चित्रों का उपयोग अपने सिनॉप्टिक चार्टों के वैल्यू एडिशन के लिए किया। लेकिन भारत में उपग्रह मौसम विज्ञान वास्तव में, 1982 में अस्तित्व में तब आया जब भारत ने अपने उपग्रह इनसैट-1ए को लाँच किया। इनसैट श्रृंखलाओं में बाद में अनेक सैटलाइटों के लाँच होने से उपग्रह मौसम विज्ञान सक्षमता और अनुप्रयोग के क्षेत्र में और अधिक सुदृढ़ हुआ। इनसैट-3D अब तक भारत का सबसे अधिक परिष्कृत मौसम विज्ञान उपग्रह है जिसमें एडवांस इमेजर के साथ-साथ सांउडर भी है। उसके डाटा से प्रचालनात्मक रूप से परिमाणात्मक उत्पाद प्रचालानात्मक रूप से प्राप्त किए जा रहे हैं। भारत में मौसम के पूर्वानुमान में अनवरत सटीकता के साथ सुधारने में उपग्रह से प्राप्त जानकारियाँ सहायक सिद्ध हुई हैं और जान-हानि में कमी आई है, विशेषकर उष्णकटिबंधीय चक्रवातों जैसी प्राकृतिक घटनाओं के मामले में। आगे आने वाले समय में उपग्रहों के नए कक्षों और संवेदकों के साथ आने की संभावना है और ये भूमंडलीय वायुमंडल और महासागरों को नए परिप्रेक्ष्य प्रदान करेंगे।

ABSTRACT. Satellite meteorology had its beginning in India in 1965 when the first facility to receive images from U.S. meteorological satellites was established in Mumbai. More such stations were set up later and field meteorologists used satellite images as value addition to their synoptic charts. But satellite meteorology truly came of age in India in 1982 with the launch of India's own satellite INSAT-1A. With the launch of many subsequent satellites in the INSAT series, satellite meteorology has grown from strength to strength in terms of capability and application. INSAT-3D is by far India's most sophisticated meteorological satellite having an advanced imager as well as a sounder. A host of quantitative products are being derived operationally from its data. Satellite inputs have helped to improve steadily the accuracy of weather forecasts in India and thereby reduce the loss of life associated with catastrophic events particularly tropical cyclones. Satellites of the future are likely to have innovative orbits and sensors providing new perspectives of the global atmosphere and oceans.

Key words – Satellite INSAT-1A, INSAT-3D.

1. Beginning

On 1 April 1960, the United States launched the world's first weather satellite, named TIROS-1 (Television Infrared Observation Satellite) and with that was born a new branch of meteorology that came to be known as satellite meteorology. In the following years, several satellites were launched in the TIROS series, each more advanced than the previous one. In 1964, a new capability called APT (Automatic Picture Transmission) was introduced on the TIROS-8 satellite. This enabled the reception of cloud imagery from the polar-orbiting satellites at ground stations located in their field of view with simple and inexpensive equipment. The India Meteorological Department (IMD) established an APT station in Mumbai in 1965, giving meteorologists a direct access to the cloud imagery of the Indian subcontinent and the adjoining seas, twice a day. This was the beginning of satellite meteorology in India.

In the seventies, six more APT stations were set up by IMD, providing satellite inputs to the field forecasters routinely. They were able to supplement their limited synoptic data over the oceans and remote land areas with inferences drawn from satellite imagery. APT images used to be printed on facsimile paper and had coarse resolution, but they helped monitor tropical cyclones on the open seas (Sikka, 1971a&b), spawned research on the monsoon (Sikka and Gadgil, 1980) and improved the understanding of western disturbances (Agnihotri and Singh, 1982), mountain waves (De, 1970) and the tropical easterly jet (Singh and Hem Raj, 1982).

2. India's meteorological satellite programme

In the mid-seventies, India embarked on its own space programme. Aryabhata was India's first satellite. It was completely designed and fabricated in India but launched by a Soviet rocket from the Soviet Union on 19 April, 1975. It was an experimental satellite with payloads for astronomy and solar physics applications. It was followed in 1979 and 1981 by the Bhaskara-I and Bhaskara-II satellites respectively, which were meant for earth observations through TV cameras and microwave radiometers. Thereafter, India's space programme really made a quantum leap when it decided to develop and execute an ambitious national meteorological and communications satellite programme.

The Indian National Satellite (INSAT) system was designed with the aim of introducing satellite-based services in as many fields as possible in the quickest possible time. The multi-purpose concept of INSAT led to the realization of the full potential of geostationary satellites in one stroke. Thus while other countries had dedicated satellites for different purposes, INSAT ushered in a new era in communications, television and radio broadcasting and meteorology all at the same time. Satellite meteorology may be said to have truly come of age in India with the launch of the INSAT-1A satellite on 10th April, 1982.

The INSAT system has had a phenomenal evolution (Table 1). The first four satellites in the INSAT-1 series were only designed by India but fabricated in the U.S. and launched by foreign rockets. The INSAT-2 series of satellites and INSAT-3A were, however, fabricated indigenously by the Indian Space Research Organisation (ISRO). The latest satellite INSAT-3DR, was not only entirely made in India but also launched from India with an Indian geostationary satellite launch vehicle.

While the INSAT-1 series consisted of multi-purpose satellites, some of the later satellites have not had any meteorological component. On the other hand, METSAT, launched in 2002 and later renamed Kalpana-1, was exclusively dedicated to meteorological imaging. INSAT-3D, which was launched in 2013, was the first Indian satellite to carry a sounder. It is primarily a meteorological satellite and has no communication transponders except for data relay and satellite-aided search and rescue.

The capability of the imaging radiometers carried by INSAT has increased with successive spacecrafts. INSAT-1A to -1D and INSAT-2A and -2B carried a 2-channel Very High Resolution Radiometer (VHRR). The two channels were visible (0.55-0.75 μ) and thermal infra-red (10.5-12.5 μ). Their resolutions at the sub-satellite point were 2.75 and 11 km respectively for INSAT-1A to -1D and 2 and 8 km respectively for INSAT-2A and -2B. The INSAT-2E satellite, for the first time carried a 3-channel VHRR with an additional water vapour channel (5.7-7.1 μ) having a ground resolution of 8 km. The design of the VHRR systems on INSAT-3A and Kalpana 1 were similar to that of INSAT-2E. INSAT-2E and 3A also carried CCD cameras for daytime imaging at a higher 1 km resolution.

INSAT-3D, launched in 2013, is by far the most advanced Indian meteorological satellite. It has a 6-channel Imager and a 19-channel Atmospheric Sounder. The INSAT-3D Imager is an improved design of the VHRR instrument flown on the Kalpana-1 and INSAT-3A missions. It is capable of generating the images of the earth in six wavelength bands significant for meteorological observations, namely, visible, shortwave infrared, middle infrared, water vapour and two bands in thermal infrared regions, offering an improved 1 km resolution in the visible. INSAT-3D also carries a newly developed 19-channel sounder, which is the first such payload to be flown on an Indian satellite mission. The sounder has 18 narrow spectral channels in shortwave infrared, middle infrared and thermal infrared regions and one channel in the visible region. The ground resolution at nadir is nominally 10 × 10 km for all the 19 channels. INSAT-3DR, launched in 2016, serves as a full on-orbit backup for INSAT-3D.

