

Tools from the Indian space programme for observing and forecasting extreme weather events - Retrospect and prospect

A. S. KIRAN KUMAR

Indian Space Research Organisation, Antariksh Bhavan, New BEL Road, Bengaluru – 560 231, India

e mail : kiran@sac.isro.gov.in

सार – मौसम चरम घटनाएं (ई डब्ल्यू ई एस) विपत्ति, आर्थिक हानि तथा खराब सामाजिक आर्थिक परिस्थितियों को पैदा करती है। इसके लिए यह आवश्यक है कि ऐसी घटनाओं के पूर्वानुमान करने की क्षमता विकसित की जाए जिससे कि इनसे होने वाली क्षति को कम किया जा सके और उचित उपायों के द्वारा इसका सामना किया जा सके। केवल सतह पर संस्थापित मौसम संजालों पर अग्रिम विधियों अब पर्याप्त नहीं हैं। अंतरिक्ष में स्थापित प्लेटफार्मों से लिए गए प्रेक्षण नियमित और जल्दी-जल्दी विस्तृत क्षेत्र की सूचनाएँ प्रदान करते हैं। भू-स्थितिक प्लेटफार्मों से लिए गए प्रेक्षण वायुमंडलीय प्राचलों की सूचनाएँ उपलब्ध कराते हैं और उसको संसाधित करते हैं जबकि पृथ्वी की निचली कक्षा में संस्थापित प्लेटफार्म उच्चतर स्थानिक विभेदनों पर सारभौमिक प्रेक्षणों को उपलब्ध कराते हैं। इस शोध पत्र में भारत के अंतरिक्ष कार्यक्रम के विकास को दर्शाया गया है जिसमें अंतरिक्ष खण्ड डेटा संसाधन एवं उत्पाद सहित मौसम प्रणालियों के प्रेक्षण एवं मानीटरन के लिए विज्ञान के उपयोग को अपनाया गया है। मौसम के मॉनीटरन के लिए हर प्रकार के विकास करने पर जोर दिया जा रहा है। मौसम की चरम घटनाओं के पूर्वानुमान को कुछ केस स्टडी के द्वारा समझाया गया है। अंतरिक्ष प्रौद्योगिकी के समावेशन से ऐसा माना जा रहा है कि पूर्वानुमान कौशल और सही समय पर पूर्वानुमान देने में सुधार होगा। इस शोध पत्र में भारतीय अंतरिक्ष मिशन की कुछ भावी योजनाओं में इसे और विकसित करने के बारे में भी बताया गया है। अंतरिक्ष प्रौद्योगिकी धरातलीय मापन नेटवर्क और तीव्र गतिवाली कंप्यूटिंग शक्ति का उपयोग करते हुए एक बहुआयामी प्रयास के द्वारा उच्च मौसमी घटनाओं के पूर्वानुमान और प्रेक्षण का आधार तैयार किया जा सकता है।

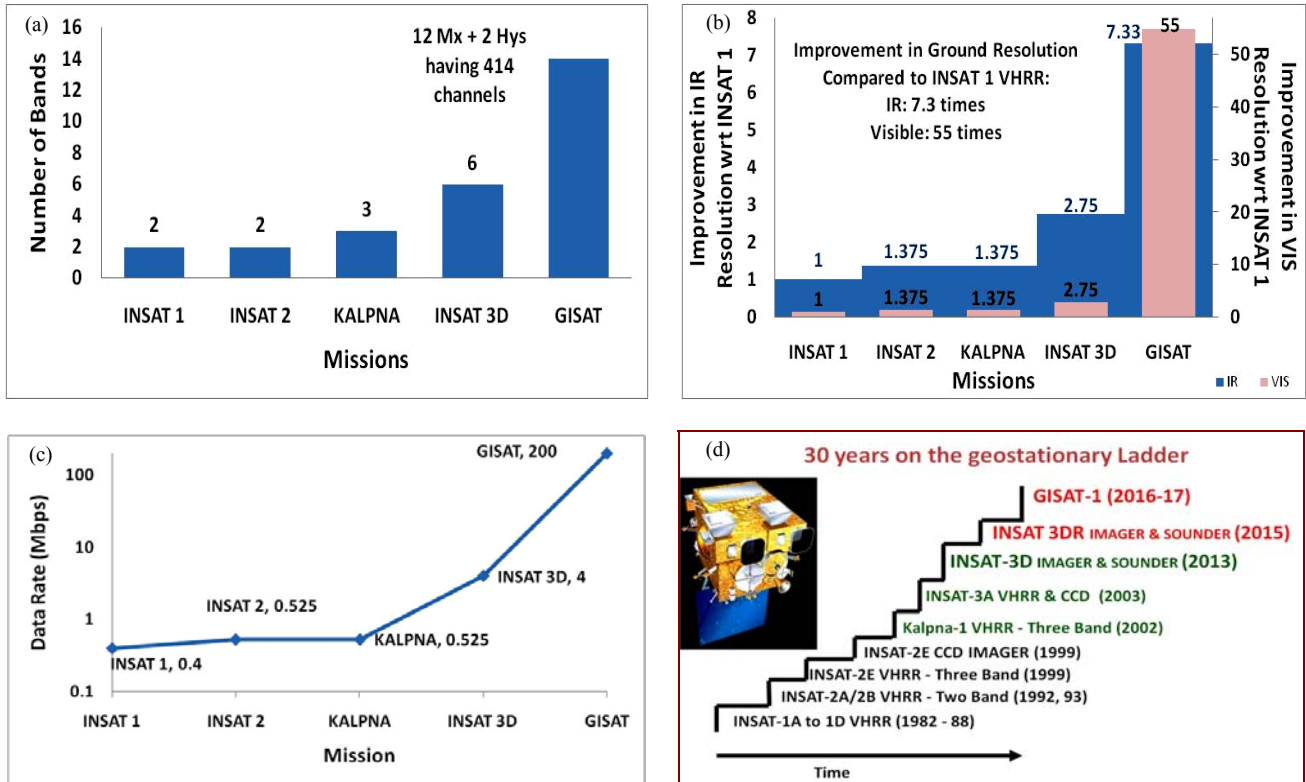
ABSTRACT. Extreme weather events (EWEs) cause hardship, economic loss and have severe socio-economic consequences. It is necessary to develop forecast capability for such events so as to minimise losses and take appropriate measures for combating. Methods relying on only ground based weather observation networks are not adequate. Observations from space platforms offer regular and frequent measurements over a wide area. Observations from geostationary platforms provide information on atmospheric parameters and processes, while low earth orbiting platforms provide global observations at higher spatial resolutions. This paper describes the evolution of space programme in India, consisting of the space segment, data processing and products, and science and applications for observing and monitoring weather systems. Emphasis is on developing end-to-end capacity in weather monitoring. Forecasting of EWEs is illustrated with a few case studies. With the integration of space technology inputs, it is expected that forecast skill and lead time of the forecast will improve. Some of the future Indian space missions planned to enhance the capacity are also described. A multidisciplinary approach comprising the use of space technology, ground based measurement network and high speed computing power, can form a backbone for observing and forecasting EWEs.

