50 Years of Satellite Meteorology in India

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ABSTRACT

During the last 50 years, satellite-based data have emerged as a very powerful tool in India for applications in day-to-day weather forecasting and atmospheric research. Right from the early stage of commencement of using this new type of data in operational work of weather forecasting from early 1970s, 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 India Meteorological Department. 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 and IMD had started using them appropriately in operations and research work. Satellite data now forms a major input to the Numerical Weather Prediction (NWP) models being run operationally at various centers in India and there is a positive impact of using satellite data. Advanced multispectral-channels based instruments are being planned onboard future Indian satellites of INSAT-4 series which will provide much improved capabilities for meteorological applications. This review article provides complete historical background of developments of space-based observations in India during the last 50 years and the outlook for future prospects.

Keywords: *INSAT-3D, Multispectral channels, RGB products, APT, HRPT, ATOVS, Sounder, METEOSAT, INSAT-2E, Cloud pictures and Microwave.*

1. Introduction

Satellite based observations of weather systems form a very important component of the observation systems all over the world for providing weather and climate related services. India Meteorological Department (IMD) established Satellite Meteorology Directorate at HQs office, New Delhi in the year 1972 to promote development and utilization of satellite based observations in India. Prior to that, 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 equipment was established at Bombay for real-time reception of low-resolution cloud pictures, called Automatic Picture Transmission (APT) data service transmitted by the polar orbiting satellites of USA in operation at that time. Lot of useful data were collected with this equipment which were used for research work of this program. 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. In particular, results of initial studies on tropical cyclones and ITCZ using satellite pictures were reported by Sikka (1971a ,1971b) and Sikka et.al. (1980). Keeping in view the usefulness of satellite pictures, IMD started further work for indigenous development of APT receiving equipment. First receiving station using such equipment was started at IMD's HQs office, New Delhi in the year 1971. Later, the network of such receiving stations was expanded to 6 during subsequent years in a phased manner. 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. 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 Polar orbiting satellites of the USA. This equipment was procured and installed at Delhi in 1981.

2. INSAT Program

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 (74 deg East) and the other on-orbit backup satellite located at secondary position (93.5 deg East) 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 onboard 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 frequent pictures of earth's cloud cover over India and surrounding areas from a 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 30 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. Processed data archival on tapes was also 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 operations of weather forecasting and research, India Meteorological Department entered the new era of using Geostationary Meteorological Satellite data. 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. Results of some studies on thunderstorms done by using INSAT pictures are reported in two papers (Bhatia et.al, 1993 and Kalsi et. al., 1992). A very good review of research work done during initial years has 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 November, 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 June, 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.

3. 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:

(a) Collection of conventional meteorological data from remote and inaccessible areas over land and oceans using a Data Relay transponder (DRT) provided as a 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 Rain gauges (ARGs) are installed at remote areas and a large number of such equipment are operational (M. R. Ranalkar et.al.,2012). Basic purpose of AWS / ARG is same as that of DCPs.

(b) 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 later on renamed as Meteorological Data Dissemination (MDD). One such station was also established at Maldives. Main purpose of this service was to provide near real-time data of INSAT cloud imagery to the field forecasting offices for utilization in day-to-day forecasting (Bhatia et.al.,1989).

(c) 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 on 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 on renamed as Cyclone Warning Dissemination System (CWDS).

4. 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). For the imaging instrument onboard INSAT-2 satellites the resolution of the radiometer was improved to 2 Km (VIS) and 8 Km (IR). 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 onboard INSAT-1 satellites. 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 exactly 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 onboard 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.

4.1 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, the 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:

(a) Provision of a third water vapor channel in the imaging radiometer in addition to earlier two channels of visible and infrared, provided on the previous instruments launched so far.

(b) 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 (1.55-1.69um).

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). 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. 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 due to the fact 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.

4.2 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 ^{0}E longitude) to provide round-the-clock cloud imagery data. This action was taken to support an International Project called Indian Ocean Expedition (INDOEX). The operational service from this position was started from 1 July, 1998 to support the above international field experiment. 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 (November, 2021) this service is being operated using one spare Second Generation satellite (METEOSAT -8) located at 41.5 deg. East longitude. An advanced 12 channel imaging radiometer called SEVIRI (Spinning Enhanced Visible and InfraRed Imager) is available onboard this satellite to provide multi-spectral images over the Indian Ocean region.

4.3 Contingency plans: First dedicated geostationary meteorological satellite (METSAT)

With a view to ensure uninterrupted availability of earth images for meteorological applications, soon after the operational 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 identical 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:

(a) 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.

(b) 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.

5. Third Generation of INSAT (INSAT-3) Satellite Series

In order 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 at all times 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 which was operating at that time. METSAT was renamed as KALPANA-1 on 5 Feb,2003.

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:

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

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

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. Even today (Nov. 21) it is operational, though it is nearing its end-of-life. Another satellite (INSAT-3DR), with identical capabilities, was launched in September,2016. It is on-orbit back up for 3D.