3. Spacecraft design and orbits

The INSAT concept of having a satellite that would serve India's needs of telecommunications as well as meteorology, placed a unique demand on its design. At that time, meteorological satellites of the U. S. and other countries were all spin-stabilized and the rotation of the spacecraft helped the radiometer to scan the earth. As INSAT required its communications antennas to be constantly pointed towards the earth, the spacecraft had instead to be 3-axis stabilized. The INSAT radiometer was designed accordingly to scan the earth in a zig-zag manner with the scan direction changing alternately from east-west to west-east.

Kelkar *et al.* (1980) developed the new methodology for the navigation and gridding of images scanned by the unique INSAT VHRR. Here, the term navigation is used in its conventional sense and implies the use of landmarks for determination and prediction of orbit and attitude. By this process, it is possible to relate points on the earth, defined by latitude and longitude, to points on the image, given by line and element numbers and *vice versa*. By gridding is meant the superposition of grid points, political boundaries or latitude-longitude lines on the navigated

TABLE 1

Chronology of the Evolution of the INSAT Meteorological Programme

Name of satellite	Launch date	Meteorological payload	Channel	Spectral range (μ)	Resolution (km)
INSAT-1A	10 April, 1982	VHRR (Very High Resolution Radiometer)			
INSAT-1B	30 August, 1983	VHRR	VIS	0.55-0.75	2.75
INSAT-1C	21 July, 1988	VHRR	IR	10.5-12.5	11
INSAT-1D	12 June, 1990	VHRR			
INSAT-2A	10 July, 1992	VHRR	VIS	0.55-0.75	2
INSAT-2B	23 July, 1993	VHRR	IR	10.5-12.5	8
INSAT-2E	3 April, 1999		VIS	0.55-0.75	2
		VHRR	IR	10.5-12.5	8
			WV	5.7-7.1	8
		CCD	VIS	0.62-0.68	1
		Charge	NIR	0.77-0.86	1
		Coupled Device Camera	SWIR	1.55-1.69	1
Metsat/ Kalpana-1	12 September, 2002	VHRR	VIS	0.55-0.75	2
			IR	10.5-12.5	8
			WV	5.7-7.1	8
INSAT-3A	10 April, 2003	VHRR	VIS	0.55-0.75	2
			IR	10.5-12.5	8
			WV	5.7-7.1	8
		CCD	VIS	0.62-0.68	1
			NIR	0.77-0.86	1
			SWIR	1.55-1.69	1
INSAT-3D	26 July, 2013	VHRR	VIS	0.55-0.75	1
			SWIR	1.55-1.70	1
INSAT-3 DR	8 September, 2017		MWIR	3.80-4.00	4
			WV	6.50-7.10	8
			TIR	10.3-11.3	4
			TIR	11.5-12.5	4
		Sounder	SWIR	3.67-4.59	10
				6 channels	
			MWIR	6.38-11.33	10
				5 channels	
			LWIR	11.66-14.85	10
				7 channels	
			VIS	0.67-0.72	10
				1 channel	

Notes:

1. Satellites in the INSAT-1 series were built in the U.S. as per Indian design and launched from abroad.
2. Satellites in the INSAT-2 series were built indigenously but launched from abroad.
3. INSAT-2E was the first geostationary meteorological satellite to have a CCD payload.
4. Metsat, India's first exclusive meteorological satellite, was launched from Sriharikota by ISRO's PSLV-C4.
5. Metsat was renamed Kalpana-1 on 5th February, 2003 in memory of Dr Kalpana Chawla, the India-born American astronaut who died in the U.S. space shuttle Columbia disaster on 1st February, 2003.

image. If geostationary satellite images produced at 30 min interval are viewed in quick succession, the landmarks should appear to be stationary. The removal of apparent earth motion from an animated sequence of images is called registration. Briefly speaking, the navigation process involves transformations among five different coordinate systems: (a) inertial system, having its origin at the centre of the dynamical earth and the *x*-axis pointing to the vernal equinox and *z*-axis normal to the equatorial plane, (b) rotating system, similar to the inertial system but with the *z*-axis passing through the Greenwich meridian, (c) local vertical system, having its origin at the centre of the satellite, (d) body-centred system, defined in terms of the pitch, roll and yaw angles and (e) picture frame system, defined in terms of line and element number.

By 1980, meteorological satellites had improved progressively from random over-passes to sun-synchronized visits and satellite operating agencies had settled down for a combination of polar orbiting and geostationary orbits. At this time, Kelkar *et al.* (1982) proposed an entirely different and innovative concept of a non-geostationary meteorological satellite in a low-elevation tropical orbit that would provide repetitive coverage of the earth's tropical belt, just as the polar orbiting satellites covered the polar regions. However, this concept was far ahead of the times and technology was not ready then to support it. Eventually, it did come into reality with the launch of the Tropical Rainfall Measuring Mission (TRMM) satellite in 1997 in a 35° N-35° S orbit at 350 km altitude (Kummerow *et al*., 2000). Megha-Tropiques was another satellite that was launched in 2011 in a tropical orbit as a joint India-France mission. Its 20° N-20° S orbit at 867 km altitude was ideally suited to capture the weak radiances from its several microwave sensors and to monitor the diurnal energy and water cycles of the tropics (Gohil *et al*., 2013).

4. Ground data processing facilities

The ground equipment required to receive APT images was simple and inexpensive. However, in order to process the real-time VHRR data stream from INSAT-1 satellites, a major data processing facility had to be set up by IMD in 1982. Named as the Meteorological Data Utilization Centre (MDUC), it was housed in a newly constructed six-storied building in the IMD Complex on Lodi Road, New Delhi. The VHRR data was received by the Network Operations Control Centre at Sikandrabad located about 70 km from New Delhi, from where it was transmitted through a dedicated microwave link to MDUC.

The MDUC system was configured around a group of six computers, two PDP 11/70s and four PDP 11/34s. The hardware was 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 of digital data and (*v*) near real-time transmission of analogue imagery to 20 field locations of IMD where Secondary Data Utilization Centres (SDUCs) were established.

While the primary functions of MDUC continued to be carried on operationally, a considerable amount of software development was done in-house in order to fully exploit the system capabilities towards the derivation of quantitative meteorological products from the INSAT VHRR data. In 1992, therefore, a new computer system named the INSAT Meteorological Data Processing System (IMDPS) was established by IMD at New Delhi to replace MDUC. The new system had vastly enhanced computing power and resources including its own co-located earth station to receive the INSAT data directly (Kelkar, 1994). The new IMDPS became functional in synchronization with the launch of the second generation INSAT-2A satellite.

