MAUSAM, **54**, 1 (January 2003), 1-12

551.508.826 : 06.051

Evolution of Indian Satellite meteorological programme

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सार – हाल में मौसम के मानीटरन और उसके पूर्वानुमान में बहुत प्रगति हुई है। इस विकास में अंतरिक्ष पर आधारित प्रेक्षण मुख्य रूप से सहायक रहे हैं। अंतरिक्ष तकनीक एक आकर्षक तकनीकी उपलब्धि के रूप में उभर कर सामने आई है तथा पृथ्वी एवं वायुमंडल के जटिल तंत्र का अध्ययन करने के लिए यह विकसित हो रही है। मौसम पूर्वानुमान की भारी मात्रा में प्रेक्षणात्मक आवश्यकताओं को पूरा करने के लिए रिपिटिटिव के आधार पर अंतरिक्ष से प्राप्त हुए प्रेक्षण आदर्श साबित हुए हैं। उपग्रह मौसम विज्ञान में भारत के कार्यक्रम सत्तर के दशक के उत्तरार्ध में भास्कर उपग्रह और अस्सी के दशक के पूर्वद्ध में इनसेट 1 श्रृंखला अब पूर्ण रूप से विकसित हो चुके हैं और यह मौसम एवं जलवायु सेवाएं और अनुसंधान के क्षेत्र में महत्वपूर्ण योगदान दे रहे हैं। इस शोध–पत्र में अब तक की उपलब्धियों और उन्नत मिशनों के भविष्य की योजनाओं के बारे में प्रमुख रूप से बताया गया है।

ABSTRACT. Recent times have witnessed great strides in weather monitoring and forecasting. One of the key contributors to this development has been space based observations. Space technology has emerged as one of the most fascinating technical achievements and is developing as a powerful tool to study the complex earth-atmosphere system. The space-based observations covering large areas on repetitive basis has been found to be ideal to meet the large observational requirements of weather prediction. Indian programme in satellite meteorology started with Bhaskara satellites in late seventies and the INSAT 1 series in early 80's and has now graduated into a full-fledged mission contributing significantly to weather and climate services and research. The paper highlights the achievements so far and future plans for advanced missions.

Key words – Indian meteorological satellites, Payload, Geostationary, Polar orbitting, Meteorological parameters, Past-present-future, Remote sensing.

1. Introduction

The launch of the first meteorological satellite TIROS-1 by United States of America on 1 April 1960 heralded the era of Space observations and gave the first synoptic glimpse of the dynamic cloud systems surrounding the Earth. Since then the technology has grown leaps and bounds in observational capabilities in terms of spatial, spectral and temporal resolutions. Over the past two decades, a global system of Space meteorological observations with both geostationary and polar orbiting systems has evolved.

The advantages of Space observations emanate from several factors such as :

(*i*) Synoptic view of large areas, bringing out the inter-relations of processes of different spatial scales.

(*ii*) Filling gaps in observations; Space data covers large oceanic areas and inaccessible and remote land areas, thus giving global coverage.

(*iii*) Frequent observations – geostationary satellites provide continuous monitoring while polar orbiting satellites give typical twice-daily global coverage; such data are relevant for study of weather system dynamics.

(*iv*) The inherent spatial averaging is more representative than the *in situ* point observations and are readily usable by weather prediction models.

(*v*) High level of uniformity of space observations overcomes the problem of inter-calibration needed by ground-based instruments.

