MAUSAM, **76**, 1 (January 2025), 31-54

MAUSAM

DOI : https://doi.org/10.54302/mausam.v76i1.6433
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 551.501.86(540)

Evolution of satellite meteorology and its future scope- India's perspective

R.C. BHATIA and A. K. MITRA

India Meteorological Department, MoES, India

email : rcbhatia1912@gmail.com

सार– पिछले छह दशकों के दौरान उपग्रह-आधारित प्रणालियाँ पृथ्वी और उसके वायुमंडल का अवलोकन करने के लिए एक बहुत शक्तिशाली उपकरण के रूप में विकसित हुई हैं। किसी दिए गए क्षेत्र में बहुत बार-बार अवलोकन करने की क्षमता के साथ संयुक्त उनकी विलक्षण क्षेत्रीय कवरेज उन्हें वायुमंडल की विभिन्न प्रकार की महत्वपूर्ण टिप्पणियों और पृथ्वी पर मौसम की घटनाओं में प्रकट होने वाली प्रक्रियाओं के लिए आदर्श मंच बनाती है। नासा, यू.एस.ए. में प्रारंभिक चरण में शुरू किए गए विकासात्मक प्रयास विभिन्न प्रकार के परिष्कृत उपकरणों की उपलब्धता में परिणत हुए हैं, जो विद्युतचुंबकीय स्पेक्ट्रम की विभिन्न वर्णक्रमीय श्रेणियों में विकिरण को मापते हैं। उपग्रहों पर स्कैनिंग क्षमताओं के साथ उपयुक्त इलेक्ट्रो-ऑप्टिकल सिस्टम का उपयोग करके, पृथ्वी के बड़े क्षेत्रों को देखा जा सकता है। इस तरह के मापों को विभिन्न कक्षाओं में उपग्रहों की एक प्रणाली का उपयोग करके वैश्विक आधार पर पृथ्वी के बादलों के आवरण के चित्रों के साथ-साथ तापमान और आर्द्रता के प्रोफाइल में परिवर्तित किया जा सकता है। उपग्रहों की ऐसी अनूठी क्षमताओं ने मौसम पूर्वानुमानकर्ताओं को त्रि-आयामी परिप्रेक्ष्य के साथ वायुमंडल की वर्तमान स्थिति का यथार्थवादी आकलन करने में सक्षम बनाया है। जब अधिक लगातार अवलोकनों के साथ जोड़ा जाता है, तो विभिन्न स्थानिक और लौकिक पैमानों पर मौसम प्रणालियों के विकास को उच्च सटीकता के साथ देखा जा सकता है। इसलिए उपग्रह प्रणालियों ने मौसम पूर्वानुमान के विज्ञान में क्रांति ला दी है। इन सभी विकासों के परिणामस्वरूप दुनियाभर में मौसम पूर्वानुमान सेवाओं में काफी सुधार हुआ है, खासकर पिछले दो दशकों के दौरान। मौसम पूर्वानुमानकर्ताओं द्वारा परिचालन उपयोग के लिए पूर्वानुमान चार्ट तैयार करने के लिए कई उपग्रहों से उत्पन्न डेटा और उत्पादों को एनडब्ल्यूपी-आधारित मॉडल में भी समाहित किया जाता है। मॉडल-आधारित पूर्वानुमान चार्ट में उपग्रह उत्पादों को समाहित करने का सकारात्मक प्रभाव पड़ता है। विशेष रूप से, ध्रुवीय उपग्रहों पर दो सेंसर, एएमएसयू-ए और आईआर आधारित हाइपरस्पेक्ट्रल साउंडर्स के डेटा का अन्य सभी प्रकार के सेंसर की तुलना में बड़ा प्रभाव पाया गया है। 1980 के दशक की शुरुआत में शुरू हुई भारतीय भूस्थैतिक उपग्रहों की इनसैट श्रृंखला ने भारत मौसम विज्ञान विभाग की मौसम पूर्वानुमान सेवाओं में महत्वपूर्ण योगदान दिया है। अन्य देशों के वर्तमान में संचालित कुछ भूस्थिर मौसम संबंधी उपग्रहों की तरह, इनसैट उपग्रहों की भावी पीढ़ियों को भी मल्टी-स्पेक्ट्रल इमेजर्स, लाइटनिंग इमेजर्स और आईआर आधारित हाइपरस्पेक्ट्रल साउंडर्स जैसे उन्नत पेलोड से लैस करने की योजना है।

ABSTRACT. During last six decades satellite-based systems have evolved into a very powerful tool for observing earth and its atmosphere. Their prodigious areal coverage combined with capability of very frequent observations over a given area makes them ideal platform for a wide variety of vital observations of atmosphere and the processes that manifest into weather phenomenon on the earth. Developmental efforts initiated in the early stage at NASA, USA have culminated into availability of sophisticated instruments of various types which measure radiation in different spectral ranges of the electromagnetic spectrum. Using appropriate Electro-Optical systems with scanning capabilities on board satellites, large areas of the earth can be viewed. Such measurements can be converted to pictures of earth's cloud cover as well as profiles of temperature and humidity on a global basis using a system of satellites in different orbits. Such unique capabilities of satellites have enabled weather forecasters to make a realistic assessment of the present state of the atmosphere with a three-dimensional perspective. When combined with more frequent observations, evolution of weather systems at various spatial and temporal scales can be seen with a high precision. Satellite systems have therefore revolutionized the science of weather forecasting. As a result of all these developments the weather forecasting services all over the world have improved considerably, particularly during the last two decades. Data and products generated from number of satellites are also assimilated in the NWP based models to generate forecast charts for operational use by weather forecasters. There is a positive impact of assimilating satellite products in the model based forecast charts. Particularly, data from two sensors AMSU-A and IR based Hyperspectral sounders on polar satellites, are found to have large impact as compared to all other types of sensors. INSAT series of Indian Geostationary satellites started from early 1980s, have made significant contributions to the weather forecasting services of India Meteorological Department. Like some of the currently operational Geostationary meteorological satellites of the other countries, future generations of

INSAT satellites are also planned to be equipped with advanced payloads like multi-spectral imagers, lightning imagers and IR based Hyperspectral sounders.

Key words– Multispectral imagers, Hyperspectral sounders, NWP models, Geostationary satellites, temperature and humidity profiles, INSAT satellites.

1. Introduction

Space-based observation systems for meteorological applications are most important tool for observing earth and its atmosphere on a global basis with a very high temporal resolution. For real-time weather forecasting these two requirements are most vital and satellites are best suited for this purpose. 1st April,1960 was a historic day for satellite observations. A beginning was made for such observations in USA when first meteorological satellite was successfully launched into a Polar orbit. During last 64 years lot of developments have taken place in use of Space-based systems for meteorology and other related disciplines. A wide variety of new payloads have been developed, successfully tested and found useful for meteorological applications. Satellite data now form an integral part of weather forecasting services all over the world. Apart from their regular use for operational weather forecasting, satellites also provide a wide variety of data and products for use in research work related to atmospheric sciences. Significant developments during last more than six decades in different parts of the world have culminated into emergence of satellite-based systems as a very powerful tool for weather forecasting services. Past data of more than last 50 years available from satellites, have proved to be extremely useful for climate related studies. Right from the early stage of commencement of using this new type of data in operational work of weather forecasting from early 1960s, analysis of cloud imagery data has provided useful inputs for better understanding of different weather systems leading eventually to improved forecasts.

A major forward step was taken in India from early 1980s when first generation of Indian National Satellite System (INSAT-1) started its operations. There was a significant positive impact of this program on the meteorological services provided by the IMD. The program was continued further with INSAT-2 and INSAT-3 series of satellites which are operating even now with much improved payloads as compared to the earlier satellites of INSAT-1 series.

Apart from pictures of earth's cloud cover, a large variety of other types of observations are also now available from meteorological satellites. All types of new data, other than pictures of cloud cover, are also found to be extremely useful all over the world for operational use and research related works. In India also scientists had started using these data appropriately in regular operations and research work. Satellite data now forms a major input to the Numerical Weather Prediction (NWP) models being run operationally at various centers all over the world and there is a clear positive impact of assimilating satellite data in the operational NWP models. As a result of this outcome weather forecasting services in different parts of the world have improved considerably, particularly during last 10-15 years.

Purpose of this review article is to describe the evolution of Satellite Meteorology and its impact on weather forecasting services. It provides complete historical background of developments of space-based observations during last 64 years and future scope, with a particular reference to the developments and applications in India.

2. Meteorological satellites in the early years

First experimental meteorological satellite, TIROS-1, was launched by the United States of America on 1 April,1960 in a Polar orbit. It provided for the first time the pictures of earth's cloud cover in day time using Vidicon camera on board the satellite which measured the reflected sunlight in the visible channel. This method of observing earth and its atmosphere from an entirely new perspective proved to be extremely useful from the point of view of large areal coverage which is essential for operational weather forecasting. Even though this satellite worked only for about 70 days, its data was found to be very useful and it laid the foundation for future satellites of similar type. Program was continued further till mid 1960s by launching 9 more satellites of this type incorporating certain improvements in each successive satellite of the series. An important feature of Automatic Picture Transmission (APT) was incorporated from 1962 which enabled direct reception of cloud imagery data by large number of receiving stations when satellite came within the visibility range of these stations. Further continuation of this program was done by launch of TIROS Operational Satellites (TOS), also known as ESSA (Environmental Science Services Administration) series of satellites. Nine such satellites were launched from mid 1960s onwards. Lot of receiving stations located all over the world were able to receive real-time pictures of earth's cloud cover and use them in daily operational work of weather forecasting. These satellites were also equipped with vidicon cameras to provide pictures during daytime.

After successful demonstration of using cloud pictures received from polar orbiting satellites in day-to-day work of weather forecasting, extensive R&D work was also initiated from mid 1960s at NASA, USA for development of new payloads. A new program, called NIMBUS series of satellites, was planned by NASA for testing of new payloads developed and to develop new capabilities in the ground stations for processing of data from new payloads. Main objective was to test and evaluate all such new payloads on the R&D missions of all NIMBUS satellites. Only after successful demonstration of capability of new types of payloads, they were later launched on board future operational satellites. Thus, NIMBUS program laid the foundation of number of new types of satellite payloads of various types and observe earth's atmosphere from different perspectives. Seven satellites were launched under this series until 1979.

Based on the experience gained with the NIMBUS program, a new series of satellites called Improved TIROS Operational Satellites (ITOS) was started from early 1970s. Main feature in this series was replacement of Vidicon cameras with new type of instrument called Scanning Radiometer (SR). It provided capability for receiving cloud pictures in Visible and Infrared channels during day and night times. After successful launch of satellites of this series they were renamed as NOAA (National Oceanic and Atmospheric Administration) satellites. For the first time real-time reception of cloud pictures was possible during night time using Infrared channel. Number of operational satellites were launched under this series to provide continuity of operational services and they were all in Polar Sun-synchronous Orbits. Improvements in capabilities of these satellites were also incorporated from time-to-time.

Under the Defense Military Satellite Program (DMSP) of USA, some meteorological satellites were planned primarily to meet weather related requirements for military use. These satellites were equipped with an imaging instrument of very high resolution. In addition, they also carried microwave-based sensors (Imager and sounder) and a new instrument for detection of lightning. Apart from their regular use for Defense related operations, these satellites were also found to be useful for some meteorological applications. Under this program, number of satellites were launched and some of these satellites are continuing to operate even now (Dec, 2024).

Pursuant to a policy decision taken by US Government in late 1990s, it was decided that the capabilities of meteorological satellites for Civil use and for defense use will be combined into a single satellite. A new program, called National Polar-Orbiting Operational Environmental Satellite System (NPOESS) was started for this purpose and launch of some new satellites was planned under this program. Under an agreement between NOAA, USA and EUMETSAT in the year 1988, all future Polar-Orbiting satellites that cross equator in the afternoon, will be launched and operated by USA and will be named after launch, as satellites of NOAA series. The satellites with their equator crossing times in the mid-morning will be named as new METOPS series of satellites and will be launched and operated by ESA/EUMETSAT. These two series of satellites will have identical payloads. First satellite in this program was National Polar-orbiting Partnership (NPP) satellite. This satellite was later renamed as SNPP (Suomi NPP) to honor a well-known and renowned scientist of CIMSS, Wisconsin, USA. Based on requirements of the users it was decided that this satellite will carry the following five payloads.

(*i*) Advanced Technology Microwave Sounder (ATMS)

(*ii*) Cross-track Infrared Sounder (CrIS)

(*iii*) Visible Infrared Imaging Radiometer Suit e (VIIRS)

(*iv*) Ozone Mapping and Profiler Suite (OMPS)

(*v*) Cloud and Earth Radiant Energy System (CERES)

Some further changes in the Policy took place from 2008 when NOAA's next generation of polar-orbiting environmental satellite system was designated as Joint Polar Satellite System (JPSS). It was named as Civilian successor to the restructured NPOESS system. The first satellite under this program (SNPP) was successfully launched into a 1330 polar orbit on 28 October, 2011.This is the first satellite in a series of Next-generation weather satellites of the JPSS. Two more satellites of this series have also been launched.

In early 1960s Russia had also launched a series of METEOR satellites in Polar orbits for meteorological applications. These satellites were equipped with instruments for scanning the earth and transmission of data in real-time to the ground receiving stations to generate pictures of earth's cloud cover. Data from these satellites was used in real-time and for research work. R&D work was also done in Russia for improving the existing systems and for developing new type of instruments to provide additional data, other than cloud pictures, for use in atmospheric science. Some advanced satellites of METEOR series are operating even now. China is also operating some Polar orbiting satellites with payloads similar to the satellites being operated by the USA.

Encouraged by the success of Polar orbiting satellites and their applications in weather forecasting, scientists and engineers started exploring the possibility of obtaining more frequent pictures of earth's cloud cover from satellites to monitor rapidly changing weather phenomenon. Concept of a "Geostationary Satellite" for meteorological applications, located over the equator in an orbit having a period of 24 hours, was found to be feasible. A satellite in such an orbit would appear to be stationary with reference to a point on the earth. About five such satellites located at equator over different longitudes can provide pictures over large areas of earth. To start with this concept, a series of satellites called Applications Technology Satellites (ATS) were launched by USA from mid 1960s on an experimental basis. Based on the experience with these satellites future operational Geostationary meteorological satellites were also planned. In early 1970s, under the World Weather Watch (www) Program of WMO, plans were formulated for launch of 5 Geostationary satellites to obtain more frequent pictures of earth's cloud cover over different parts of the globe. This program also met some of the major requirements of an important international program called Global Atmospheric Research Program (GARP) which was in active consideration of WMO at that time. As a part of this program, plans for First GARP Global Experiment (FGGE) were formulated. Under this program 5 Geostationary satellites were to be launched from mid 1970s. Two such satellites to be launched by USA, named as Geostationary Operational Environmental Satellites (GOES), One to be launched by Japan, called Geostationary Meteorological Satellite (GMS), One to be launched by European Space Agency (ESA), called Meteorological Satellite (METEOSAT) and one to be launched by Russia called Geostationary Operational Meteorological Satellite (GOMS). Most of these planned satellites were launched in time frame 1974-1980. Only GOMS was launched much later, sometime in the middle of 1990s. One of the GOES satellites was temporarily located over the Indian Ocean, called GOES-IO, during an international program, Monsoon Expedition (MONEX-1979). Lot of useful data was collected during Monsoon season of 1979 which was used for research by the international team of scientists to carry out scientific investigations. China is also operating some Geostationary meteorological satellites with capabilities of earth imaging and atmospheric sounding. South Korea has also launched a series of Geostationary meteorological satellites which are operational at present.