IMDPS was built upon eight VAX 3400 computers into an advanced distributed architecture that assured redundancy, flexibility and optimum functionality. It was capable of processing real-time data from INSAT-1, INSAT-2 and NOAA satellites simultaneously. There were four interactive work stations and thermal recorders that printed images without the need of photographic processing. The system was directly connected to the Global Telecommunications System (GTS) for reception and transmission of coded meteorological data.

INSAT-3D, launched on 26 July, 2013, is a satellite that is fully dedicated to meteorological applications. It has a radiometer that is very advanced compared to previous VHRRs and it carries a 19-channel sounder that its predecessor satellites did not have at all. In order to process the real-time data from INSAT-3D a new data processing system was established at IMD, New Delhi, in readiness for the launch. A backup on-orbit satellite, INSAT-3DR, was launched on 8 September 2017 and the system is powerful enough to process the data from both INSAT-3D satellites simultaneously as also the previous satellites, Kalpana-1 and INSAT-3A, which are still in operation. The system for end-to-end reception and processing of INSAT-3D data and derivation of meteorological parameters was indigenously designed and developed by the Indian Space Research Organization (ISRO) and installed and commissioned at IMD, New Delhi. There is also a mirror site operating at the Space Applications Centre, Bopal, Ahmedabad.

The main architecture of the new IMDPS system consists of Data Acquisition and Quick Look Display System (DAQLS), Data Reception System (DRS), Data Processing System (DPS), Data Storage System (DSS), Network Clients System (NCS) and Satellite Images Display System (SIDS). The DPS consists of five Dell PE6850 servers, a Dell PE 2950 server and two HP XW6400 servers. All the raw data from the DRS is processed in these DPS servers and the output products are generated. After processing, the data is transferred to an external system for storage.

5. Satellite imagery

As satellite images started becoming available to meteorologists around the world in the early sixties, the skills of satellite image interpretation developed very rapidly. Until then, knowledge about clouds had been documented into cloud atlases on the basis of what had been observed from the ground or aircrafts. The view from satellite altitudes was, however, completely different and clouds seen by satellites had to be interpreted in an altogether different manner.

Most of the early interpretation schemes used six characteristics to identify clouds in satellite images, which were:

(*i*) Cloud brightness relating particularly to the depth and composition,

(*ii*) Texture - whether smooth, fibrous, opaque, or mottled,

(*iii*) Form of elements - whether regular or irregular,

(*iv*) Pattern of elements - associated with topography, air flow, vertical and horizontal wind shear,

(*v*) Size - both of the patterns and the individual elements and

(*vi*) Vertical structure - for example shadows thrown below.

In addition, cloud classification schemes were developed on the basis of cloud patterns:

(1) Vertical features:

(*i*) Circular or spiral bands,

(*ii*) Crescent-shaped or comma-shaped cloud masses,

(*iii*) Quasi-circular cloud masses and

(*iv*) Curved or linear bands.

(2) Major cloud bands, in which the length is much greater than the width,

(3) General features:

(*i*) Minor bands like cloud streets, jet stream bands, lee waves,

(*ii*) Cumuliform features, polygonal cells and

(*iii*) Stratiform features, fog areas.

Nowadays of course, most of the picture interpretation work is carried out on image processing computers and various interpretation aids are available to the analysts.

In visible channel imagery, clouds which appear brighter are those which have a large albedo because of great depth, high cloud water/ice content and small cloud-droplet size. Clouds which appear gray are those having shallow depth, low cloud water/ice content and large cloud droplet size. Thus vertically grown cumulonimbus (Cb) clouds appear most prominently images whereas thin cirrus cannot be clearly seen. Small cumulus clouds usually take the form of open hexagonal cells while stratocumulus clouds appear as closed cells. Low level stratus clouds or areas covered by fog can be identified by their uniform brightness and sharp boundaries. Tall Cb cloud tops sometimes throw shadows on lower cloud layers.

Infra-red channel imagery has a very important advantage that it is available at any time unlike visible channel imagery which is available only in daylight hours. Secondly, infra-red radiances are a measure of the temperature of the radiating surface. Clouds which appear white are those which have cold cloud top temperatures such as Cb and cirrus clouds. A mature Cb cloud can be further recognized by its sharp edge on the windward side and a fuzzy edge on the other side resulting from the cirrus plume. The plume may get blown downwind over several hundred kilometres and give an indirect indication of the upper level wind speed and direction.

Water vapour channel imagery is also available at all times. In the water vapour channel, the stronger the absorption, the higher is the originating level of the emission that ultimately reaches the satellite. As the atmospheric moisture content decreases with height, the main contribution to the radiance received by the satellite comes from levels in the lower and middle and troposphere. So the brighter regions are those with high

TABLE 2

Space and time scales of atmospheric phenomena

Classification	Examples	Space scale	Time scale
Global or planetary scale	Long waves, subtropical anticyclones, tropical easterly waves	5000-10000 km	Days to a week or longer
Synoptic scale	Fronts, extratropical cyclones, anticyclones, cloud clusters, monsoon depressions, tropical cyclones	500-5000 km	Days to a week
Mesoscale	Lee waves, gravity waves, squall lines, land and sea breeze, mesoscale convective elements	20-500 km	Hours to days
Convective scale or small scale	Thunderstorms, tornadoes, convective cells	1-20 km	Minutes to hours
Microscale	Boundary layer eddies, dust devils	100 m - 1 km	Seconds to minutes

upper tropospheric humidity and the dark regions are those where the upper troposphere is very dry.

Besides the global synoptic network, meteorological satellite imagery provides a powerful means of monitoring the state of the atmosphere. Images received from geostationary and orbiting satellites reveal directly or indirectly the presence of the wide spectrum of atmospheric phenomena (Table 2), just at a glance. The value addition of satellite imagery is the highest over the vast expanse of the world's oceans and inhospitable regions where conventional observations are not available.

INSAT-1A had a short-lived mission but INSAT-1B launched in 1984, had a long and productive life and the use of its imagery soon became an integral part of IMD's operational forecasting system. The imagery was being disseminated to IMD's field offices in near real-time where also it was used as a valuable input to local and regional forecasting. With successive satellites like INSAT-1D, -2A, -2B, -3A and -3D, satellite imagery became more and more sophisticated and is now used extensively in operational weather forecasting.

All INSAT satellites having been of the geostationary type, the imagery is basically used in three ways: (*i*) to watch the *in situ* growth of weather phenomena like cumulonimbus clouds, fog, etc., (*ii*) to monitor the movement of migratory systems like tropical cyclones, western disturbances or monsoon depressions and (*iii*) to help identify or locate primary synoptic elements such as surface lows, troughs and ridges, jet streams and regions of intense convection. A major impact made by INSAT imagery has been in the area of tropical cyclone intensity and track forecasting (Kelkar, 1997). INSAT pictures have been particularly useful in monitoring the advance of the southwest monsoon into Kerala. The manner in which INSAT imagery can be used in day to day weather forecasting work has been documented in the form of a guide book by Kelkar and Yadav (1991).