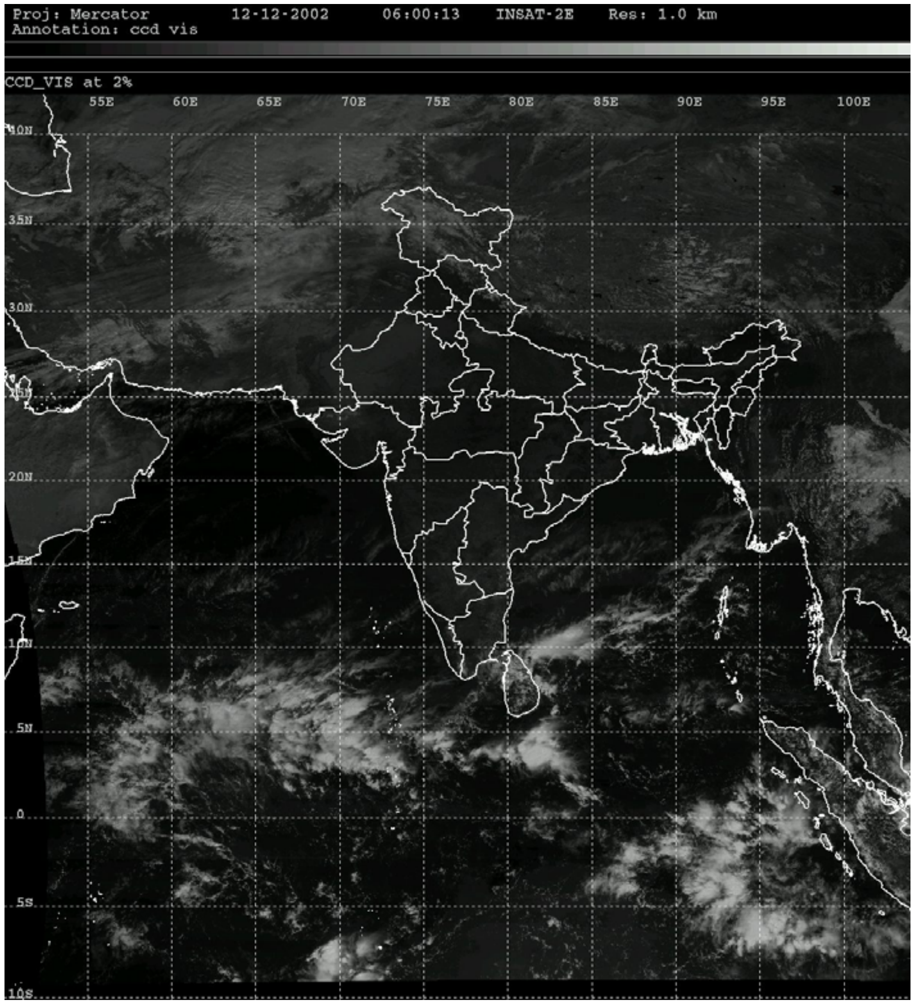

Fig. 1. CCD image in visible channel on 12 December 2002

(*vi*) New types of data and observations; parameters such as sea surface (skin) temperature, sea surface wind stress, sea level, cloud liquid water content, rainfall over oceans, radiation balance, aerosol etc. are some of the unique parameters provided only by satellites.

(*vii*) Simultaneous observations of several dynamic parameters provided by different sensors in same platform facilitates study of inter-relationships and knowledge of processes (*e.g.* sea surface temperature and deep convection, cloud development and radiative forcing, upwelling and ocean productivity etc.

Currently several operational meteorological satellite systems of various countries are providing global and regional observations. The Indian Space programme, initiated in the mid-70's, has identified meteorology and weather forecasting as one of the thrust areas of application. One of the earliest satellites, Bhaskara, had a microwave payload, SAMIR, for the observations of atmosphere and ocean. The INSAT series of geostationary satellites was conceptualized as a multi-purpose system for application in meteorology, broadcasting and communications. Some polar orbiting satellites carrying meteorological/oceanographic sensors have also been launched. In the next few years many advanced satellites are to be launched. The present paper describes in brief the evolution of the Indian Satellite Meteorological programme and future scenario.

2. Geostationary satellite programme (INSAT series)

INSAT series of geostationary satellites was conceived to meet the operational needs of meteorology and weather services besides those related to communications and broadcasting. The INSAT 1 series, launched through the 80's, carried a Very High Resolution

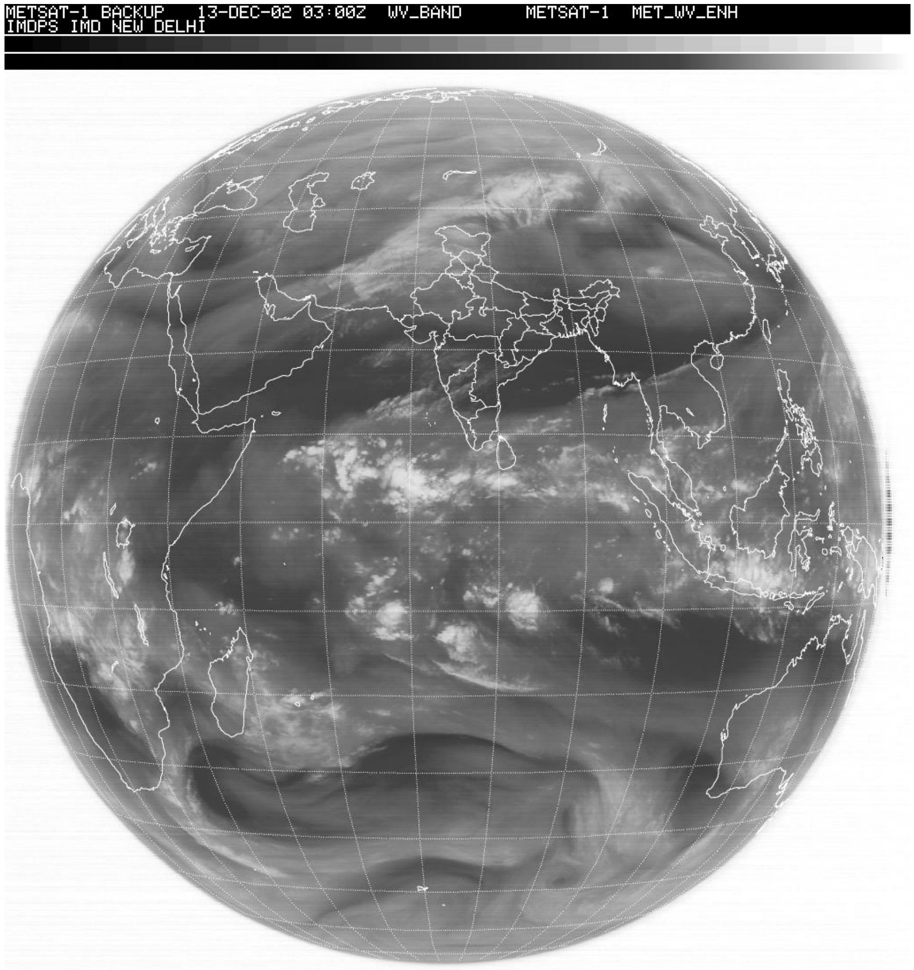

Fig. 2. Water vapour imagery from METSAT on 13 December 2002

Radiometer (VHRR) payload which operated in two spectral bands – visible [0.55-0.75 μm] and thermal infrared [10.5-12.5 μm]. The INSAT system is designed to provide the following weather services:

(*i*) Round the clock surveillance of weather systems including severe weather events around the Indian region.

(*ii*) Operational parameters for weather forecasting – cloud cover, cloud top temperature, sea surface temperature, snow cover, cloud motion vector, outgoing longwave radiation etc.