3. Satellite meteorology in India in early years

Reception of real-time satellite pictures of weather systems was started at Bombay (now Mumbai) in the year 1963 as part of an international program, called International Indian Ocean Expedition (IIOE) Program. Under this project an APT receiving equipment was established at Bombay for real-time reception of low-resolution cloud pictures, called Automatic Picture Transmission (APT) data service transmitted by the TIROS series of polar orbiting satellites of USA in operation at that time. Equipment was provided by the National Science Foundation (NSF), USA as a contribution by NSF for the IIOE Project. Lot of useful data was collected with this equipment which was used for operational work and research work of this Program. This new equipment provided lot of useful experience to the IMD scientists for utilizing data from satellites. IMD scientists also obtained lot of additional data from USA on post real-time basis and used it for research work. A national symposium on Satellite Meteorology was held from 10-13 April,1970. Research papers presented during this symposium are published in a special issue of Indian Journal of Meteorology and Geophysics, now renamed as Mausam (Vol. 22, No. 3, 1971). A paper by Dr. P. Koteswaram highlights the main achievements and benefits to IMD during the first 10 years period (Koteswaram,1971). In particular, results of initial studies on tropical cyclones using satellite pictures were reported by Sikka (1971a, b).

Keeping in view the usefulness of satellite pictures, IMD started further work for indigenous development of APT receiving equipment. It was successfully designed and developed at the Instrument Division, Pune (Datar *et al*.,1971). Another two receiving stations using indigenously developed equipment were started at IMD's HQs office New Delhi and Regional Meteorological Center (RMC), Madras in the year 1971. IMD established Satellite Meteorology Directorate at New Delhi in the year 1971 to promote development and utilization of Satellite-based observations. Network of APT receiving stations was expanded to 7 during subsequent few years in a phased manner. Three more stations where APT receiving equipment were installed were Calcutta, Gauhati and Vishakapatnam. Real-time data received from all these stations was used for day-to-day operational work of weather forecasting as well as for the research work. Certain improvements in design of APT receiving equipment were also incorporated (Rao *et al*., 1979). From mid 1970s, IMD also started planning for establishment of a station at New Delhi for reception of High Resolution Picture Transmission (HRPT) service data also available from the NOAA series of Polar-orbiting satellites of the USA. This equipment was procured and installed at Delhi in 1981.

4. INSAT program of India

An important policy decision taken by the Government of India in the year 1975 led to the cabinet approval of a major satellite related project, called Indian National Satellite (INSAT) program. Plans envisaged establishment of a multi-purpose geostationary INSAT satellite system in early 1980s with payloads for three services *viz*., Telecommunications, Television Broadcast and Meteorology. Order for procurement of first generation of INSAT satellites (INSAT-1 series) was placed by the Department of Space (DOS), Government of India with M/S Ford Aerospace and Communications Corporation (FACC), USA. The satellite system was planned to be consisting of two satellites-one main operational satellite operating from the primary position (74º E) and the other on-orbit backup satellite located at secondary position (93.5º E) for operation in the event of contingency. The first satellite of INSAT-1 series (INSAT-1A) was launched on 10 April, 1982.The imaging instrument on board this satellite had a resolution of 2.75 km in visible channel and 11 km in the infrared channel. India Meteorological Department had established in early 1982, a Meteorological Data Utilization Center (MDUC) at its HQs office, New Delhi, for real-time reception and processing of data transmitted by the meteorological payloads of this satellite. It was for the first time in April, 1982 when India started receiving meteorological data over India from its own geostationary satellite. However, this satellite failed in September,1982 five months after its launch. During this period pictures could be received with some limitations on operations because of some technical problems with this satellite. A comprehensive failure review was conducted by the Department of Space. Based on the findings of this review certain changes were incorporated on the next satellite of INSAT-1 series (INSAT-1B) which was launched successfully on 30th August, 1983. In spite of certain technical problems of minor nature with this satellite, it could be operated satisfactorily from September,1983 and it worked for a very long time. Availability of frequent pictures of earth's cloud cover from INSAT-1 series of satellites therefore started from September,1983 on a regular basis. Derivation of Quantitative Products like Cloud Motion Vectors (CMVs), Outgoing Longwave Radiation (OLR), Quantitative Precipitation Estimates (QPE) and Sea Surface Temperature (SST) using processed VHRR data from this satellite was also started on a regular basis. Processed data archival on tapes was started sometime from late 1983 early 1984. With the commencement of sustained operational use of cloud imagery data and derived products in day-to-day operational work of weather forecasting and research, India Meteorological Department entered the new era of using Geostationary Meteorological Satellite data from Indian satellite. Operational use of this new type of data improved the monitoring of weather systems like cyclones, thunderstorms, Low pressure systems, Monsoon Depressions, Western Disturbances, easterly waves, Jet streams *etc*. Use of INSAT data resulted in better quality of weather forecasting services to the users. INSAT-1B satellite continued to be used operationally for about 10 years.

After availability of data and products for the first time from a Geostationary satellite over the Indian region on a regular basis, IMD scientists had undertaken lot of studies and published research papers based on these studies. Results of a study done on satellite observed cloud distribution over the Indian Ocean during South West Monsoon Season are reported (Prasad *et al*., 1983). Based on the observations of wave patterns in Cellular clouds over Arabian sea in Monsoon season, theoretical explanation has been given in a paper (Mishra *et al*., 1987). A multi-channel simulation approach for SST retrieval from INSAT-1B was developed (Kelkar *et al*., 1989). A technique for estimation of Precipitation and OLR was also developed using INSAT-1B radiance data (Rao *etal*., 1989). Using satellite observations of mountain waves over northwest India, theoretical verification was done (Sinharay, 1988). Results of some studies on thunderstorms done by using INSAT pictures are reported in two papers (Bhatia *et al.*, 1993, Kalsi *et al*., 1992). A very good review of research work done during initial years has also been published in a recent paper (Kelkar, 2019).

Due to the failure of first satellite of INSAT-1 series the originally planned target of having two satellites at a time in-orbit could not be achieved after launch of INSAT-1B. Therefore, order for a third satellite (INSAT-1C) was placed in mid 1980s. It was successfully launched in July,1988 and after on-orbit tests it was commissioned for operational use. Its primary purpose was to serve as a back-up satellite for the already operational satellite INSAT-1B. After providing useful service for a little more than one year, INSAT-1C satellite failed in Nov, 1989. However, meteorological services continued to be available from the earlier satellite INSAT-1B but without any on-orbit back-up in the event of any contingency. It was therefore decided to launch the fourth satellite of INSAT-1 series (INSAT-1D). Department of Space had planned for procuring the fourth satellite in case the need arises for any unforeseen reason. INSAT-1 D was launched successfully on 12/06/1990 and declared fit for operational use after on-orbit tests. It served as an on-orbit back-up satellite for INSAT-1B. Meteorological services thus continued to be available with these two satellites during subsequent few years. INSAT-1D satellite was the last satellite of INSAT-1 series procured from the foreign vendor, M/S Ford Aerospace Communications Corporation, USA. It continued to be operational for almost 12 years. Research work continued at IMD and other Institutions for utilization of satellite images and other products for improvements in weather forecasting services provided by IMD.

4.1. *Use of communications capabilities of INSAT for meteorological services*

Apart from the main use of INSAT-1 satellite series for obtaining pictures of earth's cloud cover as described above, the communications capabilities of these satellites were also used to operate the following meteorological services:

(*i*) Collection of conventional meteorological data from remote and inaccessible areas over land and oceans using a Data Relay transponder (DRT) which was provided as an additional meteorological payload on all satellites of INSAT-1 series. For this purpose, 100 land-based Data Collection Platforms (DCPs) equipped with appropriate sensors, were established at remote and inaccessible areas of Indian land. Ten ocean-based DCPs were also planned. Because of practical difficulties involved in their installation over oceans, only one or two were installed. Now nomenclature of DCPs is no longer in use. Instead, Automatic Weather Stations (AWS) and Automatic Raingauges (ARGs) are installed at remote areas and number of such equipment are operational (M. R. Ranalkar *et al*.,2012). Basic purpose of AWS / ARG is same as that of DCPs. At present 2400 AWS and ARGs are operational including 200 at Agricultural meteorological observatories.

(*ii*) Spare bandwidth available in the two S-band transponders of these satellites was utilized to broadcast processed low-resolution INSAT cloud pictures to 20 Secondary Data Utilization Centers (SDUCs) located at field forecasting offices of the Department. This service was named "Meteorological Data Dissemination (MDD)". One such station was also established at Maldives. Main purpose of this service was to provide processed INSAT cloud imagery data at low resolution to the field forecasting offices in near-real time for utilization in day-to-day forecasting (Bhatia *et al*.,1989). Sometimes from 2005 this service was further upgraded to Digital MDD. However, at present this service is not being operated in S-band as better technical options are available for transmission of data / products to the field offices.

(*iii*) A part of the spare bandwidth available in the S-band transponders of INSAT-1 series of satellites was also utilized for dissemination of Cyclone warnings to the coastal areas. Initially 100 receiving stations were established in the coastal areas of Tamil Nadu and Andhra Pradesh. The network was later augmented to 400 stations to include cyclone prone areas of all coastal states of India. This service was initially called Disaster Warning System (DWS) which was later renamed as Cyclone Warning Dissemination System (CWDS). However, at present this service is not being operated in S-band. Better technical options are available for dissemination of cyclone warnings.

5. Second Generation INSAT Satellites (INSAT-2 series)

Planning for providing continuity of all services started with INSAT-1 series of satellites was started as early as 1983. Based on the service requirements projected by all user agencies for 1990s and beyond, the second generation of INSAT satellites (INSAT-2 series) were also planned as multipurpose satellites for the three services. As a major policy decision, it was decided by the Department of Space that INSAT-2 series of satellites will be designed and developed by the ISRO Satellite Centre (ISAC), Bangalore. Based on the experience of INSAT-1 series of satellites, lot of improvements were planned for the next generation of INSAT-2 satellites. Details of INSAT-2 program and the ground segment are given in a paper (Bhatia, 1991). The first indigenously built multipurpose geostationary satellite (INSAT-2A) was successfully launched in July ,1992. Very High Resolution Radiometer (VHRR), the imaging radiometer onboard this satellite had an improved resolution of 2 Km in the visible channel and 8 km in the Infrared channel as compared to 2.75 Km (VIS) and 11 Km (IR) for the radiometer on board INSAT-1 satellites. Full technical details of the VHRR instrument on board INSAT-2A satellite are given in a published paper (George Joseph *et al*., 1994). After successful launch of this first satellite, on-orbit tests showed that the VHRR instrument was operating generally satisfactorily. This satellite started the new era of operation of indigenously designed imaging radiometer from a geostationary satellite. There were some limitations with operation of IR channel on this satellite due to some technical problems related to the maintenance of patch temperature during certain times /seasons. Nevertheless, the project successfully demonstrated the indigenous capability and it paved the way for future developments in India. Second satellite of INSAT-2 series (INSAT-2B) was also launched successfully in July,1993 with identical VHRR instrument as on INSAT-2A. In subsequent years the operation of Indigenously built VHRR instruments on both satellites provided lot of useful experience in utilization of better quality of cloud imagery data for day-to-day operational use in weather analysis and forecasting. Improved resolution of imaging instruments resulted in slightly better quality of quantitative products derived from satellite data. Improvements in quality of Cloud Motion Vectors (CMVs) was also noticed and results of some specific studies done with these CMVs were reported in the Second International Winds Workshop (Kelkar *et al*., 1993).

The second satellite of INSAT-1 series (INSAT-1B) worked up to 1993, almost for 10 years. After this only one satellite of INSAT-1 series (INSAT-1D) continued to be operational for many years. From 1994 onwards, three imaging radiometers were available on-orbit for meteorological applications (INSAT-1D, INSAT-2A and

INSAT-2B). However, as stated above, the VHRRs on board 2A and 2B had some limitations on operation of IR channels. In spite of limitations, indigenous capability was demonstrated. The next two satellites of INSAT-2 series (INSAT-2C and INSAT-2D) did not carry any meteorological payloads. These satellites had payloads only for communications and TV broadcast services.

5.1. *INSAT-2E satellite*

With a view to make further improvements in capability of meteorological payloads of future INSAT-2 satellites and to provide continuity of meteorological services with INSAT-2 series of satellites, 5th satellite of INSAT-2 program (INSAT-2E) was planned. This was also a multi-purpose satellite for three services, but with improved meteorological payloads. Two main improvements were:

(*i*) Provision of a third water vapor channel in the imaging radiometer in addition to earlier two channels of visible and infrared, provided on all VHRR instruments of INSAT-1 and INSAT-2 satellite series launched so far.

(*ii*) Provision of a new 3 channel Charge Coupled Device (CCD) camera on satellite for imaging at 1 Km resolution. Main objective was to obtain images of better clarity during daytime in three channels namely Visible (0.62-0.68 um), Near Infrared (0.77-0.86 um) and Shortwave Infrared (1.55-1.69 um).

Details of improvements in meteorological payloads incorporated on the INSAT-2E satellite and the applications of new type of data available from the above two payloads are described in two papers of Current Science special issue on INSAT-2E (Bhatia *et al*., 1999). Full technical details of meteorological imaging payloads on this satellite are given in a published paper (V.S. Iyengar *et al*.,1999). This satellite was launched successfully in April, 1999. On-orbit performance tests conducted a few days after launch brought out some anomaly in the operation of VHRR instrument. The other new payload (CCD camera) was working satisfactorily. A new equipment was installed at IMD, Delhi for reception and processing of INSAT-2E data and generation of products. The technical problem experienced with the operation of VHRR resulted in non-availability of this instrument for any operational use. As a result of this round-the-clock availability of cloud images for weather monitoring was not possible with this new satellite as CCD images were possible only during day time. This situation necessitated formulation of urgent contingency plans to provide for uninterrupted availability of VHRR services during subsequent few years. The main reason for urgency was that the fourth satellite of INSAT-1 series (INSAT-1 D) launched in June,1990 had already operated for about 2 years beyond its designed life of 7 years and its continued operation during subsequent few years was doubtful. In addition, the first two satellites of INSAT-2 series (2A and 2B) were nearing their end of life. These two satellites also had some problem with the operation of IR channel at certain times.

5.2. *METEOSAT satellites availability over Indian region*

In early 1998 European Meteorological Satellite Organization (EUMETSAT) had planned for moving one of their spare satellites (METEOSAT-5) over the Indian Ocean region (at 63 deg E longitude) to provide round-the – clock cloud imagery data. This action was taken to support an International Project called INDOEX (Indian Ocean Expedition). This operational service of METEOSAT from 63 deg location was started from 1 July,1998. Subsequently EUMETSAT had continued to operate this service, called Indian Ocean Data Coverage (IODC) even after the end of INDOEX project. Now this service is available almost on a continuous basis. Even today (December, 2024) this service is being operated using one spare Second Generation satellite (METEOSAT-9) located at 44.5º E longitude. An advanced 12 channel imaging radiometer called SEVIRI (Spinning Enhanced Visible and InfraRed Imager) is available on board this satellite to provide multi-spectral images over the Indian Ocean region. Lot of new type of products derived from SEVIRI data are also available over IODC.