5.1. *Tropical cyclones*

With the launch of several geostationary satellites by the U.S., Europe, Japan and India, tropical cyclones came under a global round-the-clock surveillance right from their genesis up to landfall. Satellite imagery is most useful at all stages of development of tropical cyclones, for first detecting their formation far out at sea, then following their movement, determining their intensity and observing changes in their characteristics. In 1975, the Dvorak technique for intensity estimation of tropical cyclones from visible satellite imagery available once a day gained widespread acceptance. The scope of the technique was later enlarged to include infra-red imagery also. Dvorak's technique is basically a pattern recognition process which assumes that certain characteristics or features of the cloud organization are indicators of the intensity. By matching the current image with established patterns, the storm intensity can be estimated.

A typical satellite view of a fully mature tropical cyclone has an eye at the centre, which is a roughly circular area characterized by fair weather, comparatively light winds, lowest surface pressure and warmest temperatures aloft. Its diameter is commonly 30-60 km. The eye is surrounded by the eyewall which is a ring of deep convection. It is the area of highest surface winds in the tropical cyclone. The eye is composed of air that is slowly sinking while the eyewall has a net upward flow as a result of many strong updrafts and downdrafts. The high temperatures of the eye are due to compressional warming of the subsiding air.

The real impact of tropical cyclones depends on several factors. While the scale of destruction of property

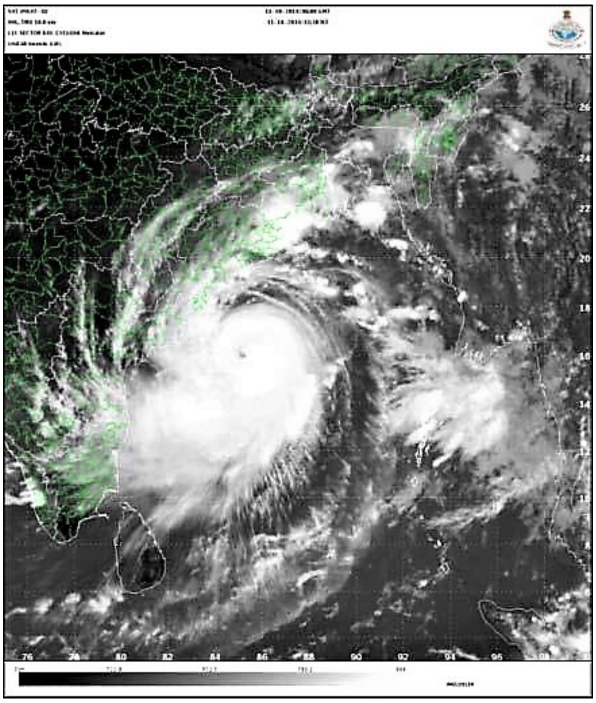

Fig. 1. INSAT-3D infrared image of 11 October, 2014 showing cyclone Hud Hud prior to landfall (*Source*: IMD web site)

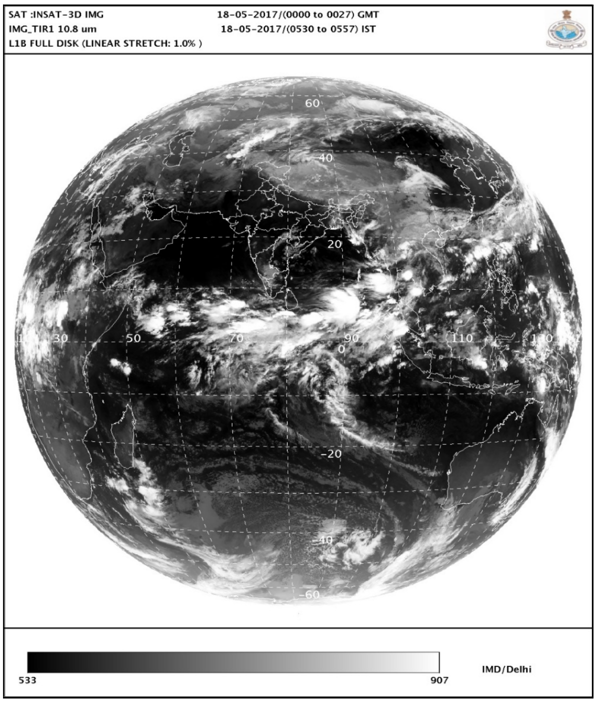

Fig. 3. INSAT-3D infrared image of 18 May, 2017 (*Source*: IMD web site)

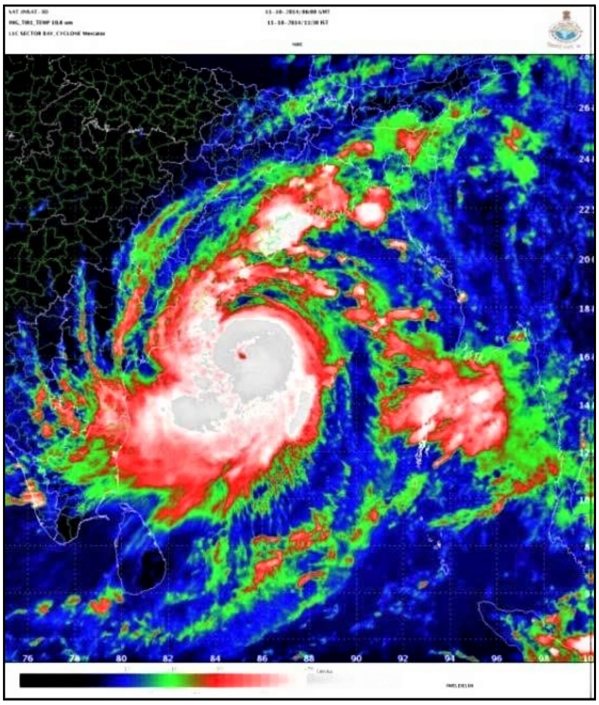

Fig. 2. INSAT-3D Pseudocolour image of 11 October, 2014 showing cyclone Hud Hud prior to landfall (*Source*: IMD web site)