(*iii*) Collection and transmission of meteorological, hydrological and oceanographic data from remote/ inaccessible areas through Data Collection Platforms (DCP).

(*iv*) Timely dissemination and warning of impending disasters such as cyclones through Cyclone Warning Dissemination Systems.

(*v*) Dissemination of meteorological information including processed images of weather systems through SDUCs.

INSAT 1 series consisted of four satellite missions with VHRR payload providing visible images with 2.75 km resolution and thermal data with 11 km resolution, with capability to provide half hourly images in normal scan mode. INSAT–1D, last in this series, gave useful information for about 12 years, much beyond its designed life. INSAT-2 series that followed was designed based on user feedback and consisted of five satellites to ensure continuity of services in an enhanced manner. INSAT-2A and 2B launched in 1992 and 1993 carried VHRR payloads with improved resolution of 2 km in visible and 8 km in thermal band. The imaging capability included three modes, *viz*., full frame, normal frame and sector mode (of 5 minutes for rapid coverage of severe weather systems).

INSAT-2E launched in 1999 carried an advanced VHRR payload operating in three channels visible (2 km), thermal and water vapour (8 km) bands. The water vapour channel operating in 5.7-7.1 μm is capable of giving water vapour distribution and flow patterns in the lower troposphere (Bhatia and Gupta, 1999). Besides this, INSAT-2E also carries a CCD camera with 3 channels – visible, near infrared and short wave infrared with 1 km resolution to map the vegetation cover (Bhatia *et al*., 1999). This also has the capability to estimate atmospheric aerosols over marine environments.

Fig. 1 shows visible channel imagery obtained from INSAT-2E CCD on 12 December 2002. The high resolution of the sensor (1 km at sub satellite point) has provided an image of very high clarity. There are no significant cloudiness over entire India, except over the northernmost parts, which are associated with a western disturbance moving eastwards. Deep convective cloud clusters are seen just north of equator between 50° of 85° E longitudes, typical of winter conditions.

Most current satellites in this series is METSAT (launched in September 2002) launched by PSLV. It carries only meteorological payloads (Kaila *et al*., 2002). VHRR onboard this satellite is analogous to that onboard INSAT-2E. Water vapour channel imagery obtained from METSAT on 13 December 2002 shows (Fig. 2) dry air in the middle levels over large parts of Arabian Sea and Bay of Bengal. Dry air also prevails over eastern and northeastern parts of India. Due to presence of a western disturbance over Afghanistan and adjoining Pakistan, moisture is being advected in the middle levels over large parts of northern India and to some extent over Rajasthan. Dry air tongue can also be seen behind the western disturbance. Deep convective clouds just north of equator between 60° of 80° E longitudes can be seen in water vapour imagery with moisture protruding from these clouds and spreading into the adjoining areas. Extra-tropical waves moving eastwards in the Southern Hemisphere can also be seen in this image.

INSAT-3A, to be launched in early 2003, will have identical payloads as INSAT-2E. INSAT-3D planned around 2005 will carry, in addition, an atmospheric sounder (for measurement of temperature and water vapour profiles) and split thermal channels (for accurate estimation of sea surface temperature).

2.1. *VHRR imaging system*

Very High Resolution Radiometer (VHRR) is the major imaging instrument for meteorological applications onboard INSAT satellites in geo-synchronous orbit. VHRR operates in three spectral bands. A wide panchromatic visible (VIS) band images the earth disc and clouds from geo-synchronous altitude of 36,000 km. A water vapour (WV) band maps the moisture patterns in the atmosphere; while a thermal infrared (TIR) takes thermal images of the earth and cloud patterns.

TABLE 1

Imaging modes of METSAT VHRR payload

Imaging Mode	Coverage	Repeatability
Full Scan	20° N-S & 20° E-W	33 minutes
Normal Scan	14° N-S & 20° E-W	23 minutes
Sector Scan	4.5° N-S & 20° E-W	23 minutes (3 times)

The instrument is equipped with ground commendable flexible scanning geometry to allow tradeoff between coverage area and frequency of imaging.

VHRR onboard INSAT-2 and METSAT takes images in VIS band (0.55 to 0.75 μm) with 2 km resolution, TIR band (10.5 to 12.5 μm) with a resolution of 8 km for thermal mapping and WV band (5.7 to 7.1 μm) with a resolution of 8 km to map the atmospheric moisture patterns which provide wind velocity and moisture content in various regions over of the earth view. The following paragraphs describe in brief the configuration and operation of the instrument onboard METSAT.

The incoming radiation from the earth is reflected onto an 8-inch primary mirror of the reflective telescope by a two-axis gimbal-mounted beryllium scan mirror. A gold film-dichroic beam-splitter placed in the converging beam from the secondary mirror of the telescope bifurcates the radiant energy. The visible energy is transmitted through the dichroic while combined WV and TIR energy is reflected at right angles to the original direction. This allows the radiation from the earth to be channelled to visible and combined IR focal planes simultaneously with high optical efficiency.

The detector configuration for the VIS band consists of two staggered arrays of four silicon photodiodes each; while for WV and TIR bands, the detector package contains two sets of dual mercury-cadmium-telluride (MCT) photoconductive detector elements in close proximity to band defining filters. This detector package was specifically designed such that the original design of radiant cooler for INSAT-2A/2B could be utilized with only minor modifications. The IR detectors are operated nominally at a temperature of 100 K to limit thermally generated noise. One of the detectors in each band is energized, while the other set provides the cold redundancy. Both sets are identical in function and can be switched 'on' and 'off from the ground through radio command.