5.3. *Contingency plans: first dedicated geostationary meteorological satellite (METSAT)*

With a view to ensure uninterrupted availability of earth images for meteorological applications, soon after the technical problem experienced with the operation of VHRR onboard INSAT-2 E satellite, the following two actions were initiated on very high priority.

(*i*) Procurement of a ground station for real-time reception of METEOSAT-5 satellite images at IMD, Delhi.

(*ii*) Design and fabrication of a dedicated meteorological geostationary satellite for earth imaging in three channels (Visible, InfraRed and Water vapor) with same specifications as of INSAT-2E VHRR. This satellite was planned to be launched using India’s Polar Satellite Launch Vehicle (PSLV). A new project called METSAT (Meteorological Satellite) was conceived by ISRO for implementation with a very high priority. This project thus marked the beginning of a new era of launching dedicated geostationary meteorological satellites.

The outcome of two above mentioned actions performed with very high priority resulted in:

(*iii*) Establishment of a ground station in IMD Headquarters office at New Delhi in late 1999- early 2000 for real-time reception of METEOSAT-5 images. This provided the back-up capability for the operational INSAT-1D satellite which was the only satellite fully operational at that time.

(*iv*) Successful launch of first dedicated geostationary meteorological satellite (METSAT) in September,2002. Prior to this, the last satellite of INSAT-1 series (INSAT-1D) had stopped functioning from 14 May,2002 after providing useful service for almost 12 years, much beyond the normal useful life of this satellite. During the last few years of its life, it was operated in an inclined orbit mode. The launch of METSAT in September,2002 provided the required capability of round-the-clock imaging from our own satellite. During the intervening period of few months between the end-of-life of INSAT-1D and beginning of operations with METSAT (from September, 2002) work was managed with METEOSAT-5 images. In February, 2003 METSAT was renamed as KALPANA.

6. Third generation of INSAT (INSAT-3) satellite series

To provide continuity of operational services after end-of-life of INSAT-2 satellite series, planning was started for third generation of INSAT satellites sometimes in 1996. In addition, on-orbit back up satellites with adequate working instruments are also required all the time to take care for any contingency during operations. Keeping this in view it was decided that first satellite of new INSAT-3 series (INSAT-3A) can be identical to INSAT-2E satellite with a three channel VHRR and a three channel CCD camera. Specifications of these two instruments were almost identical to the similar instruments on INSAT-2E. However, certain modifications in the designs of these instruments were made based on the on-orbit operational experience gathered from 2E satellite. Like INSAT-2E, INSAT-3A satellite was also a multipurpose satellite for three services. It was launched successfully in April, 2003 providing back-up capability for METSAT/ KALPANA which was operating at that time.

6.1. *First dedicated satellite of INSAT series (INSAT-3D) with advanced payloads*

With a view to make further improvements in the capabilities of meteorological payloads on board future satellites of INSAT series, IMD had projected for requirement of a dedicated meteorological satellite with advanced technology payloads. Based on the increased service requirements for the meteorological payloads and the preliminary feasibility studies done by ISRO, a new dedicated meteorological satellite (INSAT-3D) was planned for launch during 2006-2008. Two payloads planned for this satellite were:

(*i*) A 6- channel imager with improved resolution of 1 Km in visible channel and 4 km in IR channels.

(*ii*) A 19-channel atmospheric sounder for obtaining vertical profiles of temperature and humidity with a resolution of 10 Km.

A Data Relay Transponder (DRT) was also planned as a payload for collection of conventional meteorological data from remote and inaccessible areas. INSAT-3D was therefore the first most advanced satellite planned at that time for meteorological applications. Because of the major improvements planned for meteorological services on board this satellite, as compared to the earlier satellites of INSAT-1 and 2 series, lot of design and development work was initiated at ISRO. After a series of design reviews of the above two payloads the instruments were fabricated and tested satisfactorily before launch. There were also some delays in implementation of this important project due to certain critical components being not available in time. This most advanced dedicated meteorological satellite (INSAT-3D) was successfully launched in July, 2013. After providing lot of useful data for more than 10 years this satellite has been decommissioned in June,2024. Another two satellites of this series, with identical capabilities, have also been launched. Second satellite, INSAT-3R, was launched in September,2016. Third satellite INSAT-3S, has been launched on 17 February, 2024. These two satellites are currently available for operational use.

A new ground segment was established in 2008 at IMD, New Delhi for real-time reception and processing of data received from INSAT-3D. For processing of imager and sounder data from INSAT-3D, the following four steps are broadly involved :

(*i*) Ground Receiving system to receive data.

(*ii*) Data Reception (DR) system to generate raw data (L0) files

(*iii*) Data Processing (DP) system to process L0 data and produce calibrated, geolocated data files

(*iv*) Product generation and dissemination system

TABLE 1

INSAT-3D Imager and Sounder Products

S.No.	Data Product	Processing Level	Code	Format	Remarks
			Standard Products		
1	Standard Product Full Disk	L1B	STD	HDF	Per Pixel Lat & Lon as viewed by Satellite
2	Standard Product Full Disk Fixed Grid	L1C	STD	HDF	Projected on Fixed Grid
3	Standard Sector Product	L1C	Sector mnemonic	HDF	Map Projected
			Geo-Physical Parameters		
1	Outgoing long wave radiations	L2B	OLR	HDF	Per Pixel
2	Rainfall using Hydro Estimator	L2B	HEM	HDF	Per Pixel
3	FOG	L2C	FOG	HDF	Per Pixel
4	SNOW	L2C	SNW	HDF	Per Pixel
5	Cloud Mask	L2B	CMK	HDF	Per Pixel
6	Upper Troposphere Humidity	L2B	UTH	HDF	Per Pixel
7	Sea Surface Temperature	L2B	SST	HDF	Per Pixel
			Geo-Physical Parameters (Point)		
1	FIRE	L2P	FIR	KML	Point
2	SMOKE	L2P	SMK	KML	Point
3	Atmospheric Motion Vectors	L2P	AMV	HDF	VIS, TIR, WV, MIR (Point)
			Geo-Physical Parameters (Gridded)		
1	INSAT Multi-Spectral Rainfall Algorithm (IMSRA)	L2G	IMR	HDF	0.1 deg x 0.1deg
2	Quantitative Precipitation Estimation	L2G	QPE	HDF	1 deg x 1 deg
3	Aerosol Optical Depth	L2G	AOD	HDF	0.1 deg x 0.1 deg
			Binned Geo-Physical Parameters (Temporally Binned)		
1	Outgoing long wave radiations	L3B	OLR	HDF	Daily, Weekly, Monthly and Yearly Per Pixel
2	Rainfall using Hydro Estimator	L3B	HEM	HDF	Daily, Weekly, Monthly and Yearly (Per Pixel)
3	Sea Surface Temperature	L3G	SST	HDF	Daily, Weekly, Monthly and Yearly 0.5 deg X 0.5 deg
4	Upper Troposphere Humidity	L3G	UTH	HDF	Daily, Weekly, Monthly and Yearly 0.1 deg x 0.1 deg
5	INSAT Multi-Spectral Rainfall Algorithm (IMSRA)	L3G	IMR	HDF	Daily, Weekly, Monthly and Yearly 0.1 deg x 0.1deg
6	Quantitative Precipitation Index	L3G	QPI	HDF	Daily, Weekly, Monthly and Yearly (1 deg x 1 deg)
			INSAT-3D Sounder Products		
			Standard Products		
1	Standard Product	L1B	STD	HDF	Per Pixel Lat & Lon as viewed by Satellite
			Geo-Physical Parameters		
1	Vertical Profiles and Derived products	L2B	PFL	HDF	Profile on 3x3 Pixels (Average)

In addition to the processing of INSAT-3D data, this system was also capable of processing data from other meteorological satellites available at that time, *viz*. KALPANA-1 and INSAT-3A. The quantitative products being derived from the system using imager and sounder data are shown in Table-1 (Reference: IMD/SAC Technical document on INSAT-3D Products Catalog, 2010). Sample products OLR, Water vapor winds, precipitation index and Cloud Motion Vectors derived on 8 July, 2023 at 09Z are

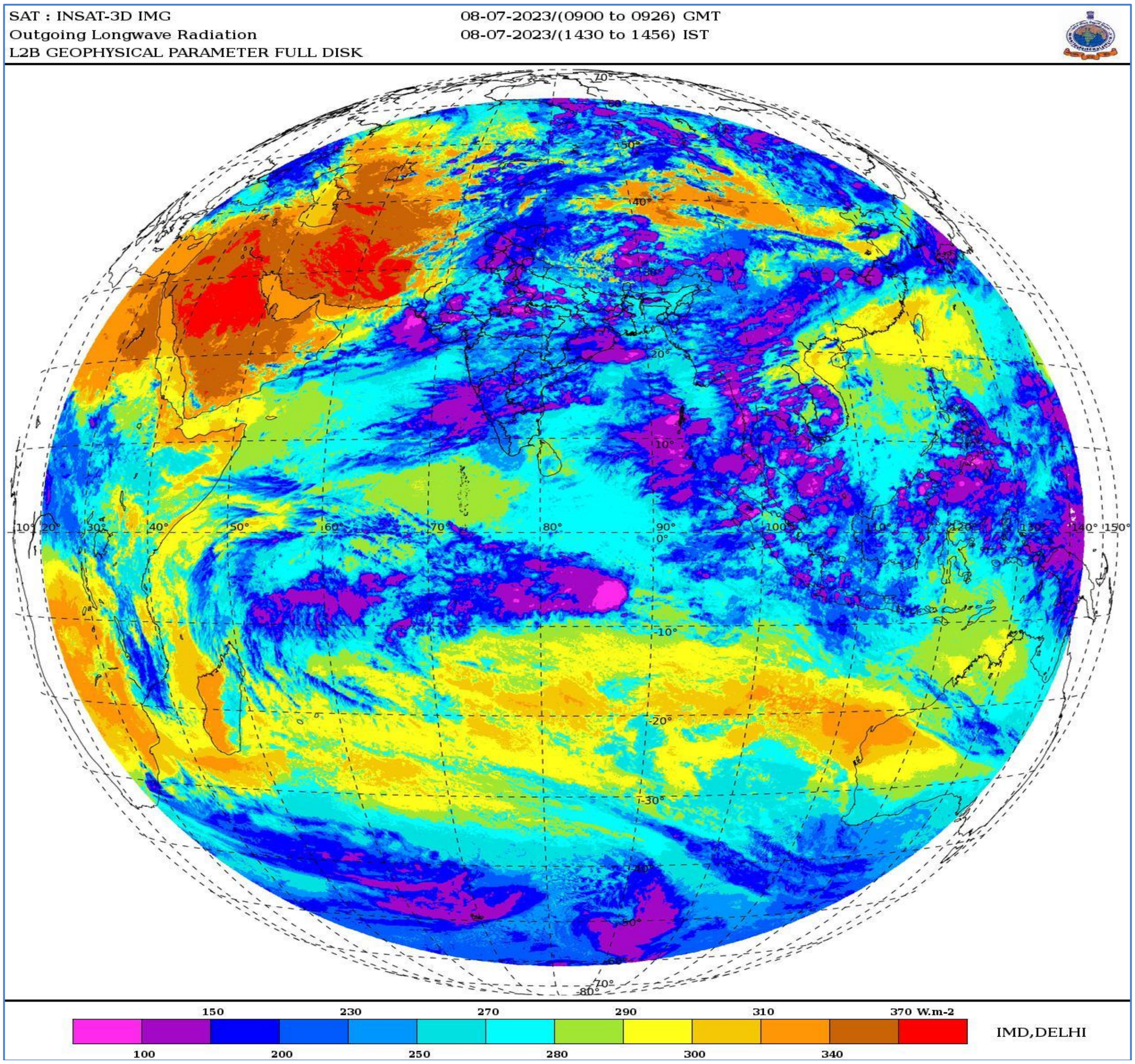


Fig. 1: Full frame OLR product derived from INSAT-3D on 8 July, 2023 at 09Z. It shows convective clouds over North West India and adjoining areas of Himachal Pradesh that developed due to interaction of Low- Level monsoon flow with a middle level trough in Westerlies giving rise to unprecedented heavy rains over Northern parts of India

shown in Figs. 1-4. They bring out important features associated with an unprecedented Heavy rainfall event that occurred on this day over Northwest India due to interaction of strong low level monsoon flow with a middle troposphere trough associated with a Western disturbance. This resulted in Extremely Heavy rainfall over Northwest India.

Lot of research work has been done during last more than two decades using INSAT data. Amudha *et al*., (2016) reported results of some studies done on northeast monsoon using INSAT OLR data. Results of some studies done on rainfall estimation of landfalling Tropical cyclones over Indian coasts using satellite imagery have been reported by Singh *et al*., (2012). Results of a specific study done on validation of Advanced Dvorak Technique (ADT) over North Indian Ocean are reported by Goyal *et al.*, (2017). Results of a satellite- based study of premonsoon thunderstorms over eastern India have been reported (Tyagi *et al*., 2012). A special issue of Mausam, 2003 (see list of references) also brings out lot more papers on remote sensing applications in meteorology. Results of a preliminary evaluation study of INSAT-3D vertical profiles retrievals at IMDPS, Delhi have been reported by Mitra *et al*., (2015). Recently, Kumar *et al*., (2019) have reported results of a quality assessment of OLR derived from INSAT-3D. More recently, results of a few important papers published prior to and after launch of INSAT-3D have also been reported in a paper (Kishtawal, 2019).