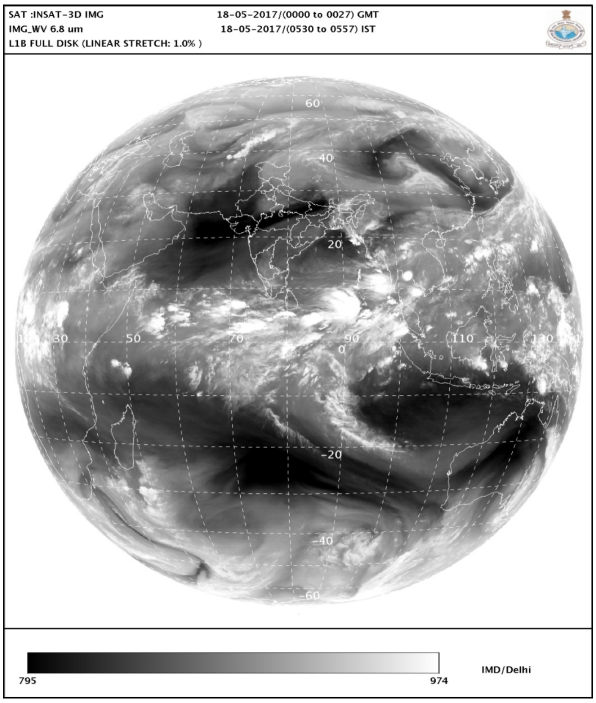

Fig. 4. INSAT-3D water vapour image of 18 May, 2017 (*Source*: IMD web site)

depends upon the intensity of the system and the associated wind speeds, rainfall amounts and rain rates, the loss of human life is more often caused by the storm surge and inundation. While the winds and rainfall are

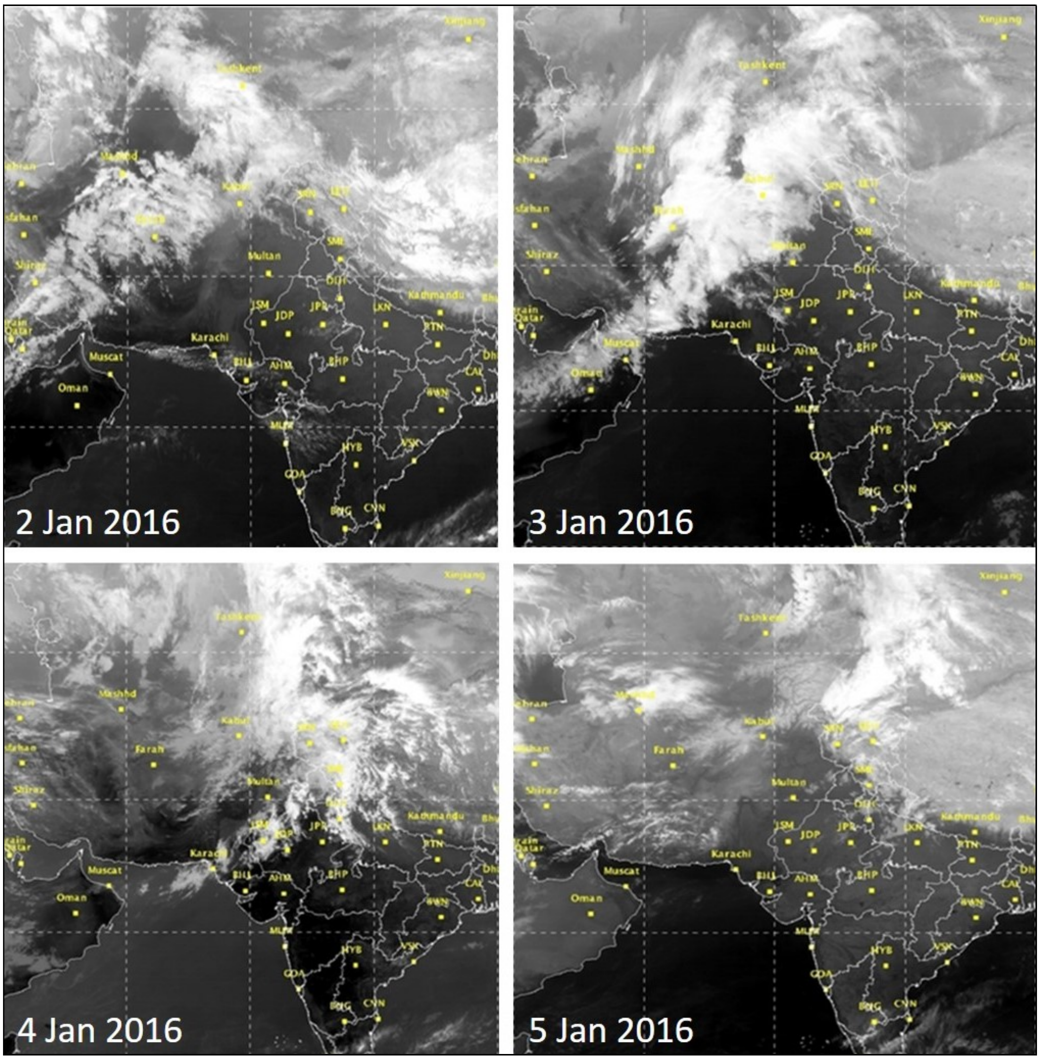

Fig. 5. Daily sequence of INSAT-3D infrared images for 2 to 5 January, 2016 showing the passage of a western disturbance over north India (*Source*: IMD web site)

related to the degree of organization of the cyclonic system, the storm surge depends to a great extent on the nature of the coastline at the place of landfall, the slope of the sea bed and the land use pattern. However, satellite monitoring is decidedly the most crucial factor in increasing preparedness and thereby reducing the loss of life caused by tropical cyclones.

A case in point was the Hud Hud cyclone of October 2014 that originated as a low level circulation over the Tenasserim coast on 6 October, 2014. It developed into a vortex over the north Andaman Sea and continued to intensify over the Bay of Bengal, moving towards the Andhra Pradesh coast. On 10 October its intensity was T4.0 with organized spiral bands and a well-defined central dense overcast. The eye was clearly seen on 11 October and Hud Hud was a T5.0 storm before making its landfall on 12 October (Figs. 1&2). In a major disaster mitigation exercise, as many as 1.35 lakh people were evacuated prior to landfall and the loss of life was limited to 46.

5.2. *Monsoons*

South of Kerala is the expanse of the Indian Ocean over which there are no surface observatories except over a few islands. INSAT imagery therefore provides the best means of monitoring the developments over the region. The normal date of the onset of monsoon over Kerala is 1 June with a standard deviation of a week. However, the monsoon onset in south Bay of Bengal, the Andaman Sea and Myanmar takes place in May itself. The INSAT images of 18th May, 2017 show clearly the strong buildup of the monsoon clouds and the moisture influx over peninsular India ahead of the monsoon (Figs. 3&4). As the southwest further advances over the country, establishes itself and then retreats over the 4-month monsoon season, INSAT imagery continues to guide forecasters and help predict heavy rainfall areas, flash floods and wet and dry spells.