TABLE 2

Comparison of geosynchronous meteorological satellites

Parameters	METEOSAT	GOES	GMS	INSAT/Metsat
Operating agency	EUMETSAT/ESA	NASA/USA	NASDA/JAPAN	ISRO/INDIA
First launch	1977	1974	1977	1982
Current satellite	METEOSAT 7	GOES 12	GMS 5	METSAT
Orbit (long.)	0 ° E	75 ° W/ 135 ° W	140 ° E	74 ° E / 84 ° E
Scan modes	Full Earth Disc	Full Earth Disc	Full Earth Disc, programmable N-S	Full Earth Disc programmable N-S
Instrument	Vis/IR/WV imager	Vis/IR/WV/CO_2 Sounder	Vis/IR/WV	Vis/IR/WV
Resolution	Vis 2.5 km IR 5 km	Vis 1.0 km IR 4.0 km	Vis 1.25 km IR 5 km	Vis 2 km IR 8 km
Digital data	Vis 6 bits IR 8 bits	Vis 6 bits IR 8 bits	Vis 6 bits IR 8 bits	Vis 10 bits IR 10 bits

The two-dimensional image of the earth is generated by sweeping the instantaneous geometric field of view of the detectors by rotation of the scan mirror-gimbals around two orthogonal axes. For every sweep of the mirror, four contiguous lines of VIS band and one line each of WV and TIR bands are generated in east-west direction. At the end of the sweep, the mirror is stepped south through an angle equivalent to eight kilometers on the ground and data collection is resumed in the reverse direction for the next sweep. This improves the scanning efficiency, which, in turn, enables faster coverage rate at reduced noise bandwidth of the system.

The three modes of operation of VHRR are given in Table 1.

Table 2 summarises the comparative performance of INSAT VHRR with meteorological payloads on other geosynchronous satellites.

2.2. *Products from INSAT series of satellites*

Besides the monitoring capability through imageries, satellites are capable of providing several operational parameters for diagnosing the system and for assimilation in weather prediction models and atmospheric research. Some of the key parameters derived from INSAT VHRR data are :

(*i*) Cloud Motion Vectors (CMV) are derived using three half-hourly images by analyzing movement of cloud tracers through a detailed pattern matching process. The CMVs are derived for lower troposphere and upper troposphere using visible and thermal images. With the availability of water vapour channel, wind vector is derivable in the mid-troposphere as well. The CMVs derived thrice daily, besides being disseminated to the global data system, are useful for studying monsoon flow, formation of eddies, cross-equatorial flow, offshore vortices etc.

(*ii*) Outgoing Longwave Radiation (OLR) is derived from thermal infrared data using physical and statistical algorithms, based on radiative transfer principles. The OLR derived using 3 hrly data on daily/weekly/monthly time scales is an important indicator of convective activity and has direct bearing to weather development. The OLR is a key parameter in monsoon onset assessment and has been well correlated with rainfall patterns.

(*iii*) Quantitative Precipitation Estimation (QPE) is derived based on Arkin *et al*., (1989) method using 3 hrly cloud top temperature accumulated over 2.5° × 2.5° latitude/longitude grids and correlated to rainfall. The QPE over the oceans fill up an important gap in rainfall measurements and is a key input to numerical weather models.

(*iv*) Water vapour channel data (5.7 – 7.1 µm) provides information on mid-tropospheric water vapour and flow patterns associated with incursion of water vapour during monsoon onset. A combination of visible/thermal and water vapour data is found to be useful in cloud characterization and identification of convective regions.

(*v*) Sea Surface Temperature is derived using the single channel (10.5 – 12.5 µm) brightness temperature. Though of coarse resolution (estimated accuracy of about 1.5° K) it is found to be well suited to study the large scale thermal fronts and upwelling associated with monsoon currents.

Quantitative Precipitation Estimates (QPE) derived from the Infrared channel output of METSAT for November 2002 is shown in Fig. 3. It shows accumulated