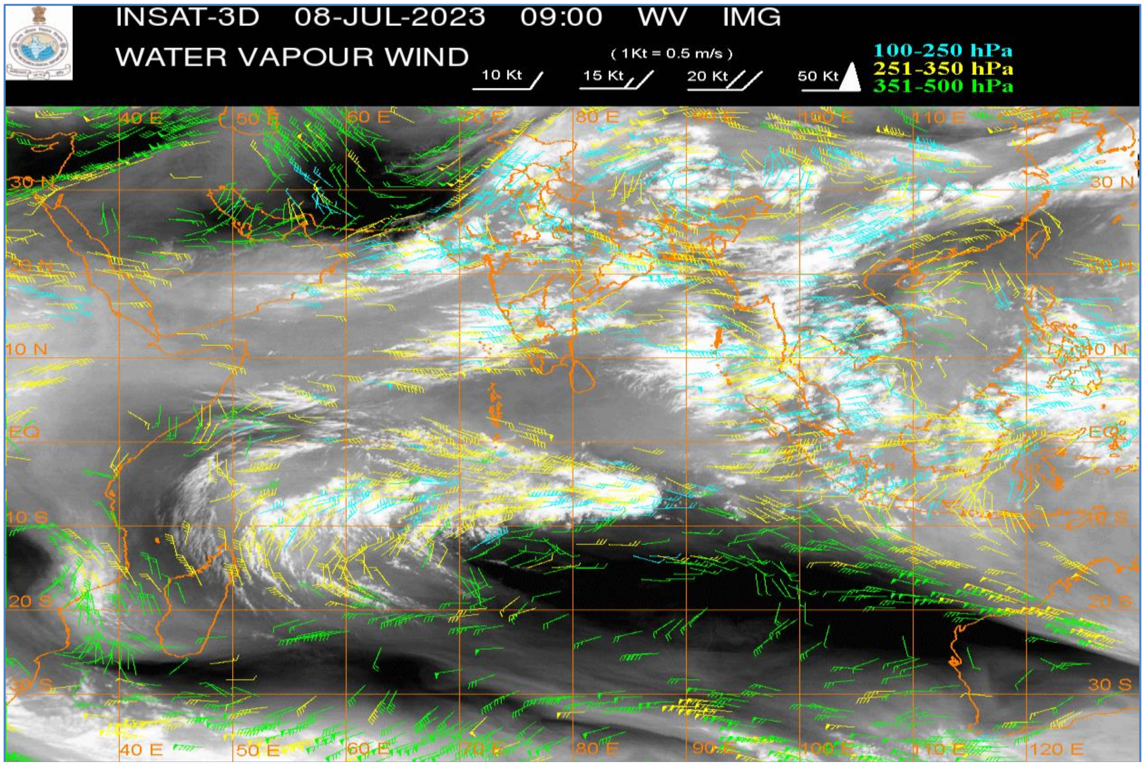


Fig. 2 : Water vapor winds derived from INSAT-3D data on 8 July,2023 at 09Z. The westerly trough referred to in Fig.1 is clearly seen in these water vapor winds at around 65 deg. East and North of 28 deg. North

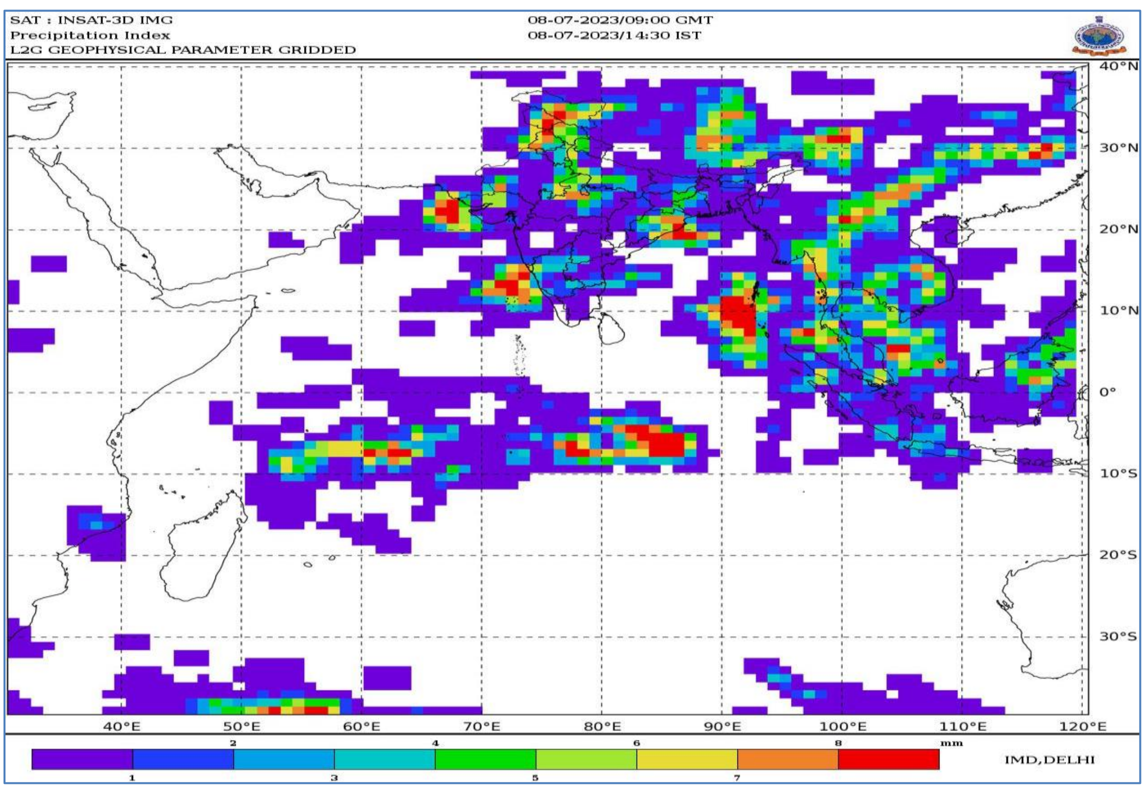


Fig. 3: INSAT-3D derived Precipitation Index for 8 July,2023 at 09 Z showing

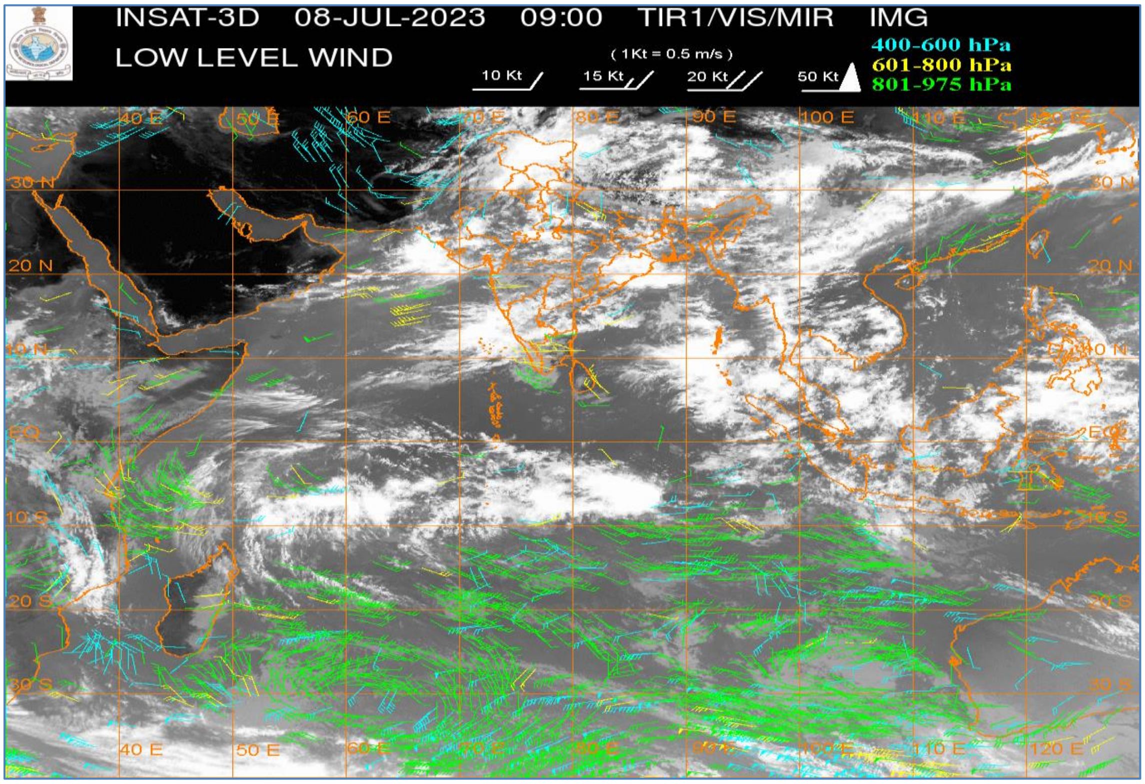


Fig. 4: INSAT-3D derived Low and middle level Cloud Motion Vectors (CMVs) on 8 July, 23 at 09Z. Middle level winds (Blue) clearly show the trough referred to in Figure 1

7. Applications of satellite cloud images and derived products for monitoring of Monsoon

A report entitled "Monsoon Monograph (Volume 1) published by India Meteorological Department in 2012 (Editors, Tyagi *et al*.,) contains a full chapter No. 8(i) contributed by Dr. O. P. Singh (Singh,2012) which covers all aspects of monsoon monitoring using satellite data. It has very well brought out all important features in INSAT images and products useful in monitoring onset of monsoon over Kerala coast for which satellite- based inputs are most vital. Important products such as Outgoing Longwave Radiation (OLR) and Low-level Winds are used in the objective criteria for declaring the onset of Monsoon over Kerala. Satellite images and products also provide useful inputs for monitoring further progress and advancement of monsoon till it covers the entire country. Based on use of KALPANA satellite images and the derived products, the report highlights applications for monitoring active, break and withdrawal phases of monsoon. In this regard results of several studies done in the past have been reported in the above publication.

8. Availability of new types of data from satellites other than cloud pictures

After the successful demonstration of using cloud pictures received from polar orbiting satellites in day-to-day work of weather forecasting from early 1960s in the USA, a series of such satellites were planned by the USA to provide continued availability of this new tool to the operational forecasters. Improvements in the capabilities of operational satellites were also incorporated from time-to-time based on the experiences gained in the earlier missions and the results of R&D work with NIMBUS program described in para 2 above. In addition to the most popular use of meteorological satellites in the form of cloud imagery data in different spectral channels, a large variety of other types of data are also available from meteorological satellites. These are, vertical profiles of temperature and humidity available from infrared and microwave based sounding instruments onboard various satellites, ocean surface wind speed, ocean surface wind speed and direction, precipitation measurements from space-based Radars, Total precipitable water vapor, soil moisture, hyperspectral sounders providing very accurate vertical profiles of temperature and humidity with a high vertical resolution, vertical profiles of temperature and humidity using GPS based Radio Occultation, atmospheric trace gases constituents, air pollution, land surface features, Lightning mapper, forest fires *etc*. Particularly data from Passive Microwave-based sensors

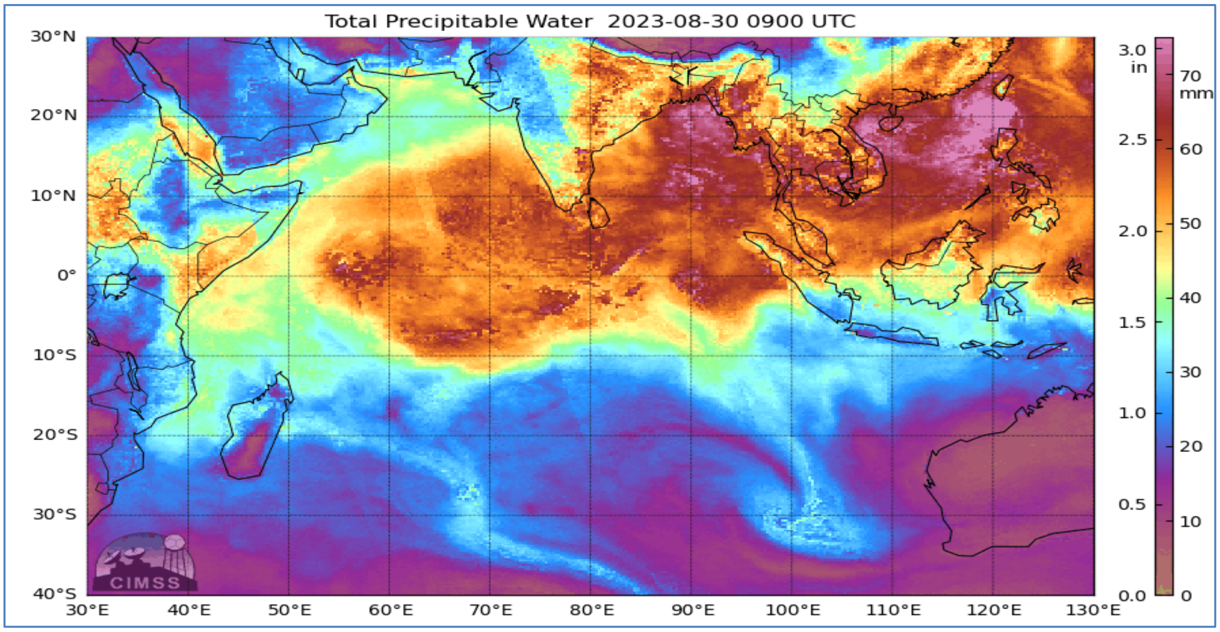


Fig. 5. Total Precipitable Water (TPW) imagery for 30 August,2023 associated with Break Monsoon conditions over India showing dry air over northwest India and very low levels of moisture over India (Source: Website of Cooperative Institute of Meteorological Satellite Studies, Wisconsin University, USA)

has been found to be extremely useful for providing additional information over cloudy regions and areas of rain where IR based sensors have some limitations. For example, after launch of NOAA-K, L, M series of polar satellites from 1998 onwards with microwave sounder of improved resolution, better observations of upper tropospheric warm core anomaly in cyclones were available which led to more accurate estimates of cyclone intensity (Kidder *et al*., BAMS, 2000). Data from microwave radiometers currently being operated on some polar satellites are also being used to generate animation sequences of Total Precipitable Water. Real-time availability of this product over land and oceanic areas is extremely useful for identifying areas of low pressure formations and for monitoring progress of monsoon and its different phases. A sample of this product for a Break Monsoon condition on 30 August,2023 is shown in Fig. 5. An excellent review of use of all types of satellite observations for weather prediction has recently been published in Mausam (Kishtawal, 2019).

R&D satellites series of NIMBUS program referred to above were later replaced by EOS (Earth Observation System) program of NASA, USA. Now such satellites for R&D purpose are being launched under Earth Enterprise System program. European Space Agency (ESA) have also their own program of launching R&D satellites for demonstrating capabilities of new payloads and they have launched many such missions. A joint INDO-FRENCH mission called Megha-Tropique is also an R&D mission launched successfully in 2011. India is also launching somenew satellites under Earth Observation System (EOS) program for R&D purpose of testing new payloads.

8.1. *Processing of sounder data at IMD*

Vertical temperature profile retrievals from satellite data were started in mid 1980s initially on a limited experimental basis at MDUC, Delhi by using the International TOVS Processing Package (ITPP) of Wisconsin University, USA available at that time. A study of temperature retrievals over the Indian region made on 13 selected stations data from different seasons in 1989-91 was done by Comparison of satellite retrievals with co-located Radiosonde stations (Khanna and Kelkar, 1993). Starting from the year 1992 when a new INSAT Meteorological Data Processing System (IMDPS) was installed at IMD as part of the INSAT-2 program, IMD started processing of sounder data transmitted by polar orbiting satellite series of the USA. New IMDPS had the capability of ingesting HRPT data stream and extracting the imager and sounder data for further processing to generate products for operational use. The system had some special software packages to generate profiles of temperature and humidity using the processed sounder data. These profiles were assimilated in the NWP models run at NCMWRF and IMD on an experimental basis. Later, in mid 1990s, another HRPT receiving station was established at Chennai to increase the coverage area (more southern latitudes) over the Indian Ocean region. It had the capability of generating high resolution images of earth's cloud cover and temperature and humidity profiles. These were used in day-to-day operations and for research work. Results of a few studies on North East monsoon, Tropical Cyclone movements and Ozone concentration using ATOVS data have been reported in some research papers of Mausam by R. Suresh (2001, 2002 and 2006).