5.3. *Winter weather*

The winter-time migratory systems enter India from a westerly direction and are therefore referred as western disturbances or western depressions (WDs), depending upon their intensity. They bring the much-needed winter precipitation over north and northwest India after the southwest monsoon has withdrawn. The stronger WDs also produce snowfall in the higher mountain regions of Jammu and Kashmir, Himachal Pradesh and Uttaranchal and may trigger cold waves that penetrate even into central and more southern parts of India. Because of the lack of data and the shallowness of the disturbances, WDs may not always show up clearly in synoptic weather charts except in the case of stronger systems. Satellite cloud imageries are therefore a valuable source of information on the origin and movement of western disturbances. When a series of satellite images is examined, cloud masses are seen to move from west to east across north India. Some of them develop into extra-tropical depressions and they display an organized comma-shaped clouding with a banded structure and vortex. Fig. 5 is a sequence of daily INSAT-3D images from 2 to 5 January, 2016 which vividly show the approach of a western disturbance towards India, its gradual movement and dissipation. Srinagar and the Kashmir valley received their first snowfall of the season because of this system.

6. Quantitative product derivation

While cloud imagery can reveal a lot of information at a glance, it is further possible to use the satellite-measured radiances to indirectly estimate several atmosphere, ocean and land parameters from either physical considerations or by developing suitable statistical techniques. Satellite retrievals afford two distinct advantages over *in situ* measurements in that the oceans can be covered very well and that fresh retrievals can be made with every satellite pass.

Cloud Motion Wind Vectors (CMV), Outgoing Longwave Radiation (OLR) and Quantitative Precipitation Estimation (QPE), were the earliest quantitative products derived operationally, starting with INSAT-1B. They continue to be derived with the INSAT-3D imager data albeit with more robust algorithms than before. In addition, with the availability of the new MIR channel and the split TIR-1 and TIR-2 channels, a host of new quantitative products are now being generated with the INSAT-3D imager data operationally. These are Water Vapour Wind Vector, Quantitative Precipitation Index, INSAT Multi-Spectral Rainfall Algorithm, Hydro-Estimator, Upper Tropospheric Humidity, Cloud Mask, Sea Surface Temperature, Aerosol Optical Depth, Snow Cover, Fog, Fire and Smoke.

Additionally, several geophysical parameters are being estimated from INSAT-3D sounder data. The Temperature and Humidity Profiles are derived operationally from sounder channels 1-18 and Ozone from sounder channel 19. Using these temperature and humidity profiles, the following parameters are derived operationally: Geo-potential Height, Layer Precipitable Water, Total Precipitable Water, Lifted Index, Dry Microburst Index, Maximum Vertical Theta-E Differential profiles and Wind Index. Complete details are available in the INSAT-3D Products Catalogue (IMD, 2014).

7. Cloud motion winds

The basic principle of extraction of winds from satellite imagery is essentially simple. A cloud is selected in a geostationary satellite image and is identified in a successive image. The cloud displacement is measured and divided by the time elapsed between images, usually 30 minutes, to get the wind speed and the direction is obtained from the geometric orientation of the displacement vector. The derived Cloud Motion Wind (CMW) has to be assigned to a proper height and this is usually done with reference to the cloud top temperature.

All types of imagery can be used for CMW extraction, but they all have their relative advantages and disadvantages. Visible images have higher resolution compared to other channels and the cloud features are sharply defined. The low clouds and thunderstorms are predominant but their brightness changes with time. In infrared images, the resolution is not as good and the cloud features are not sharply defined. High clouds mask the middle and lower clouds. The cloud top temperature may change during the derivation process if the cloud grows vertically. In water vapour channel images, large-scale moisture patterns can be tracked, but these are mainly in the middle troposphere.

One of the difficult parts of the CMW derivation is the assignment of an appropriate height to the vector. This is generally done by considering the cloud top temperature and by applying a vertical temperature profile. Other

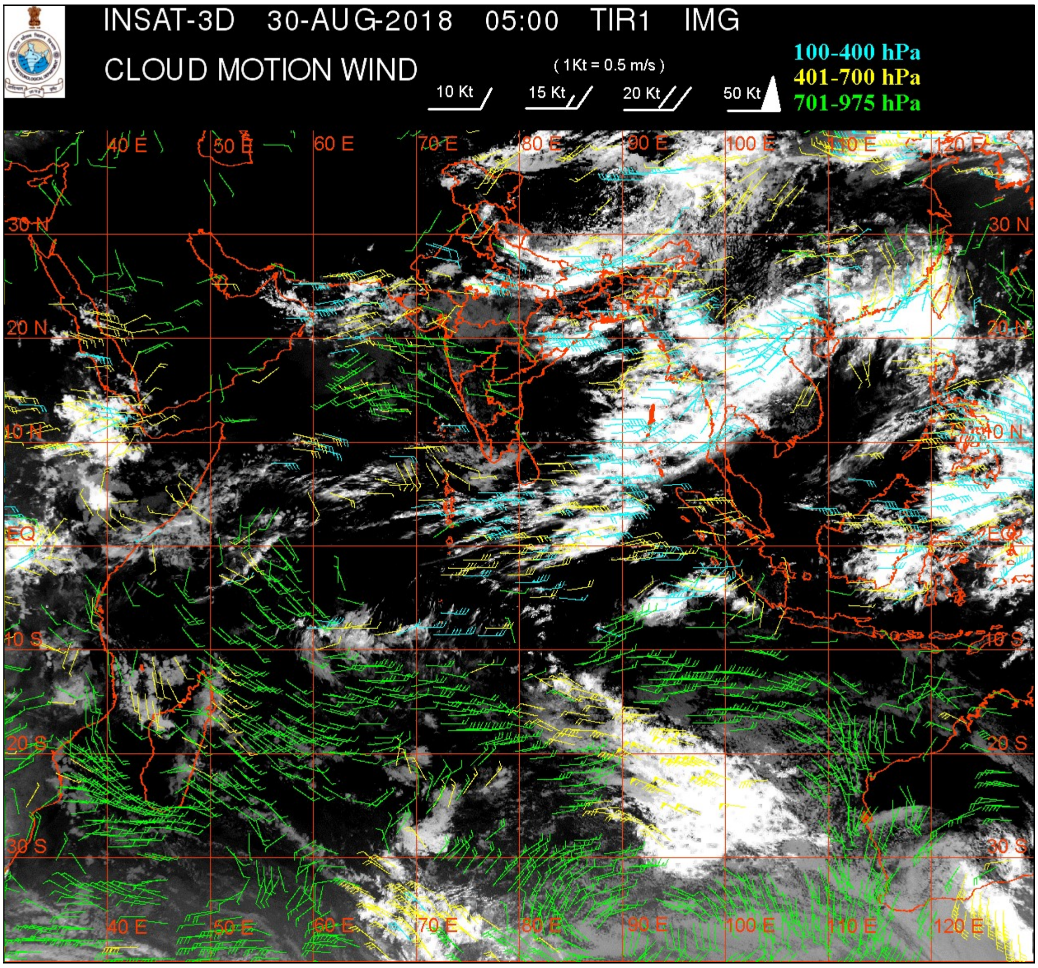

Fig. 6. Cloud motions winds derived from INSAT-3D on 30TH August, 2018 (*Source*: IMD web site)

difficulties arise from the fact that the target pattern may consist of a mixture of clouds at different levels or the target cloud could also be gaining height or dissipating. In case of low level cumulus clouds seen more in visible images, the CMW usually corresponds to the cloud base at 900 or 850 hPa. Middle level clouds are still more difficult to handle. The assumption that a cloud is drifting with the prevalent wind may itself be invalid under certain conditions, for example over mountains. Therefore, all cloud movements cannot be assumed as being wind-driven. Quality control is therefore a vital part of the operational CMW extraction process.