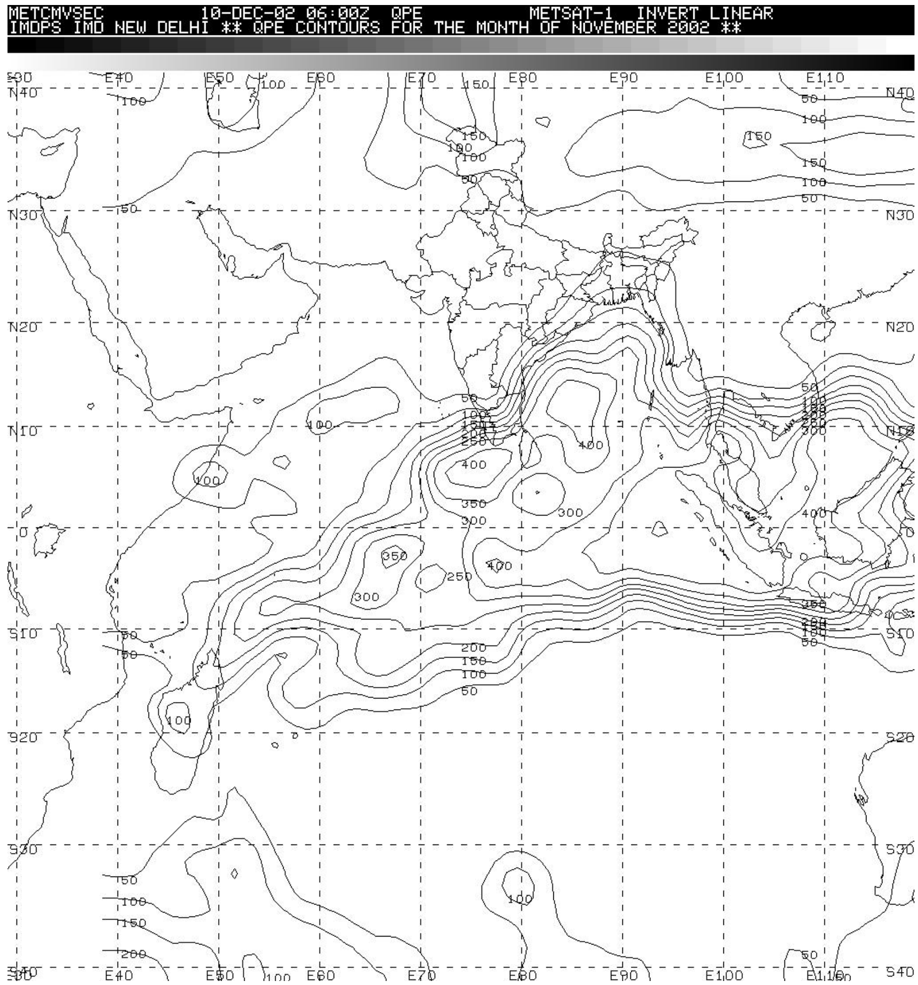

Fig 3. Precipitation estimated from IR radiance during November 2002 (Accumulated precipitation in mm)

precipitation in mm derived over a 1° × 1° Lat./Long. grid using the well-known Arkin's technique. The high precipitation areas over Bay of Bengal are typical pattern for winter season. There is no rainfall over most central parts of the country. Over the northern parts of the country some rainfall can be seen associated with movement of western disturbances, which is typical for this season.

3. Polar orbiting satellites (IRS) series for meteorological applications

The IRS series is primarily designed for land and coastal resource surveys, but some of the payloads have potential applications to meteorology. An extensive description of IRS-missions is given by Jayaraman (2002). Under this series IRS–P3 and IRS–P4 had sensors related to meteorological applications.

3.1. *IRS-P3*

The Indian Remote Sensing Satellite IRS-P3 launched on 21 March 1996, was an experimental mission oriented towards earth remote sensing. It carried the following three payloads :

(*i*) Wide Field Scanner WiFS for land observation.

(*ii*) Modular Optoelectronic Scanner (MOS), provided by DLR, Germany (mainly for ocean observation).

(*iii*) X-Ray sensor for astronomical observations.

The MOS payload is in a multi spectral imaging spectrometer for remote sensing of the earth environment with particular emphasis on ocean applications (Chauhan *et al.*, 1997). It has three optical blocks: MOS-A, MOS-B

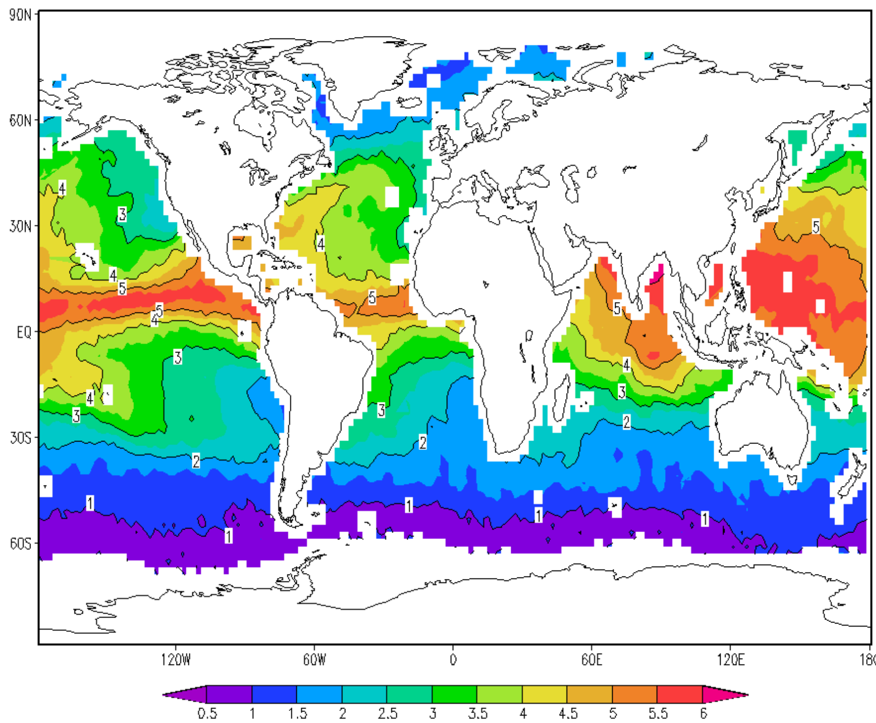

Fig. 4. MSMR derived Total Precipitable Water Vapour (g/cm^2) during July 2001

and MOS-C. MOS-A is a sensor meant for the layerwise detection of atmospheric aerosols using the differential scattering/absorption of radiation in four narrow band channels within the oxygen O_2A band at 760 nm. MOS-B is an ocean colour sensor with 13 bands in the VIS-NIR region meant for the detection of oceanic water constituents (chlorophyll, total suspended matter, dissolved organic carbon and diffused attenuation coefficient) and also for introducing atmospheric corrections in the ocean colour data. MOS-B has additional capability for the detection of atmospheric aerosol optical depth, columnar water vapour and ozone. MOS-C is a line array camera with a single band at 1600 nm for monitoring clouds, vegetation moisture and snow/ice discrimination. MOS has a swath of ~ 200 km, repeativity of 24 days and spatial resolution of 1.5 km × 1.5 km for MOS-A and 0.5 km × 0.5 km for MOS–B and C.