A new receiving equipment was installed at IMD, New Delhi in the year 2000 to provide continuity of reception and processing of data to generate high resolution cloud pictures and processing of sounder data. Using data of Advanced Microwave Sounding Unit (AMSU) available from this equipment, results of some studies done on cyclones have been reported in Mausam (Singh *et al*., 2003). A case study with GONU cyclone data has been done (Mitra *et al*., 2010) using temperature retrievals from AMSU-A onboard NOAA-15 and 16 satellites using a neural network approach. Due to some major technical snag, this equipment stopped functioning from 2005. Later, as part of another new scheme, more versatile equipment were installed at three stations Delhi, Chennai and Gauhati in 2010 for reception and processing of high resolution imagery data and sounder data from METOPS and NOAA series of polar orbiting satellites. Derived products generated from these data were used at NCMWRF and IMD for assimilation in NWP models. Data was also used for research work. At present these equipment are not functional at IMD. Sounder data from INSAT-3 series of Geostationary satellites is however being processed operationally.

8.2. *Use of data from microwave based sensors*

From early 1990s IMD started using data from some of the Microwave based sensors available on polar-orbiting satellites of USA. Most prominent among these was Special Sensor Microwave Imager (SSMI) available on DMSP (Defense Military Satellite Program) series of US satellites. These data were found to be particularly useful for analysis of inner core structure and rain band structure of Tropical storms. They were not available in real-time mode. They were available in a delayed mode for research purposes. Jha *et al*., (2013) reported results of a study to estimate intensity of cyclone over Bay of Bengal using microwave imagery. Kalsi (2006) used this data for analysis of Orissa Super cyclone,1999. ISRO had also planned to launch some new satellites with microwave-based sensors. First such satellite launched in 1999 was OCEANSAT-1. It provided data on ocean surface wind speed and total precipitable water vapor. These were used to study the heavy rainfall producing events along the west coast. IMD also collaborated with SAC, Ahmedabad for study of onset of Southwest Monsoon over Kerala using these new types of data available from OCEANSAT-1. Joint IMD-ISRO reports were generated for the years 2000, 2001 and 2002 bringing out the results of findings. IMD had also started using data on ocean surface wind speed and direction available from the Scatterometers (Active Microwave based instruments) which were available from foreign satellites. These data were particularly found to be useful for monitoring of cyclones and low pressure systems forming over the oceans. Later, ISRO had also launched a satellite with a scatterometer payload and its data used by IMD in real-time for monitoring of systems over oceans. Amudha *et al*., (2018) studied the differential patterns of surface winds over Bay of Bengal during various phases of Indian northeast monsoon derived from QuickSCAT scatterometer data. Recent advances in observational support from space-based systems for tropical cyclones have been covered adequately in a paper (Bhatia *et al*., 2013).

8.3. *GPS based Total precipitable water vapor*

A new initiative was started by IMD in the year 2003 to establish some ground-based GPS stations for monitoring of Total precipitable water vapor at a few locations. This is a well-known technique being operationally used by some of the weather services in the world. Some countries have a very large network of such stations and they assimilate this data in NWP models. Hence a beginning was made in IMD by planning a network of 5 stations to start with. These systems were procured and installed in 2007 and operational use of this new type of data started soon thereafter after performing validation tests. Details of this system are presented in a paper published in Mausam (Puviarasan *et al*., 2010). Results of a detailed study done on the impact of using this data in NWP models have been reported (Surya K. Dutta *et al*., 2014). A data quality analysis of IPWV (Integrated Precipitable Water Vapor) using different GNSS antenna has been done and results reported in a paper (Yadav *et al*., 2012).

9. Use of satellite data in NWP

Satellite based observations now form a very important part of data assimilated into the Numerical Weather Prediction models all over the world. More than 90% of data assimilated in NWP models comes from the Space based systems. Many studies have brought out positive impact of assimilating data from space-based systems into the NWP models in operational use at all centers of the world. Satellite data of various types therefore forms most essential input to the NWP models. Maximum impact comes from Advanced Microwave Sounding Unit (AMSU-A) onboard NOAA and METOPS series of - orbiting satellites.

9.1. *Results of Impact studies at NCMWRF, India*

Many studies have reported the importance of wind observations compared to the mass observations in NWP over the Tropics due to the non-existence of quasi-geostrophic balance. Satellite winds, commonly known as Atmospheric Motion Vectors (AMVs) play an important role over the remote regions and over the Oceans where in-situ observations are sparse. NCMRWF assimilates AMVs from many geostationary and polar satellites. Geostationary AMVs from INSAT, Meteosat, Himawari, COMS, and GOES platforms, polar AMVs from AQUA, Terra, NOAA and MetOp series satellites, and the dual satellite winds derived from MetOp series of satellites are routinely assimilated in the NCMRWF assimilation systems. AMVs have very high positive impact in reducing the error in the short-term forecasts (Kumar *et al*., 2021).

NCMRWF validated the quality of Kalpana Satellite AMVs and continuously provided feedback to ISRO and IMD. This consistent feedback and hence modification/developments in the AMV retrieval algorithms improved the quality of Kalpana winds and became comparable with that from other satellites over the same geographical region (Rani and Gupta, 2013). Similar validation and quality control of INSAT-3D/3DR AMVs has also been carried out routinely at NCMRWF. Observing System Experiments (OSEs) show that the impact of INSAT-3D/3DR AMVs is similar to that of Meteosat derived winds over the IODC region. Along with Indian Geostationary satellite AMVs, NCMRWF evaluates the impact of other AMVs, particularly over the Indian region. An assimilation experiment to check the impact of Meteosat-Indian Ocean Data Coverage (IODC) satellite AMVs revealed that the analysis increments in the humidity and wind are largely driven by the AMVs (Bushair *et al*., 2021).

Similar to the AMVs from the Indian satellites, NCMRWF also ensures the quality of sea surface winds onboard Indian satellites. Oceansat-2 sea surface winds were validated against in-situ buoy observations and other global scatterometer missions. These studies have reported that the quality of Oceansat-2 scatterometer winds are within the mission goal, better than 2m/s error in wind speed and better than 20° error in wind direction (Rani, *et al*., 2014). After the successful validation of Oceansat-2 winds NCMRWF assimilated the same in the operational models. Scatsat-1 was the next Indian scatterometer mission after decommissioning of Oceansat-2. The validation and assimilation of Scatsat-1 winds shows their quality and impact are similar to the Oceansat-2 winds in the NWP system (Bushair *et al*., 2021 and Johny *et al*., 2019).

Scatterometers provide reliable wind information over the ocean surfaces, but no information aloft. More wind observations at all levels of the troposphere and stratosphere are required for a better understanding of tropical dynamics. NCMRWF ventured to analyse and assimilate the wind profiles from the first space-based Doppler Wind Lidar (DWL) onboard the European satellite, Aeolus launched in 2018. Validation against various in-situ winds, AMVs and NWP model equivalents suggest that the characteristics of Aeolus winds at different vertical levels and geographic regions remain same irrespective of the validation datasets. The Indian summer monsoon features like Low Level Jet (LLJ) and Tropical Easterly Jet (TEJ) are well represented in the Aeolus winds, both in the ascending and descending passes (Rani *et al*., 2022). Assimilation of Aeolus winds in the NCMRWF NWP systems showed beneficial impact, particularly in the upper tropospheric wind. Aeolus wind assimilation also helped to improve the track and intensity simulation of tropical cyclones (George *et al*., 2021).

NCMRWF assimilates radiances from various geostationary and polar satellites in its operational systems. Radiances from various polar multispectral (ATMS, ATOVS, AMSR-2, SSMI/S, GMI) and hyperspectral (IASI, CrIS, AIRS) instruments along with geostationary multispectral radiances (INSAT-3D, INSAT-3DR, SEVIRI, ABI, AHI) are operationally assimilated in the NCMRWF data assimilation systems. Impact of various satellite observations in the NCMRWF assimilation systems are investigated through Forecast Sensitivity to Observation Impact (FSOI) technique. Special effort and emphasis are given to the assimilation of radiances from Indian satellites. Assimilation of INSAT-3D Water vapor channel clear sky radiances shows the impact on the humidity and upper tropospheric winds over the Tropics (Rani *et al*., 2019). This study also brought out the complementarity of AMV and clear sky radiance assimilation over the Tropics. Similar results are obtained when the OSEs were repeated for Meteosat-IODC observation. Apart from multispectral infrared radiances from geostationary satellites, NCMRWF receives hyperspectral infrared radiances from many instruments onboard polar orbiting satellites. NCMRWF routinely assimilates hyperspectral radiances from IASI, AIRS and CrIS instruments. The combined impact of hyperspectral radiance assimilation in the NCMRWF NWP system has been analysed using Observing System Experiments.

The humidity Sounder observations from SAPHIR onboard Megha-Tropiques were utilized in almost all the leading global operational NWP centres. NCMRWF was the first to assimilate SAPHIR data in an NWP system by introducing a new methodology to remove the radiance pixel significantly affected by clouds (Kumar and Prasad, 2017). The impact of different SAPHIR channels and their comparison with similar channels from instruments onboard other satellites were also studied in details at NCMRWF. The impact of assimilating various SAPHIR channels on the simulation of tropical cyclones over the North Indian Ocean was also explored at NCMRWF. EOS-07 is an experimental mission recently launched by ISRO. Both Megha-Tropiques (20°) and EOS-07 (37°) are satellites in the inclined low earth orbits. NCMRWF carried out a brief review of the NWP requirements of microwave instruments in the low earth inclined orbits. The Millimeter Wave Humidity Sounder (MHS) onboard EOS-07 is the successor to SAPHIR with 6 channels in the 183.31 GHz. A thorough analysis of the weighting functions of the two instruments shows that EOS-07 channels peak slightly lower in the atmosphere compared to the SAPHIR channels. NCMRWF computed the FASTEM coefficients to assimilate the EOS-07 sounder radiances. Preliminary OSE results show that assimilation of EOS-07 sounder radiances slightly reduced the errors in the analysis.

In addition to the satellite winds (AMVs, Sea surface winds, and Aeolus wind profiler), NCMRWF routinely assimilates global GNSS-RO data from different satellites. COSMIC-2 series (5), MetOp Series (2), FY-3D, KOMPSAT, Sentinel-6, SPIRE and Geo-Optics are to name a few. The impact of various GNSS-RO observations in the NCMRWF assimilation systems are well documented. ROSA, GNSS-RO onboard Megha-Tropiques is another space-based observation from Indian satellites explored extensively at NCMRWF. GNSS-RO observations act as an anchor for the bias correction of satellite radiances. GNSS-RO has sharper weighting functions in the vertical and hence they can see the vertical structures that are in the "null space" of the satellite radiances. Since the GNSS-RO information content is largest in the "core region, between 7 and 35 km, a large NWP impact on upper tropospheric and lower/middle stratospheric temperatures is noticed.

Land surface variables such as soil moisture play a major role in the exchange of moisture and heat between the land surface and the atmosphere. Assimilation of land surface variables aims at constraining errors of the numerical weather prediction by providing the improved initial surface conditions. NCMRWF assimilates MetOp ASCAT soil moisture in the global and regional data assimilation systems. ASCAT soil moisture assimilation improves the prediction of monsoon depressions and influences the track and intensity of the tropical cyclones during landfall (Routray *et al*., 2023).

NCMRWF has produced two atmospheric reanalyses, one global based on NGFS and the rgional based on the Unified Model. The regional reanalysis, Indian Monsoon Data Assimilation and Analysis (IMDAA) is the satellite era reanalysis over India and surrounding Oceanic regions. IMDAA used satellite data throughout the period of 42 years (1979 -2020), starting from TOVS. Various satellite radiances assimilated in the NCMRWF reanalysis are TOVS, ATOVS, SEVIRI, MVIRI, AIRS, IASI, CrIS, ATMS and SAPHIR in addition to the satellite winds (AMVs and Sea surface winds). Different satellite observations used in the NCMRWF reanalysis and their quality control and impact are well documented (Rani *et al*., 2021). These are the only reanalyses which assimilated the Indian satellite observations.

9.2. *Important Impact studies at other centers* :

In NWP, introduction of new satellite measurements has substantially improved forecasts over recent decades. One of the early use of satellite information in NWP was assimilation of Temperature and Humidity profiles (Derived from TOVS onboard NOAA series of satellites) in the NWP models. A positive impact in the Radiosonde rich Northern Hemisphere was found initially. After a paradigm shift of using TOVS measured radiances directly in the variational assimilation system, instead of derived soundings, the positive impact was established more clearly. In the area of satellite derived winds, more positive impact on NWP was found after height assignments to derived wind vectors was improved. Wind information from satellites is most important, particularly over Tropical and Subtropical oceans as emphasized by ECMWF in the early years. Forecast skills have also improved considerably. Some improvements in forecast skill are also attributable to advances in modelling and assimilation. However, the gap between the forecast skills for the Northern and Southern Hemispheres has vanished from late 1990s onwards primarily due to satellites. The addition of satellite observations in NWP systems have enabled the forecasts to be equally skillful in the Northern and Southern Hemispheres.

One of the major types of satellite information for use in data assimilation system is IR radiances, particularly from the hyperspectral sounders on board polar-orbiting satellites. There is a large positive impact of using them in NWP models. Latest research has shown that provision of a hyperspectral sounder on Geostationary satellites would be more useful for observing the evolution of rapidly changing weather systems. Most of the countries have their future plans for hyperspectral sounders on Geostationary satellites. Results of an OSSE to evaluate impacts of future Geostationary hyperspectral

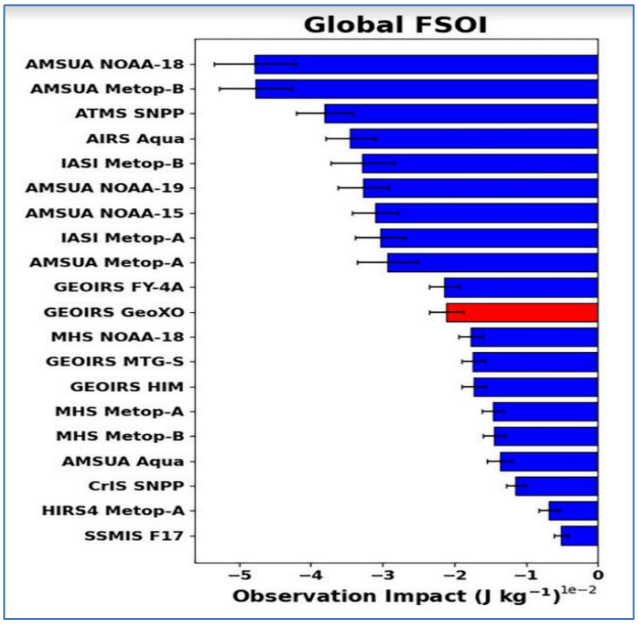


Fig. 6. FSOI per analysis as a function of satellite radiance instrument calculated globally for the 0000 UTC analysis, (J kg-1). The impact of the GEOIRS instruments was computed without the influence of the assimilated channels that are outside the specification of the proposed GXS instrument. Error bars indicate significance at the 90% level. The GXS instrument is highlighted in red. (Source : Erica L. et al., JAOT, Dec.2022)

sounders on NWP have been recently reported in an excellent paper (Erica L *et al*., December,2022). Particular focus is on the proposed sounder on board the Geostationary Extended Observations (Geo-Xo) program's central satellite of the USA.