The extraction of cloud motion winds using INSAT-1B data commenced in 1984 (Kelkar and Khanna, 1986). Visible channel data was used for the displacement computation and infra-red channel temperature was used for the height assignment. Hence, winds could be derived only during daytime. The methodology underwent several refinements later with the launch of INSAT-2A which had a better resolution and the establishment of powerful ground processing systems (Kelkar *et al*., 1993; Prasad, 1990).

With the launch of INSAT-3D and the availability of a 6-channel imager with high resolution, a variety of cloud motion winds are now being extracted operationally. These products are of an excellent quality and are being shared globally. Visible, thermal infrared and water vapour channel data are being used individually and in combination to derive low level, medium level and high level winds over the INSAT disc. Fig. 6 shows an INSAT-3D cloud motion wind product for 30 August 2018, typical of the southwest monsoon situation. It clearly shows the low level cross-equatorial flow, the monsoon southwesterlies over the Arabian Sea and the high level easterly jet, which are all characteristic features of the monsoon.

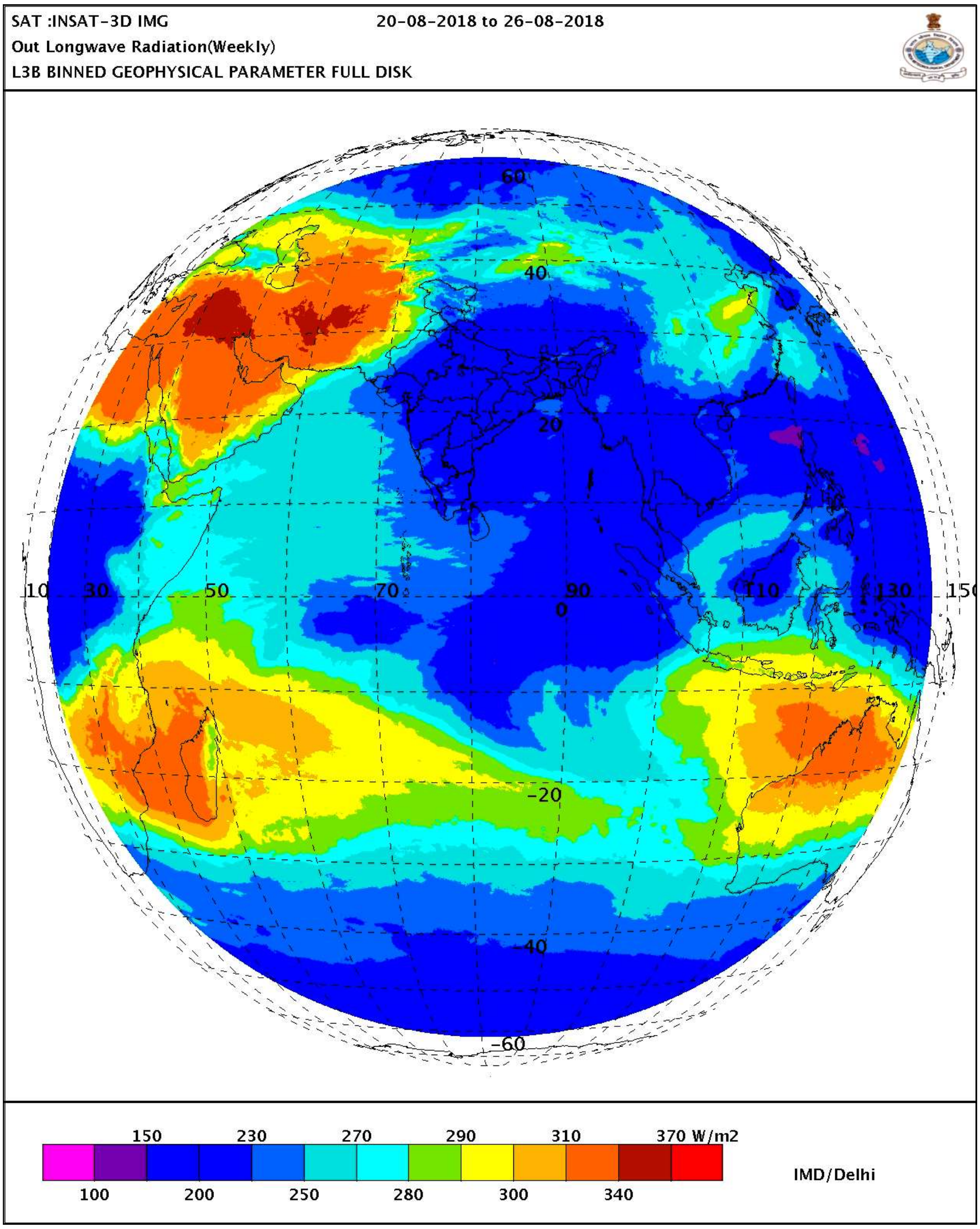

Fig. 7. OLR derived from INSAT-3D for the week 20 to 26 August, 2018 (*Source*: IMD web site)

8. Outgoing longwave radiation

The Outgoing Longwave Radiation (OLR) at the top of the atmosphere is an important component of the radiation budget of the earth-atmosphere system. However, in recent years satellite-derived OLR has also been found useful as a proxy for other meteorological parameters which cannot otherwise be observed globally. In the process of derivation of OLR the minor variations in cloudiness get averaged out and the OLR values can be plotted as a field and subjected to a spatial and temporal analysis which is not possible with simple cloud imagery. Most important is the strong relationship that has been found to exist between OLR and convective activity and large-scale precipitation over the globe. Low OLR usually indicates cold surface temperatures or presence of clouds, while high OLR indicates warm surface temperatures and absence of convection. The Inter-Tropical Convergence