3.2. *IRS-P4*

The IRS P4 (Oceansat – 1) launched in May 1999 carried a Multichannel Scanning Microwave Radiometer (MSMR) and Ocean Colour Monitor (OCM). MSMR, operating in 6.6, 10, 18 and 21 GHz in both vertical and horizontal polarizations, is capable of providing marine atmospheric parameters such as total columnar water vapour, cloud liquid water content besides sea surface winds and temperature. The first microwave payload developed in India was the SAMIR (SAtellite MIcrowave Radiometer) flown onboard Bhaskara in the year 1979 with multiple frequencies 18, 21 ; and 31 GHz was added in Bhaskara-2 launched in 1981 (Gohil *et al.*, 1982; Pathak 1987).

TABLE 3

Specifications of IRS-P4 and MSMR

Satellite	
Altitude	720 km
Swath	1360 km
Repetivity	2 days
Orbit inclination	98°
MSMR	
Weight	65 kg
Frequency	6.6, 10.7, 18, 21 GHz
Polarization	Vertical & Horizontal
Spatial Resolution	40 to 120 km
Temperature Resolution	1 °K

The specifications of the MSMR instrument and the products available from it are listed in Tables 3 and 4. Fig. 4 shows an example of the MSMR retrieved water vapour during July 2001. High water vapour can be

TABLE 4

Operational parameters retrievable from MSMR and their applications

Frequency	Retrievable parameter	Grid size (km)	Range	Expected accuracy	Application potential
21 with 18 & 10.6 GHz (V & H)	Atmospheric Total Water Vapour (TWV)	50	0.2-7.5 g/cm^2	0.25 g/cm^2	• Input to medium range forecast system
21 with 18 &10.6GHz (V & H)	Cloud Liquid Water (CLW)	50	0-80 mg/cm^2	------	• Validation of numerical models
10.6 with 6.6, 18 & 21 GHz	Sea Surface Wind Speed (SSW)	75	2-24 m/s	2 m/s	• Assimilation in medium & extended range weather forecasting • Air sea exchanges
6.6 with 10.6, 18 & 21 GHz (V & H)	Sea Surface Temperature (SST)	150	273-303° K	1.2° K	• Monsoon convective systems • Tropical cyclone genesis • Latent heat input to ocean models

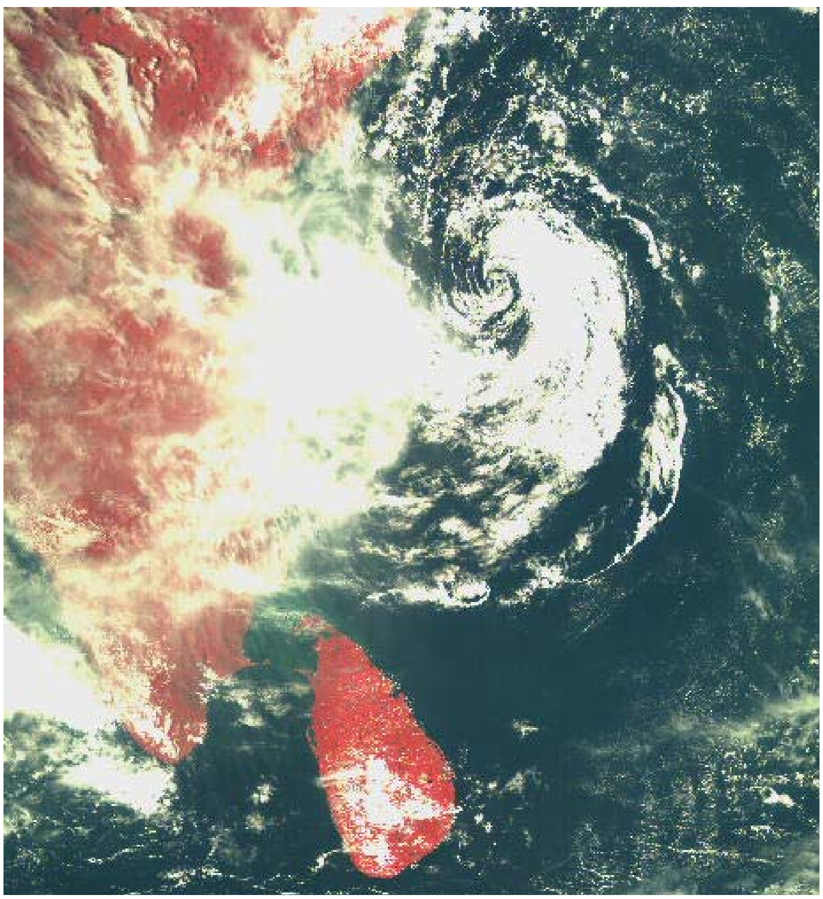

Fig. 5. OCM image during 20 September 2000

seen over north Indian Ocean. Geophysical parameters obtained from MSMR observations have been used to study various atmospheric and oceanic processes (Gopalan *et al*., 2000; Sarkar 2000; Vyas and Dash 2000; Gohil *et al*., 2000; Simon *et al*., 2001; Sharma *et al*., 2002 etc).

The parameters have been extensively validated through special ship cruise campaigns, contemporary satellite observations and model analysis.