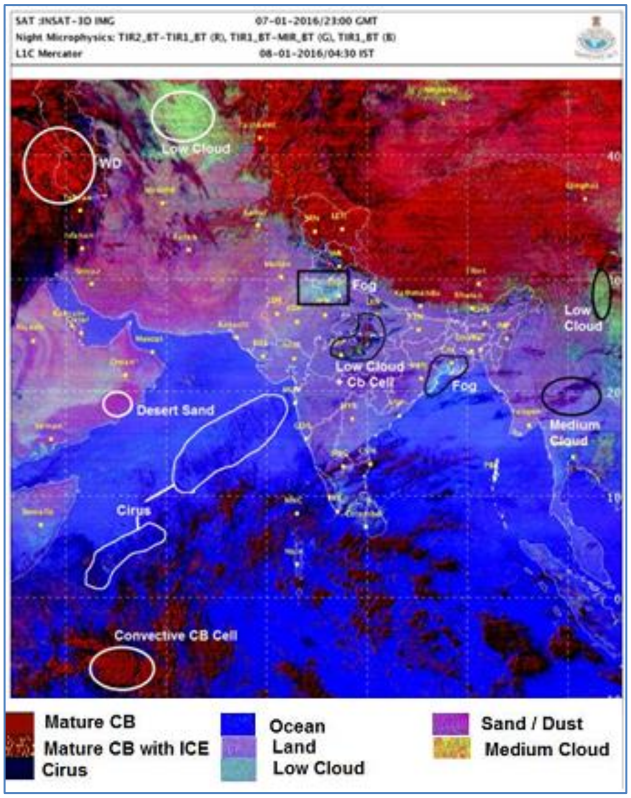
The global FSOI, examining only satellite radiances, is shown in Fig. 6. These results show the 24 h error impact for the 0000 UTC forecasts only and it is apparent that polar orbiters generally perform better than observations from geostationary orbit using this global metric. This is due to polar orbiters always sampling somewhere in the domain and are capable of observing the full globe. Since observations are always occurring within the domain, the disadvantage of only sampling a given area twice a day is not strongly felt by this metric and all observations are capable of impacting the error calculation. Among the geostationary infrared sounders, the GXS instrument performs well, roughly in the middle based on this metric. Globally, the GXS performs more poorly than the polar-orbiting satellites because it is incapable of observing regions outside its specified domain and therefore cannot directly impact error reduction in areas far away. However, operation of hyperspectral sounders on geostationary satellites is found to be more useful for improving forecast skill.

10. Latest trends of multispectral images and RGB products

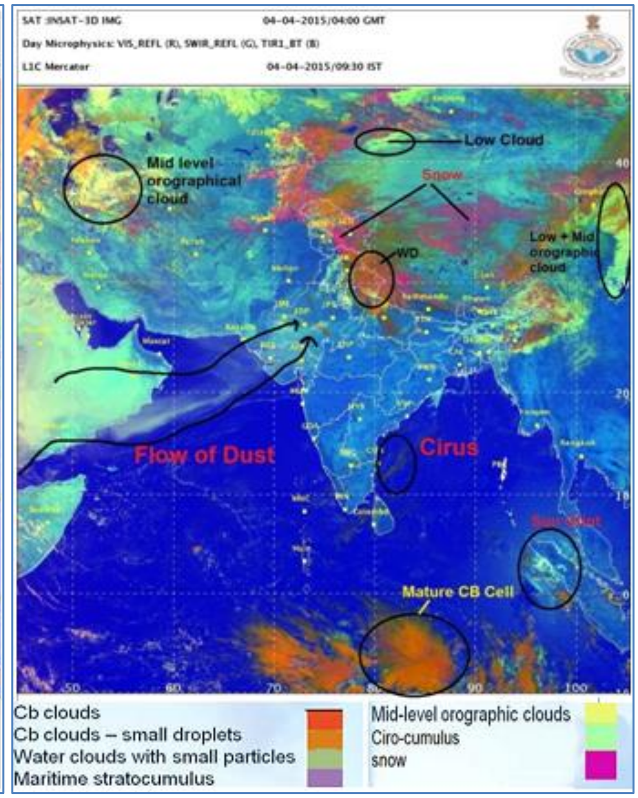
Developments in technology of earth imaging instruments over the years have resulted in much improved capability of imagers onboard meteorological satellites. Starting with just two channels (VIS and IR) in early 1960s, the imagers onboard polar orbiting satellites in late 1970s had six channels. Later, well known MODIS instrument onboard Aqua and Terra satellites of the USA had the capability of earth imaging in 36 channels. Thus, a new era of multispectral imaging onboard polar orbiting satellites was started with MODIS instrument. Large number of channels provide much more detailed information about earth's atmosphere and land surface properties than what is available from a few channels. In addition, by combining different channels, certain specific features can be brought out which enables much better analysis for various applications. Number of useful products can be derived by combining different channels. Multi-spectral composites combine satellite data collected at different wavelengths of the electromagnetic spectrum and present them as red-green-blue (RGB) images, which serve as enhanced representations of specific phenomena such as fog, convection, fire, low clouds, dust, snow, ice, volcanic ash, air masses of different characteristics *etc*. RGBs are an excellent way to display multi-spectral information in a single easy-to-interpret image. They help to enhance meteorological features of specific interest and provide critical information to forecasters for situational awareness and nowcasting rapidly changing weather.

Now the latest trend in imagers onboard Geostationary Satellites is multispectral imaging in 12-16 channels. Most of the satellite operators in the world are having this capability on their operational Geostationary satellite systems. In India, the imagers on current series of operational Geostationary Meteorological satellites (INSAT-3DR and 3DS) are of six channels. Some limited RGB products are being derived even with the 6 channels data at the INSAT-3D/R/S data processing facility of IMD. However, multi-spectral images and derived products are also available over the Indian region from the EUMETSAT's METEOSAT-9 satellite located over the equator at 44.5 deg. East longitude since September,2016. RGB products are also available over large parts of India from HIMAWARI satellites of Japan and FY series of Chinese satellites.

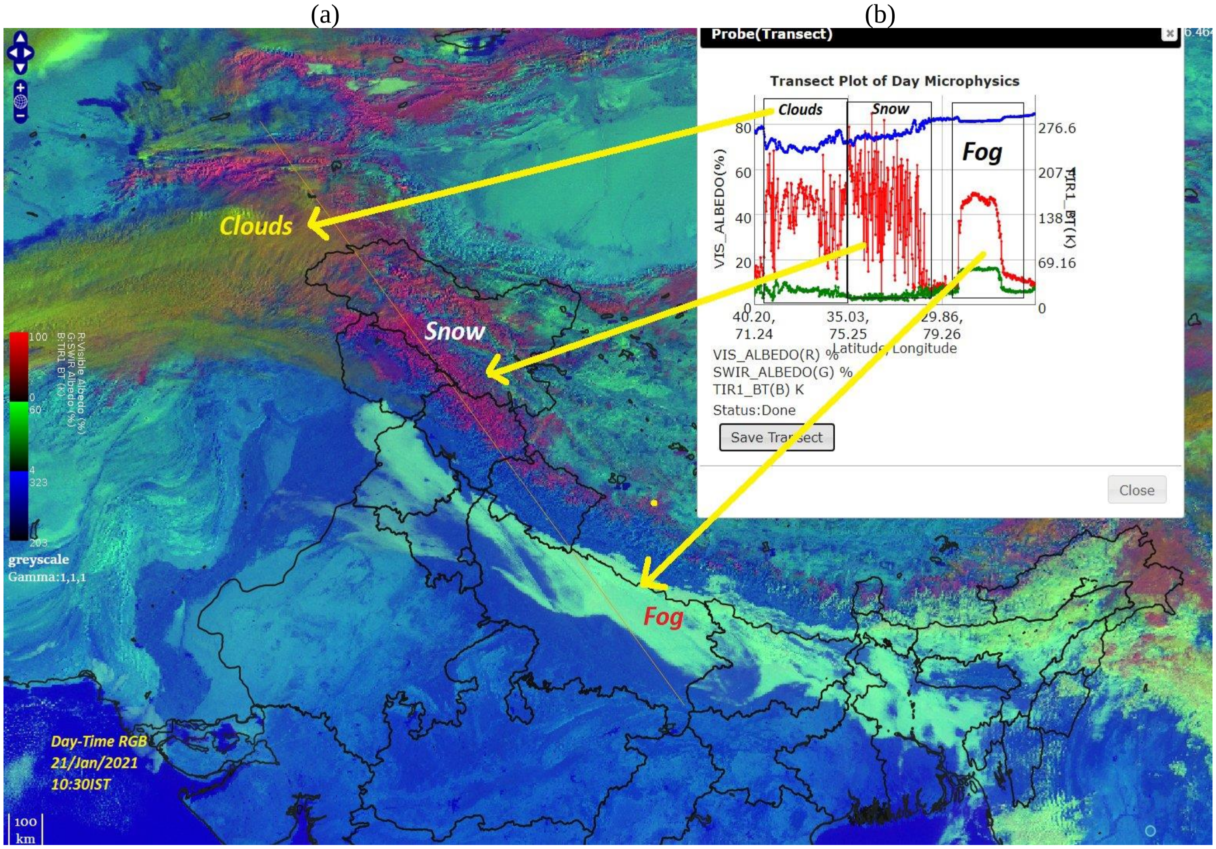
Mitra, *et al.*, (2019), have presented a day and nighttime microphysics RGB scheme using RAPID visualization tool for INSAT-3D data on a real-time basis for identification of weather events. A threshold technique has been developed for both RGB products for years


WD
Low Cloud
Fog
Low Cloud
Low Cloud + Cb Cell
Fog
Desert Sand
Medium Cloud
Cirus
Convective CB Cell
Mature CB
Mature CB with ICE
Cirus
Ocean
Land
Low Cloud
Sand / Dust
Medium Cloud

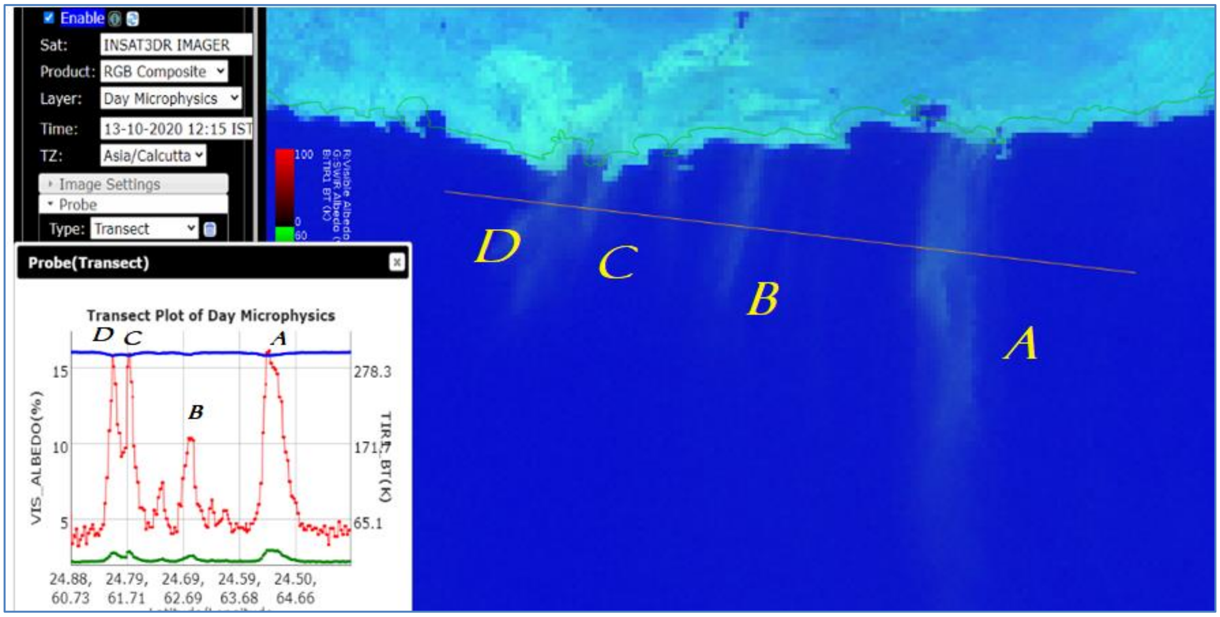
(a)


Low Cloud
Mid level orographical cloud
Snow
WD
Low + Mid orographic cloud
Flow of Dust
Cirus
Mature CB Cell
Cb clouds
Cb clouds – small droplets
Water clouds with small particles
Maritime stratocumulus
Mid-level orographic clouds
Ciro-cumulus
snow

(b)


Probe(Transect)
Transect Plot of Day Microphysics
Clouds
Snow
Fog
VIS_ALBEDO(%)
TIR1_BT(K)
Latitude, Longitude
VIS_ALBEDO(R) %
SWIR_ALBEDO(G) %
TIR1_BT(B) K
Status:Done
Save Transect
Close
Clouds
Snow
Fog
greyscale
Gamma:1,1,1
Day-Time RGB
21/Jan/2021
10:30IST
100 km

(c)



(d)

Fig. 7. INSAT-3D RGB composition of the (a) DTMP color scheme and (b) NTMP color scheme (c) Spectral signature of Snow/Fog and cloud and (d) Dust

2015-16 and 2016-17 for the months March-June. The technique yields very good results on probability of Thunderstorm detection more than 94% and 93% with false alarm conditions of less than7% and 9% for the two RGBs. It is found to be very useful for day-to-day weather forecasting. In another paper similar study has been done for fog, snow and low cloud detection (Mitra, *et al*., 2018). Fog detection probability has been found to be 94% and 85% with false alarm conditions of less than 8% and 10% for the two RGBs.

Recently, Mitra, (2023) has demonstrated identification of snow/fog/cloud and dust regions using visible, shortwave IR and thermal infrared satellite RGB imagery during daytime. When these phenomena appear in the scene at the same time, interpretation via single-channel imagery comparisons becomes extremely difficult. In Fig.7(a), snow and ice clouds appear red because they strongly absorb in 1.6µm. In western disturbance, small particles of ice cloud look orange, whilst giant particles of ice cloud (Mature Cumulonimbus (CB) cell) appear with a higher red component. Snow grains are usually larger than cloud ice particles, and they appear full red on the ground. Fig. 7(b) is designed to monitor the evolution of night-time fog / low stratus and different types of clouds in the night time. Apart from this, other applications are detection of night time fog, detection of fires, low-level moisture boundaries and cloud classification and dust movement. BT difference between the 12.0 and 10.8µm channels (12.0-10.8) in Night Time Micro Physics (NTMP) is a measure of cloud opaqueness and is shown in red, whereas the BT difference between the 10.8 and 3.9µm channels (10.8-3.9) modulates the green beam.