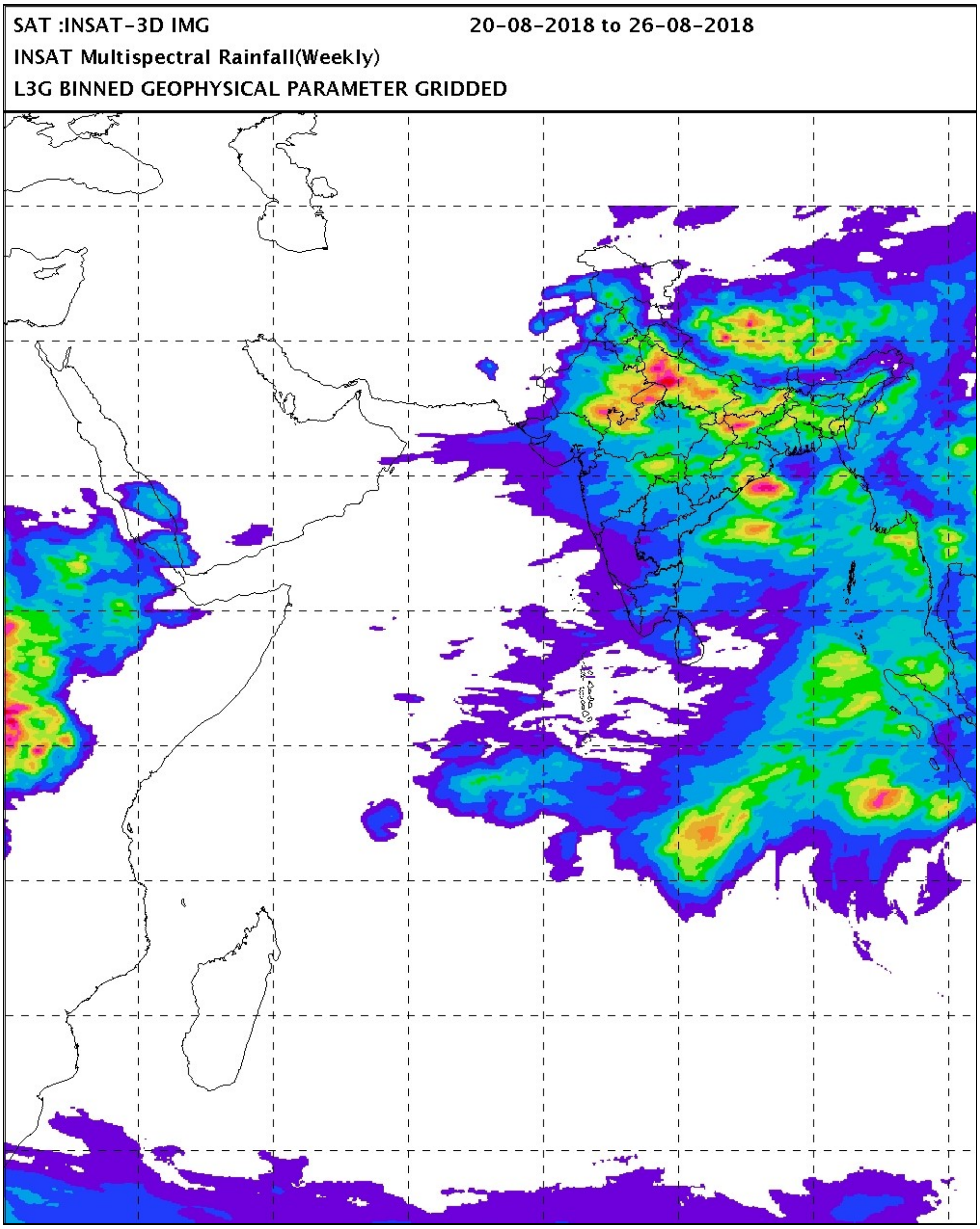

Fig. 8. An example of INSAT-3D rainfall accumulation estimate for the week 20 to 26 August, 2018 based on IMSRA algorithm (*Source*: IMD web site)

Zone (ITCZ), a region of persistent thunderstorms in the vicinity of the equator is marked by low values of OLR. Major deserts and oceanic subtropical highs have the largest OLR during summer.

The basic premise in the OLR derivation process is that the broad-band radiation can be estimated from narrow-band infra-red channel radiances measured by a satellite radiometer. This is somewhat like extrapolating the whole from a part and is done with the help of statistics involving the application of the radiative transfer equation to a host of vertical temperature and humidity profiles. Pioneering work on the derivation of OLR from INSAT-1B radiance data was done by Kelkar *et al*. (1993); Arkin *et al*. (1989) and Rao *et al*. (1989). The algorithms have been further refined over time. Fig. 7 is an example of the OLR field over the INSAT-3D disc during the monsoon season. The blue region stands out as the convectively active region of the monsoon in stark contrast with the yellow region that shows a lack of convection.

9. Satellite-based estimation of precipitation

One of the earliest estimations of large-scale precipitation from INSAT data were done by Kelkar and Rao (1990); Arkin *et al.* (1989) and Rao *et al.* (1989). They used an algorithm that marked thermal infrared channel pixels of temperatures colder than 235° K as raining pixels and those warmer as non-raining pixels. Such estimates were however vitiated by the fact that cirrus clouds are very often colder than 235° K but do not give rain, especially in the tropics. Moreover, the basic algorithms had been calibrated only over sea and not over land and so orographic rain introduced another cause of uncertainty.

With INSAT-3D it has become possible to make much better rainfall estimates using the many channels available on the imager (Singh *et al*., 2018). The INSAT-3D Hydro-estimator algorithm provides pixel-scale half-hourly estimates of precipitation over both land and oceanic regions using the two thermal infrared data as well as the water vapour channel data. It checks temperature changes over time and horizontal temperature gradients to filter out possible errors and to include warm rain. Another algorithm named INSAT-3D Multispectral Rainfall Algorithm combines a variety of techniques to classify clouds and types of convective processes. This algorithm is more helpful in computing rainfall accumulations. Fig. 8 is an example of the precipitation estimates made from INSAT-3D over a week during the 2018 monsoon season.

10. Future directions

Conventional meteorological instruments are long lasting. Decorative and artistically shaped wind vanes have adorned European church steeples for centuries and are still working well. Thermometers installed in Stevenson screens, barometers and rain-gauges continue to function for decades and provide error-free data that is used for decoding signals of global warming and climate change. Meteorological satellites by contrast have a very short life. Many missions are in fact designed only for 3 or 4 years. Some of them do not even last that long. This offers opportunities to employ new technological innovations to redesign meteorological satellites and aim at higher goals.

In the beginning, satellite images printed on quickly fading brown paper were used by meteorologists as a value addition to their synoptic knowledge of the global atmosphere, which they had gathered from meticulously plotted weather charts. We have come a long way from that situation. The data is now too voluminous to print in visual form and efforts are in progress to assimilate satellite radiances directly into global numerical weather prediction models. Attempts to assimilate INSAT-3D radiances in numerical models have shown promising results towards improving the accuracy of short-range weather forecasts (Singh *et al*., 2016).

Meteorological satellites have over time undergone a radical metamorphosis. Television cameras have long been dispensed with and replaced by radiometers, imagers and sounders. Resolutions are continuously improving. New innovative orbits are being tried. India's own satellites like Oceansat-2 and the recent Scatsat-1, have flown radars on board to measure the surface wind fields of tropical cyclones. The Global Precipitation System of satellites has radars to monitor precipitation in the tropics and extra-tropics. The latest European satellite, Aeolus, carries a laser system which measures the wind profiles in the global atmosphere.

The future of satellite meteorology looks bright and exciting and surely it is going to be full of surprises.

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