The parameters have been assimilated in the NCMRWF model to assess the quality of the data. The

TABLE 5

Current important satellite observations over Asian monsoon region

Satellite	Sensors	Parameters
Geostationary		
INSAT – 2	VIS, TIR, WV, CCD	Cloud cover, CMV (3 levels), SST, WV image, QPE, OLR
METSAT	VIS, TIR, WV	Cloud cover, CMV (2 levels), SST, QPE, OLR
METEOSAT	VIS, TIR, WV	Clouds, WV image, SST, OLR
GMS – 5	VIS, Split TIR, WV	Clouds, WV image, SST
Polar		
NOAA	AVHRR TOVS / ATOVS	Cloud cover, precipitable water vapour, 15 layer temp., SST, vegetation index
IRS P3	MOS (13 channels)	Ocean colour, aerosol
IRS P4	MSMR, OCM	Liquid water content, SST, sea surface wind, WV, sea ice, aerosol
Research satellites		
ERS – 2	Scatterometer, altimeter, SAR, ATSR	Sea surface wind, waves, sea ice, SST, ozone
TRMM	Rain radar, TMI	Precipitation rates, rain structure
DMSP	SSM/I	Rainfall, wind speed, total WV, LHF

(CMV : Cloud motion vector , WV : Water vapour, LHF : Latent heat flux, SST : Sea surface temperature, OLR : Outgoing long wave radiation, QPE : Quantitative precipitation estimation, CCD : Charge coupled device camera)

TABLE 6

Payload characteristics & applications of future Indian satellites

Satellite	Payload	Bands/Resolution	Resolution (km)	Applications
INSAT 3D	6 Channel IMAGER	Spectral Bands (μm)		
		Visible : 0.55 - 0.75	1 km	
		Short Wave IR : 1.55 - 1.70	1km	
		Mid Wave IR : 3.70 - 3.95	4km	Cloud characterization
		Thermal IR – 1 : 6.50 - 7.10	4km	
		Thermal IR – 2 : 10.30- 11.30	4km	Mesoscale processes
		Water Vapour : 11.30- 12.50	8km	
	19 Channel SOUNDER	Spectral Bands (μm)	10 × 10 for all bands	Atmospheric water vapour / temperature
		Short Wave Infra Red : Six bands		
		Mid Wave Infra Red : Five Bands		
		Long Wave Infra Red : Seven Bands		
		Visible : One Band		
Megha-Tropiques	SAPHIR	Six bands around 183 GHz	10 km Horizontal Resolution	Water vapour profile Six atmospheric layers upto 12 km height
	SCARAB	Radiation instrument in short long wave	&40 km Horizontal Resolution	Radiation budget
	MADRAS	89 &157 GHz radiometer 10, 18 &37 GHz radiometer	10 km Horizontal resolution	ice particles in cloud tops cloud liquid water and precipitation; sea surface wind speed 23 GHz : Integrated water vapour

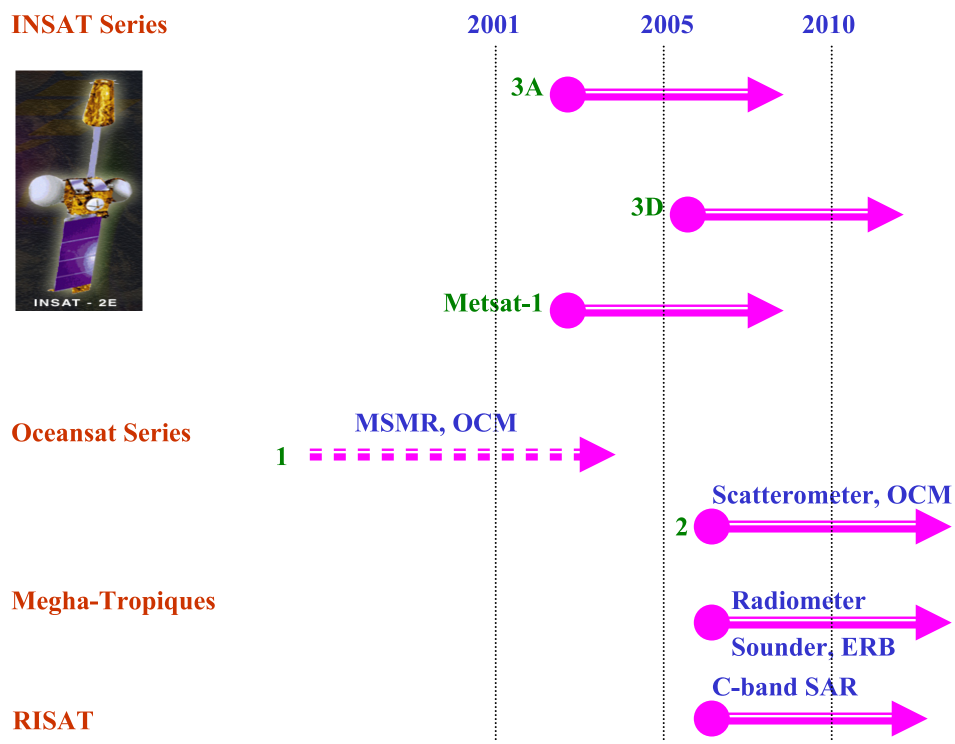

Fig. 6 Future Indian Meteorological Satellites

MSMR winds have been also used in Ocean State Forecast (OSF) pilot study. Besides the above four operational products, oceanic rainfall, Antarctic sea ice extent and soil moisture have been estimated with good accuracy from the MSMR data.

The OCM is a linear array CCD based solid state camera operating in eight narrow spectral bands in the VIS–NIR range. In fact, this is the first sensor based on "push broom technique" for Ocean colour studies. The spectral bands have been selected such that while the first 6 bands provide measurements on the biological properties like chlorophyll concentration, the last two bands are used for the atmospheric corrections. The OCM provides a ground resolution of 360 meters and a swath of 1420 km in each channel. Very high-resolution cloud information have been obtained from there data. Fig. 5 gives a false colour composite of blue/red/near IR bands of an OCM image of 20th September 2000. The detailed features of the cloud bands in the tropical cyclone in the Bay of Bengal are clearly discernible. The finer aspects of atmospheric circulation are also seen from the cloud formation. OCM data have also been utilized in estimating atmospheric aerosols over marine environment (Das *et al.*, 2002).