In NTMP, white fog occurs with small drips or shallow clouds. These spectral signatures of the snow/fog and clouds can be well analysed with RGBs and are shown in Fig. 7(c). On January 21, 2021, a western disturbance with induced cyclonic circulation was approaching towards western Himalayas and northern parts of the country. At 10:30 IST, DTMP RGB shows 3 different colour schemes *i.e*., clouds over northern Afghanistan, snow over Jammu and Kashmir and fog over Indo Genetic plains. Transect plot of these events can be seen in Fig. 7(c). High cirrus cloud exhibits lower thermodynamic temperature than a snow-covered background. However, in the visible (0.5 µm) region, highly reflective snow cover contrasts fog and cloud features (VIS>SWIR), whereas the lower absorption (SWIR>VIS) properties of SWIR (1.6µm), clearly distinguishing fog from cloud and snow. Because of the larger reflectance in the SWIR (1.6µm), and visible (0.5 µm), dust appears bright cyan. Here, unlike snow and cloud, dust exhibits higher temperature from the TIR band. Transect plot of dust on 13 October 2020 across northern parts of Arabian sea marked as A,B,C and D is shown in Fig. 7(d). In all the cases (A,B,C and D), reflectance from SWIR (40-55%) is higher than the visible (15-18%) (SWIR>VIS) along with higher TIR (10.8-µm) values (>293K). It is because dust is less absorptive at the 10.8-µm wavelength and largely influenced by the

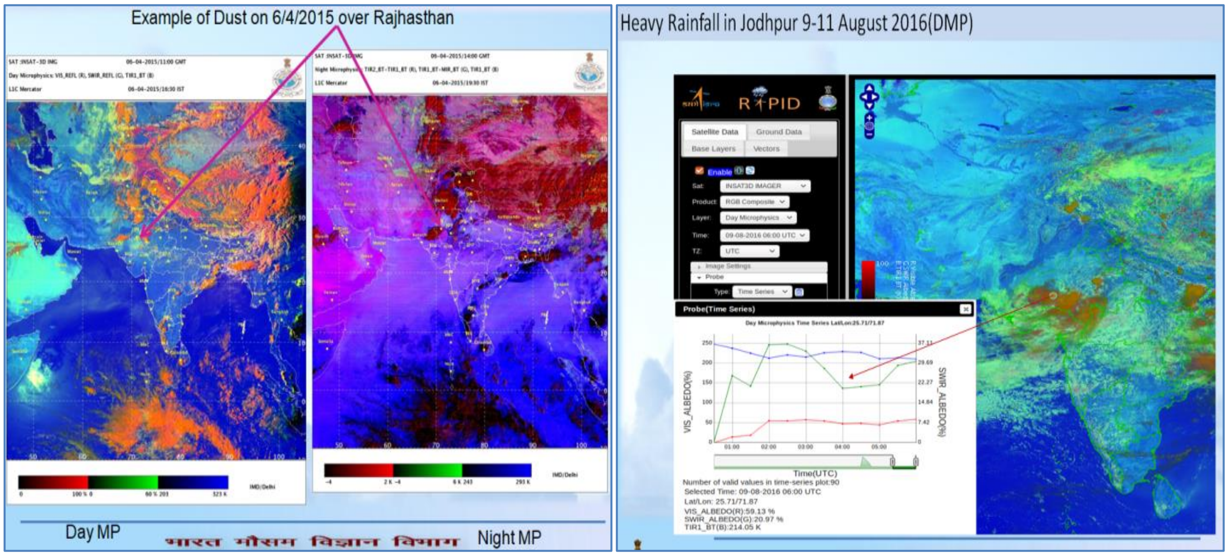


Fig. 8. Examples of Dust storm on 6 April,2015 and Heavy rainfall on 9-11 August,2016 from RGB DMP

underlying surface emissions, therefore have a warmer brightness temperature.

Another example of RGB products is shown in Fig. 8. It shows dust over Rajasthan on 6 April,2015 and Heavy Rainfall over Jodhpur in August, 2016

In another recent research article (Mohapatra *et al*., 2021) have very nicely brought out the utility of Rapid scan (Every 4 minutes) observations from INSAT-3DR satellite. Such observations are found to be very valuable for mesoscale data assimilation schemes. A time sequence of 4 minute of 10.7-μm IR window channel imagery demonstrates the rapid convective development in the form of higher degrees of brightness temperature (BT) variation with satellite derived INSAT Multispectral rainfall (IMR) product between successive images. In most of the areas there is an increase in BT of 1K to 20K. In certain areas increase of more than 20K and a decrease of up to 30K can also be seen simultaneously. Usually, the cold cloud top (decrease in the BT in successive image) pixels associated with over shooting cloud tops are especially important when monitoring rapidly developing systems and it represents the cloud-top emissivity (CTE). The time change in CTE can be interpreted as a cloud-top cooling rate. In the normal scan mode these cooling rates are not properly represented. Similar variations were also noticed in the INSAT IMR product. Between 06 UTC to 0630 UTC, it has been observed that IMR increased by 0.05-0.15 mm in certain areas and in some other areas it decreased by 0.3mm. This demonstrates that the higher time resolution is especially important when monitoring rapidly developing convective systems and associated weather with heavy rainfall spells and thunderstorms. The rapid variations on CTBT can also be used for monitoring the cloud-to-ground lightning over the Indian region.

The most important information obtained from INSAT3DR RAPID SCAN mode include more number of cyclone images at shorter scan intervals of 4 minutes approximately, relative to the operational normal scan mode of 30-minute full disk over the Indian region. The 4 minute satellite scan image data could aid in the recognition of weakening or intensifying trends during lack of texture of cyclones, helping in nowcasting, variation of internal structure in terms of eye and eye wall characterization, associated convection and precipitation. The early clue can be detected by rapid warming or cooling in the 4-min IR imagery, it is especially important to forecasters at night in the absence of visible imagery. One such event of strengthening (in Fig. 9) and weakening (in Fig. 10) of VSCS 'TITLE' is demonstrated.

There is also scope to derive the atmospheric motion vectors (AMV) and quantitative precipitation estimates (QPE) from the RAPID SCAN for direct use in NWP modelling as well as severe weather forecasting.

11. Outlook for future

At present operational meteorological services are available from the two satellites of INSAT-3 series viz., INSAT-3R and INSAT-3S. Therefore, availability of adequate space-segment for next few years for operation of meteorological services is ensured. The most recent satellite (INSAT-3S) is expected to provide operational services sometime up to 2032. This is the last satellite of INSAT-3 series.

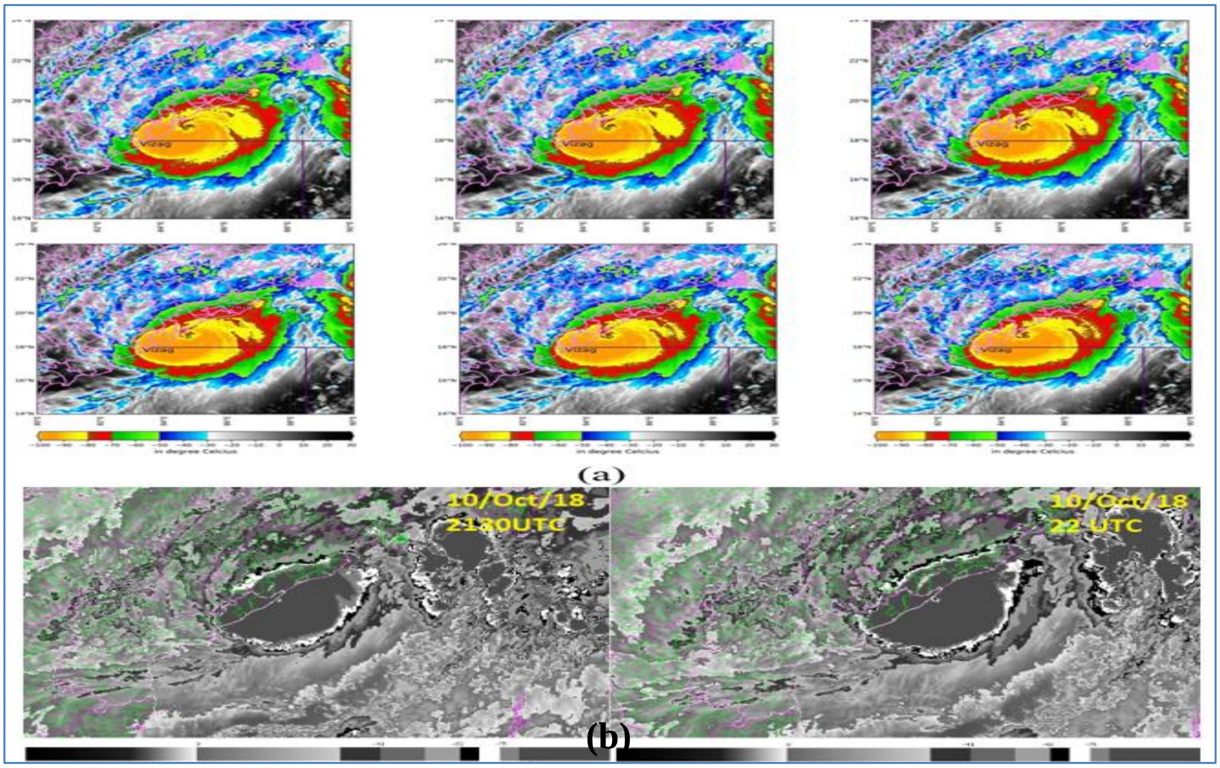


Fig. 9. (a) Rapid Scan Images for TIR1 Temperature from 2115 to 2206 UTC of 10th October (b) Normal Scan of TIR1 from 2130UTC to 22 UTC. (Source: Mohapatra *et. al.*, 2021)

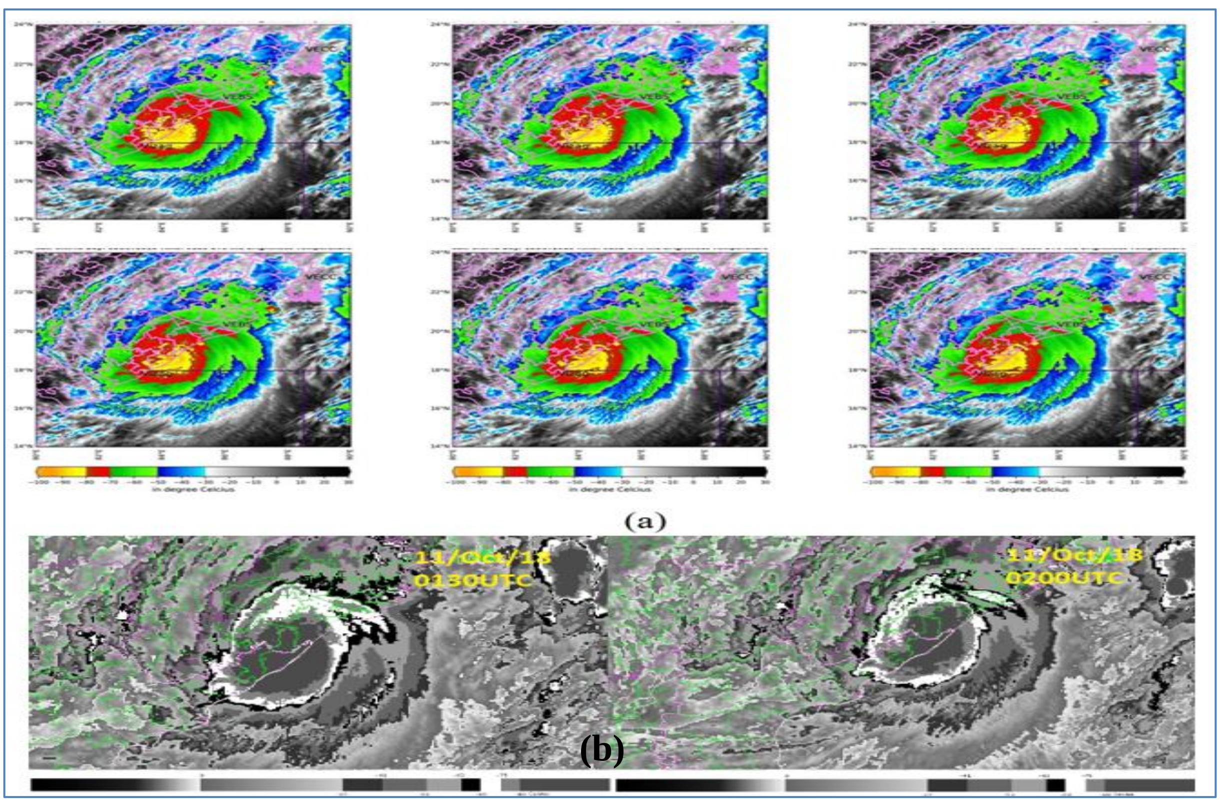


Fig.-10. (a) Rapid Scan Images for TIR1 Temperature from 0145 to 0206UTC of 11th October 2018 (b) Normal scan of TIR1 from 0130UTC to 0200 UTC. (Source: Mohapatra, M *et.al*., 2021)

In order to further upgrade the capability of future operational satellites of INSAT series for meteorological applications, provision of a payload with multi-spectral imaging is being considered with a very high priority. Other advanced countries of the world are already operating such satellites. As a major step in this direction, an experimental satellite equipped with a multi-spectral imager of very high resolution has been planned by ISRO for launch sometime in the year 2025. A new experimental satellite called GISAT-1 (Geostationary Imaging Satellite), an Indian earth observing satellite, will be launched in a geostationary orbit to facilitate continuous observations of Indian subcontinent for quick monitoring of natural hazards and disastrous events. Its imaging payload will consist of a multispectral imager (In visible, Near IR and Thermal Infrared bands) with resolutions ranging from 50 m to 1.5 km. Some hyperspectral channels of very high resolution will also be included.

Planning work is also in progress to define the meteorological payloads onboard the next generation of INSAT satellite series (INSAT-4 satellites) to be launched sometime in 2027-2029 time frame. After lot of technical discussions in meetings of the Joint IMD-ISRO task group, it has been decided to include the following major payloads on INSAT- 4 satellite series. (*i*) High Resolution multi-spectral Visible/ IR imagers (*ii*) IR based hyperspectral sounders (*iii*) Lightning Imagers. Instruments design and fabrication related work for this project has been initiated at ISAC, Bangaluru of the Indian Space Research Organization (ISRO). Meteorological payloads of future Indian satellites will therefore be on par with those of other countries operating similar satellites. Foundation for accomplishing this objective will be laid during the year 2025 after launch of GISAT-1 as described above. This will provide useful experience for future operational Indian satellites with more advanced payloads for meteorological applications.

12. Summary

During the last 64 years there has been considerable growth all over the world in the field of Satellite Meteorology. Starting with a very modest beginning in early 1960s, of receiving low resolution cloud pictures twice a day from the polar orbiting satellites at a few locations, at present round-the-clock pictures are being received from advanced Geostationary meteorological satellites equipped with powerful instruments. Satellite Meteorology is no longer limited to the use of only cloud pictures for monitoring of weather systems for day-to-day operational work of weather forecasting. Satellite-based systems now offer a very wide variety of instruments to provide different types of data useful for many applications. In fact, amount of data available from satellite systems is very large. Powerful computers are needed for real-time processing of data, generation of a large variety of products for operational use and assimilating the data and products in different types of NWP models. In fact, it is difficult to think of running the NWP models without any data inputs from space-based systems. Large amount of data (More than 90%) that goes as an input to the numerical models for defining the initial conditions, comes from the space-based systems. This is true for all NWP centers of the world and India is not lagging in this regard. NWP centers in India are assimilating a large amount of satellite data from Indian as well as foreign satellites. There is a large positive impact of using satellite data in NWP models being run operationally at various centers in the world.