Lot of research work has been done during last more than two decades using INSAT data. Amudha et. al. (in 2 papers of 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). Singh (2012) studied the satellite derived SST variability over Bay of Bengal. Results of a specific study done on validation of Advanced Dvorak Technique (ADT) over North Indian Ocean are reported by Goyal et. al (2017). Tyagi et al. (2012) reported results of a satellite- based study of premonsoon thunderstorms over eastern India. A special issue of Mausam, 2003 (Vol. 54, No. 1) 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 specifically, results of a few important papers published prior to and after launch of INSAT-3D have been reported in Kishtawal (2019).

6. 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. At the same time extensive R&D work was also initiated at NASA, USA for development of new payloads. A new program called NIMBUS series of satellites was also conceived for testing of new payloads developed and also to develop all 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 on launched onboard future operational satellites. Thus, NIMBUS program laid the foundation of a large number of new types of satellite payloads of various types and observe earth's atmosphere from different perspectives. 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 now 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. An excellent review of use of all types of satellite observations for weather prediction has recently been published by Kishtawal (2019). Satellite based observations now form a very important part of data assimilated into the Numerical Weather Prediction (NWP) 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) onboard NOAA and METOPS series of polar orbiting satellites.

R&D satellites series of NIMBUS program 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 missions. A joint INDO-FRENCH mission called Megha-Tropique is also an R&D mission launched successfully a few years back.

6.1 Processing of sounder data at IMD

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 operational NWP models run at NCMWRF and IMD. Later, in mid 1990s, another HRPT receiving station was established at Chennai in order 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 by Suresh (2001, 2002, 2002, 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 by Singh et.al. (2003). A case study during GONU cyclone 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 was 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 equipments were used at NCMWRF for assimilation in NWP models.

6.2 Use of data from microwave based sensors

From early 1990s, IMD started using data from some of the Microwave based sensors available on some polar orbiting satellites of USA. Most prominent among these was Special Sensor Microwave Imager (SSMI) available on the Defence Meteorological Satellite Program (DMSP) 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 by Bhatia et al. (2013).

6.3 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 by Puviarasan et al. (2010). Results of a detailed study done on the impact of using this data in NWP models have been reported (Dutta et al., 2014). A data quality analysis of Integrated Precipitable Water Vapor (IPWV) using different GNSS antenna has been done and results reported in a paper (Yadav et al., 2012).

Keeping in view the usefulness of this new type of data, IMD has planned to expand the network of such stations. At present 25 stations are operational and in near future it is planned to expand the network to 100 stations.

7. Latest Trends of Availability 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. A large 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.

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-3D and 3DR) are of six channels. Some limited RGB products are being derived even with the 6 channels data at the INSAT-3D data processing facility of IMD. However, multi-spectral images and derived products are also available over the Indian region from the EUMETSAT's METEOSAT-8 satellite located over the equator at 41.5 deg. East longitude since September,2016.

Recently, 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 of years 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. In a most recent research article Mohapatra et.al. (March, 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.

8. Future Plans

Currently operational INSAT-3D satellite, launched in 2013, is now nearing its end-of-life. An on-orbit backup satellite (INSAT-3DR) is already available and operations can be shifted to this satellite soon after INSAT-3D satellite completes its useful operational life. In addition, another satellite of exactly identical specifications (INSAT-3DS) is available as a ground spare satellite. It can be launched at appropriate time during next few years in order to provide capability of two satellites in-orbit at a time (one operational and the other back up). Therefore, availability of adequate space-segment for next few years for operation of meteorological services is almost ensured.

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 early next year (2022). A new experimental satellite called Geostationary Imaging Satellite (GISAT-1), 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 in 2025 and beyond. After lot of technical discussions in meetings of the Joint IMD-ISRO task group, inclusion of following payloads on INSAT-4 satellite series have been short-listed.

(i) High Resolution Multi-spectral Visible/IR imagers

(ii) IR based Hyperspectral Sounders

(iii) Lightning Imagers

(iv) Narrow Band High Spectral and Hyperspectral Resolution Visible/ Near IR Imagers

(v) Earth Radiation Budget Monitoring Instruments

(vi) Space Weather Monitoring Instruments.

Final recommendations in this regard are being made shortly. Multi-spectral imagers will most probably be included on future operational meteorological satellites of INSAT series. Some of the other advanced technology payloads as described above, could also be included in the space-segment capability of future satellites. Meteorological payloads of future Indian satellites will therefore be on par with those of other countries operating similar satellites. Basic foundation for accomplishing this objective will be laid next year after launch of GISAT-1 as described above. This will provide useful experience for future operational Indian satellites with meteorological applications.

9. Summary

During the last 50 years there has been considerable growth in the field of Satellite Meteorology in India. Starting with a very modest beginning of receiving low resolution cloud pictures twice a day from the polar orbiting satellites of the USA at a few stations in India, at present round-the -clock pictures are being received from India's 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. A major chunk of data 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 has not lagged behind in this regard. NWP centers in India are assimilating a large amount of data from Indian as well as foreign satellites. There is a large positive impact of using satellite data on NWP model- based forecasts.

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 a sophisticated multi-channel payload 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.

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