3.3. *Other satellites in Asian monsoon region*

Besides the above Indian satellites, those of other countries are also providing useful information over Asian monsoon region. A summary of the current satellite coverage of the Asian monsoon region by Indian and other international satellites is given in Table 5.

4. Future Indian satellite missions

Future missions planned to meet the requirements of the Indian meteorology/oceanography community are given in Fig. 6. The INSAT-3D, to be launched around the year 2005 will carry an improved 6-channel VHRR and a 19 channel sounder for temperature/humidity profiles.

The Megha-Tropiques mission slated for 2006 is a joint effort of ISRO and CNES, France for studying of the water cycle and deep convection in the tropical region. The unique payloads of the Megha-Tropiques are MADRAS (5 channel multi-frequency microwave radiometer – including 157 GHz), ScaRaB (radiation budget – for both short and long wavelengths) and SAPHIR (atmospheric sounder). The mission will operate

TABLE 7

Future international satellites of relevance to Indian programme

Satellites	Sensors	Parameters
NOAA – N	AVHRR, ATOVS, AMSU-A, B	Temp./humidity profiles, SST Radiation budget
EOS – PM	AIRS, MODIS, ALT	Humidity profile, Ozone column, Veg. Index, Sea level
METOP-1	IASI, AVHRR-4, ASCAT, GOME-2, MHS	Temp./humidity profiles, Ozone profile, SST, Sea ice cover, Wind vector
ADEOS-2	IMG, ILAS-2	Temperature profile, Ozone profile, SSW, SST
GPM	Precipitation Radar, Microwave Radiometer	Global precipitation, SSW, TWV
SMOS	MIRAS (microwave imaging)	Soil moisture, Ocean salinity
CALIPSO	LIDAR (3 channel) Microwave Radiometer	Cloud properties, Aerosol, Radiative flux
CLOUDSAT	Radar (94 GHz)	Radiative properties, Cloud properties, Precipitation

in an inclined equatorial orbit of 20˚ for repetitive coverage of tropical ocean areas. Table 6 lists the important instruments onboard INSAT-3D and Megha-Tropiques.

The Indian Oceansat – 2 is expected to carry a pencil beam scatterometer for estimation of surface wind vector, beside an 8 channel OCM. The RISAT, with a C–band radar will provide important information on ocean waves spectrum.

5. Global satellite missions for weather and climate

The ENVISAT launched recently by ESA carries GOMOS for Ozone estimation, AATSR for improved SST retrieval (< 0.5 K) and several other instruments for retrieval of trace gases. Several other missions of importance to climate and weather are also being planned globally. Table 7 summarises them. The NOAA – K satellite carries advanced TIROS operational vertical sounder (ATOVS) providing improved temperature profiles (1.5 K at 2 km vertical resolution) and humidity profiles from microwave sensors even under cloudy conditions. The METOP will carry a scatterometer.

Under NASA's Earth System Science Pathfinder Project, a constellation of satellites *viz*. CloudSat, CALIPSO, PARASOL and Aqua will be flown to provide concurrent observations of radiative fluxes and other atmospheric variables, in particular on cloud and aerosol. ESA's SMOS mission will carry the Microwave Imaging Radiometer using Aperture Analysis (MIRAS) operating in passive L band in 2D interferometer mode. This mission is expected to provide for the first time ocean salinity and soil moisture globally, two very critical parameters for climate models. The Global Precipitation Mission (GPM), a follow-on of TRMM, will carry a dual-frequency precipitation radar and passive microwave radiometers in a constellation of 8 satellites to provide global precipitation every 3 hours. Indo-French Megha-Tropiques may be a part of GPM.

6. Meteorological applications

The foremost applications (Kelkar, 1993) from meteorological satellite data are towards operational services in terms of :

(*i*) Watch and monitor growth of weather phenomena like cumulonimbus cells, thunderstorm, fog etc. and their decay;

(*ii*) Track movements of migrating systems such as tropical cyclones, monsoon depressions, western disturbance etc.;

(*iii*) Identify and locate primary synoptic systems like surface lows, troughs/ridges, jet streams, regions of intensive convection, inter tropical convergence zones etc.;

(*iv*) Monitor onset and progress of monsoon systems;

(*v*) Detect genesis and growth of tropical cyclones and monitor their intensification and movement till landfall.

(*vi*) Use in Numerical Weather Prediction

There are a number of satellite meteorological applications (Joshi *et al*., 2001; Joshi *et al*., 1990; Rao *et al*., 1998; Pal *et al*., 1999) in the context of tropical meteorology. Mainstay of the applications have been in the field of monsoon studies and the tropical cyclone studies. Many papers describing some of these applications appear in the current volume.

7. Conclusions

The developments in technology and mathematical tools augur well for tackling the complex problem of weather and climate prediction. The recent years have amply demonstrated the capabilities of space systems in meeting the information requirements of the meteorological community. In not so distant future, we can expect fully operational products from satellites after extensive validation meeting the resolution and accuracy requirements of prediction models. Efforts are also called for, for intensive basic research to understand mesoscale processes and integration to the models through appropriate parameterization. Only an appropriate technology convergence of Space observations, modeling and analysis techniques can lead to the long cherished desire of humanity to forecast future weather with known reliability.

Acknowledgements

The authors gratefully acknowledge the encouragement given by Dr. K. Kasturirangan, Chairman, ISRO and the valuable inputs provided by way of his lecture delivered in honour of late Prof. Satish Dhawan at Ahmedabad on 25 September, 2002.

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