Future of Satellite Meteorology in India is very bright as more powerful sensors are being planned for deployment onboard future generations of Indian meteorological satellites. Therefore, there are lot of challenges in developing the advanced technology payloads for use on future satellite systems of India. Since the amount of data available from the future satellite systems is going to be very large, appropriate developments also need to be done for processing of data at the ground stations and generating new products for operational use. There is a need for very fast processing using combinations of different channels available from sophisticated multi-channel payloads and analyzing quickly all the data products to enable effective use during real-time operations. End objective is to issue better forecasts and timely warnings for adverse weather expected from different weather situations. Maximum use of all available products will ensure timely warnings for the users. Lot of emphasis also needs to be laid on proper human resource development to handle a large variety of tasks and challenges before the weather forecasters.

Acknowledgements

Authors would like to express their sincere thanks to Dr. V. S. Prasad, Head, NCMWRF and Dr. Indira Rani, Scientist, NCMWRF for their valuable inputs on results of recent scientific works done at NCMWRF on assimilation of satellite data and their impacts on NWP model based forecasts. Thanks are also due to Tropical Cyclones Team at CIMSS, Wisconsin, USA for their support on use of satellite products available on website

References

Tyagi, Ajit, Asnani, G. C., De, U. S., Hatwar, H. R. and Majumdar, A. B., 2012 "*Monsoon Monograph*, **1**, India Meteorological Department.

Kumar, Amit, Singh, Virendra, Mukherjee, Sunil and Singh, Randhir 2019, "Quality assessment of Outgoing Longwave Radiation (OLR) derived from INSAT-3D imager: Impact of GSIC correction", *Mausam*, **70**, 2, 309-320.

Rao, A. V. R. K., KELKAR, R. R. and Arkin. P. A., 1989, "Estimation of precipitation and outgoing longwave radiation from INSAT - 1B radiance data", *MAUSAM*, **40**, 2.

Bhatia, R. C. and R. K. Jain, 1993, "Arc clouds in INSAT images and their operational utilization in aviation meteorology, *Vayu Mandal*, **23**, 1-2, 19-24.

Bhatia, R. C., Meena, L. R. and Thomas, S. I. T., 1989," Meteorological data dissemination through INSAT, *Vayu Mandal*, 19, 3-4, 114-118.

Bhatia, R. C., 1991, "Second Generation INSAT system (INSAT-II) and meteorological ground segment", *Vayu Mandal*, **21**, 3-4, 91-100.

Bhatia, R. C., Brij Bhushan and V. Rajeswara Rao ,1999, "Applications of water vapor imagery received from INSAT-2E satellite", *Current Science*, Special Section: INSAT-2E, **76**, 11, 10, 1448-1450.

Bhatia, R. C. and H. V. Gupta, 1999, "Use of Charge Coupled Device payload on INSAT-2E for meteorological and agricultural applications", *Current Science*, Special Section: INSAT-2E, **76**, 11, 1444 – 1447.

Bhatia, R. C. and A. K. Sharma, 2013, "Recent advances in observational support from space-based systems for tropical cyclones", *Mausam*, **64**, No.1, 97-104 (Special Issue: BOBTEX 2011).

B. Amudha, Y. E. A. Raj and Rm. A. N. Ramanathan, 2018, "Differential patterns of surface winds over Bay of Bengal during the various phases of Indian Northeast monsoon derived from QuickSCAT data, 1999-2008", *Mausam*, **69**, 1, 1-18.

B. Amudha, Y. E. A. Raj and R. Asokan, 2016, "Spatial variation of clouding/ rainfall over southeast Indian peninsula and adjoining Bay of Bengal associated with active and dry spells of northeast monsoon as derived from INSAT OLR data", *Mausam*, *67*, N3, 559-570.

Bushair, M. T., Rani, S. I., Jangid, B. P. et al., 2021, "Evaluation of the benefits of assimilation of Meteosat-8 observations in an NWP system over the Indian Ocean region", *Meteorol Atmos Phys* **133**, 1555-1576. doi : https://doi.org/10.1007/s00703-021-00826-w.

Bushair, M. T., Rani, S. I., George, G. et al., 2021, "Role of Space-Borne Sea Surface Winds on the Simulation of Tropical Cyclones Over the Indian Seas", *Pure Appl. Geophys.* **178**, 4665-4686. doi : https://doi.org/10.1007/s00024-021-02890-0.

Singh, Charan, Sunit Das, R. B. Verma, B. L. Verma and B. K. Bandyopadhyay, 2012, "Rainfall estimation of landfalling tropical cyclones over Indian coasts through satellite imagery", *Mausam*, **63**, 2, 193-202.

Erica, L. Mcgrath-Spangler, A, B Will Mccarty, C N. C. Privé, A, B Isaac Moradi, B, D Bryan M. Karpowicz and Joel McCorkel, 2022, "Using OSSEs to Evaluate the Impacts of Geostationary Infrared Sounders", *Journal of Atmosphere and Ocean Technology*, **39**, 1903-1918.

George, Joseph, V. S. Iyengar, K. Nagachenchaiah, A. S. Kiran Kumar, B. V. Aradhye, V. N. Kaduskar, R. K. Dave, C. M. Nagrani, 1994, "Very high resolution radiometers for INSAT-2," *Current Science*, **66**, 1, 42-56,

Gibies George, Gemma Halloran, Sumit Kumar, S. Indira Rani, M.T. Buhair, BuddhiPrakash Jangid, JohnP. George, Adam Maycock, 2021, "Impact of Aeolus horizontal line of sight wind observations in a global NWP system", Atmospheric Research, 261, 105742.

Rani, Indira, S., Das Gupta, M., Sharma, P., and Prasad, V. S., 2014, "Intercomparison of Oceansat-2 and ASCAT winds with in situ buoy observations and short-term numerical forecasts", *Atmosphere-Ocean,* 52, 1, 92-102.

Johny, C. J., Singh, S. K. and Prasad, V. S., 2019, "Validation and Impact of SCATSAT-1 Scatterometer Winds", *Pure Appl. Geophys*, **176**, 2652678. doi : https://doi.org/10.1007/s00024-019-02096-5.

Yadav, J. K. S., R. K. Giri and L. R. Meena, 2012, "IPWV estimation and data quality analysis from different GNSS antenna", *Mausam*, **63**, 1, 77-88.

Kalsi, S. R. and Bhatia, R. C, 1992, "Satellite observations of development of thunderstorm complexes in weekly forced environments", *Vayu Mandal*, **22**, 65-76.

Kalsi, S. R., 2006, "Orissa Super cyclone- A synopsis", Mausam, 57, 1, 1-20.

K. C. SINHARAY, 1988, "Satellite observations of mountain waves over northwest India and neighbouring regions and theoretical Verification", *MAUSAM*, **39**, 3, 257-262.

Kelkar, R. R., 2019, "Satellite Meteorology in India: Its beginning, growth and future ", *Mausam*, **70**, 1, 1-14.

Kelkar, R. R., V. S. Tiwari, and Sant. Prasad, 1989, "Retrieval of sea surface temperature from INSAT-IB radiometer measurements using a multi -channel simulation approach", *MAUSAM*, **40**, 1, 25-30.

Kishtawal, C. M., 2019, "Use of satellite observations for weather prediction ", *Mausam*, **70**, 4, October, 2019, 709-724.

Ranalkar, M. R., R. P. Mishra, Anjit Anjan and S. Krishanaiah, 2012, "Network of Automatic Weather Stations : Pseudo random burst sequence type", *Mausam*, **63**, 4, 587-606.

Mitra, A. K., Kundu, P. K., Sharma, A. K. and Roy Bhowmik, S. K., 2010, "A neural network approach for temperature retrieval from AMSU-A measurements onboard NOAA-15 and NOAA-16 satellites and a case study during GONU cyclone", Atmosfera, **23**, 3, 225-239.

Mitra, A. K., S. C. Bhan, A. K. Sharma, Nithesh Kaushik, Shailesh Parihar, Riddhi Mahandru and P. K. Kundu, 2015, "INSAT-3D vertical profile retrievals at IMDPS, NEW Delhi: A preliminary evaluation", *Mausam*, **66**, 4, 687-694.

Mitra, A. K., Shailesh Parihar, R. Bhatla and K. J. Ramesh, 2018, "Identification of weather events from INSAT-3D RGB scheme using RAPID tool", *Current Science Research communication*, **115**, 1-9.

Mitra, A. K. Shailesh Parihar, R. Bhatla and R. S. Singh, 2019, "Monitoring of severe weather events using RGB scheme of INSAT-3D satellite", *Journal of Earth System Science*, **128**, 36, 1-28.

Mitra, A. K., 2023, "Use of Remote Sensing in Weather and Climate Forecasts. In: Gahalaut, V.K., Rajeevan, M. (eds) Social and Economic Impact of Earth Sciences. Springer, Singapore. doi : https://doi.org/10.1007/978-981-19-6929-4_5

Mishra, D. K. and B. BASU, 1987, "Wave pattern observed in cellular clouds over the Arabian Sea", *Mausam*, **38**, 1, 119-122.

Mohapatra, M., et al., 2021, "INSAT-3DR rapid scan operation for weather monitoring over India", *Current Science Research article*, **120**, 6, 1026-1034.

Singh, O. P., 2012, "Observational Aids and monitoring of Monsoon (i) Satellite monitoring of monsoon", 360-395, *Monsoon Monograph*, **1**, by Ajit Tyagi and four others.

Onkari, Prasad, D. K. Misra, and R. K. Jain, 1983 "Satellite observed cloud distribution over the Indian Ocean during the southwest monsoon season", *Mausam*, **34**, 4, 449-454.

Koteswaram, P., 1971, "Satellite Meteorology A Decade of Satellite Meteorology in India", *Mausam*, **22**, 3, 273-278.

Khanna, P. N. And R.R. Kelkar, 1993 "Temperature Sounding of The Atmosphere Over the Indian Region Using Satellite Data", *Mausam*, **44**, 2, 167-174.

Puviarasan, N., Giri, R. K. and Ranalkar, Manish, 2010, "Precipitable water vapor monitoring using ground- based GPS system", *Mausam*, **61**, **2**, 203-212.

Rani, S. I. and Das Gupta, M., 2013, "An inter-comparison of Kalpana-1 and Meteosat-7 atmospheric motion vectors against radiosonde winds and NWP forecasts during monsoon 2011", *Meteorological Applications*, **21**, 820-830. doi : https://doi.org/10.1002/met.1411.

Rani, S. Indira, Buddhi Prakash Jangid, Sumit Kumar, M. T. Bushair, Priti Sharma, John P. George, Gibies George and M. Das Gupta, 2022, "Assessing the quality of novel Aeolus winds for NWP applications at NCMRWF, QJRMS, **148**, 744, Part-A, 1344-1367. doi : https://doi.org/10.1002/qj.4264e.

Routray, Abhishek Lodh, Devajyoti Dutta, John, P. George and Ashis K. Mitra, 2023, Influence of ASCAT soil moisture on prediction of track and intensity of landfall tropical cyclones", *International Journal of Remote Sensing*, **44**, 1, 341-380, doi : 10.1080/01431161.2022.2164232.

Datar, S. V. and C. P. Joseph, 1971, "A satellite automatic picture transmission (APT) ground receiving station", *Mausam*, **22**, 3, 377-380.

Singh, Sanjeev Kumar and Prasad, V. S., 2017, "Impact of Megha-Tropiques SAPHIR radiances in T574L64 global data assimilation and forecasting system at NCMRWF", *International Journal of Remote Sensing*, **38**, 16, 4587-4610, doi : 10.1080/01431161.2017.1323279.

Sikka, D. R., 1971a, "Evaluation of the use of satellite photography in determining the location and intensity changes of tropical cyclones in the Arabian sea and the Bay of Bengal, Proceedings of the National Symposium (10-13 April, 1970) on Satellite Meteorology", *Indian J. Meteor. Geophys*., **22**, 3, 305-312.

Sikka, D. R., 1971 b, "Development of Tropical cyclones in the Indian seas as revealed by satellite radiation and television data", *Indian J. Meteor. Geophys*. **22**, 317-324.

Sikka, D. R. and Gadgil, S., 1980, "On the maximum cloud zone and the ITCZ over Indian Longitudes during the Southwest Monsoon", *Mon. Wea. Rev*.,**108**, 1840-1853.

Singh, D., Bhatia, R. C., Srivastav, S. K. and Singh, S. B., 2003," An experiment of the ICI3 scheme for retrieving temperature parameters over the Indian region using AMSU data from NOAA-16 satellite", *Mausam*, **54**, 1, 107-110.

Goyal, Suman, Mohapatra, M., Priyanka Kumari, S. K. Dube and Kushagra Rajendra, 2017, "Validation of Advanced Dvorak Technique (ADT) over north Indian ocean", *Mausam*, **68**, 4, 689-698.

Suresh, R., 2001 "Some aspects of Indian Northeast monsoon as derived from TOVS data", *Mausam*, **52**, 4, 727-732.

Suresh, R., 2002, "On forecasting cyclone movement using TOVS data", *Mausam*, 53,2, 215-224.

Suresh, R., 2006, "On thermodynamical structure and forecasting tracks of Tropical disturbances using ATOVS data over Bay of Bengal", *Mausam*, **57**, 4, 609-618.

Dutta, Surya K., V. S. Prasad and D. Rajan, 2014, "Impact study of integrated precipitable water estimated from Indian GPS measurements", *Mausam*, **65**, 4, 461-480.

Kumar, Sumit, Gibies George, Buddhi Prakash J., M. T. Bushair, S. Indira Rani and John P. George," 2021, "NCUM Global DA System: Highlights of the 2021 upgrade", NCMRF/TR/05/2021, 1-25.

Rani, S. I., Taylor, R., Sharma, P. et al., 2019, "Assimilation of INSAT-3D imager water vapour clear sky brightness temperature in the NCMRWF's assimilation and forecast system", *J. Earth Syst Sci*, **128**, 197. doi : https://doi.org/10.1007/s120.

Rani, S. Indira, et al., 2021, "IMDAA: High-Resolution Satellite-Era Reanalysis for the Indian Monsoon Region", *Journal of climate*, **34**, 12, 5109-5133.

Special Issue on "Remote Sensing Applications in Meteorology", *Mausam*, 2003, **54**, 1.

Jha, T. N., M. Mohapatra and B. K. Bandyopadhyay, 2013, "Estimation of intensity of tropical cyclones over Bay of Bengal using microwave imagery", *Mausam*, **64**, 1,105-116.

Tyagi, A., Sikka, D. R., Suman Goyal and Bhowmik, M., 2012 "A satellite-based study of pre-monsoon thunderstorms (Nor'westers) over eastern India and their organization into Mesoscale Convective Complexes", *Mausam*, **63**, 1, 29-54.

Rao, U. V. Gopala, R. C. Bhatia and N. P. Jauhari, 1979, "A solid state amplifier for recording APT cloud pictures", *Mausam*, **30**, 1, 157-158.

Iyengar, V. S., C. M. Nagrani, et al., 1999, "Meteorological imaging instruments on-board INSAT-2E," *Current Science*, **76**, 11, 11436-1444.