Key words – Satellite, Geo-synchronous earth orbit (GEO), Low earth orbit (LEO), Radiometer, Imager, Sounder, Synthetic aperture radar (SAR), Scatterometer, Spatial resolution, Spectral region, Data product, Data assimilation, Numerical weather prediction (NWP).

1. Introduction

Extreme weather event (EWE) implies unusual or severe or unseasonal weather phenomenon with respect to time and space. The values of EWE's are defined on frequency, amplitude or persistence of a weather variable. EWEs such as cyclones, floods, droughts, extreme temperatures, etc. are a subset of natural disasters. The EWEs cause hardship and economic loss. The exact value of economic loss due to EWEs is difficult to estimate. The losses reported are mainly monetized direct damages to

assets (IPCC, 2011). Evaluation of economical loss due to events such as loss of human life, extinction of a specie and destruction of cultural heritage are impossible to assess. Frequency of occurrence and number of persons affected by natural disasters is increasing. However, the loss of human-life from such events is reducing. This has happened due to better understanding of weather phenomenon, use of appropriate technology and multi-disciplinary approach to forecast and combat it. Therefore, it is essential to observe and forecast the EWEs.



Figs. 1(a-d). Progress in Indian GEO sensor development in (a) Spectral bands, (b) Spatial Resolution, (c) Data rate and (d) Over time

The ground based weather observation networks are not appropriately positioned and sparse. These are not adequate for accurate forecasting of EWEs. Measurements of atmospheric components from space, particularly from geostationary platforms, offer repeated and regular measurements over a wide area as well as over the areas not accessible by conventional methods. Space platforms facilitate observation of surface and atmospheric condition in different regions of electromagnetic spectrum (visible, Infrared, microwave). Measurements allow derivation of geophysical parameters such as albedo, temperature, incoming solar radiation, rain, humidity, winds etc. Geostationary orbit enables near instantaneous observations with high temporal capability. 3D observations are needed for better understanding of structure of an atmospheric system. Space based system are able to meet this requirement by observing vertical profiles *i.e.*, sounding of some of the important atmospheric parameters (Temperature, Humidity, Aerosols, Green House Gases (GHGs)) which are difficult and costly from ground based systems.

India has a committed series of satellites *viz.*, Indian National Satellite System (INSAT) for meteorological and communication applications; Indian Remote Sensing

(IRS) & Cartosat satellites for Earth observations and Oceansat satellites for Ocean observations (www.isro.gov.in/applications). At present, INSAT-3D is the main meteorological satellite carrying imager and sounder payloads. Its immediate predecessors Kalpana-1 and INSAT - 3A are also operational with Very High Resolution Radiometer (VHRR) instruments. These Meteorological satellites are also equipped with data relay transponders used to relay weather data from remotely located Automatic Weather Stations (AWS) and Buoys deployed in the oceans. These data are used to initialize the weather prediction models. Derived geophysical products such as rainfall, atmospheric motion vector, outgoing long wave radiation, upper tropospheric humidity, sea surface temperature from Imager and vertical profiles of temperature and humidity from Sounder are available operationally in near real time. These are freely made available to the researchers all over the world (Ramakrishnan *et al.*, 2010; www.mosdac.gov.in). Earth Observation satellites such as, RESOURCESAT-2 provide data for land process studies. RISAT-1 with C-band Synthetic Aperture Radar (SAR) provides useful data during floods generally associated with cloudy conditions. Oceansat-2 Scatterometer is - also an important sensor for the early detection of EWEs like cyclones.

TABLE 1

Sensor specifications for INSAT 3D Imager

Channel	Spectral width (μm)	IGFOV at Nadir (km)	S/N or NEDT (K)	Scene condition	Dynamic range
VIS	0.55 to 0.75	1	150 : 1	100 % Albedo	0 - 100 % Albedo
SWIR	1.55 to 1.70	1	150 : 1	100 % Albedo	0 - 100 % Albedo
MIR	3.80 to 4.00	4	1.4K	300 K	180 – 320 K
WV	6.5 to 7.10	8	1 K	230 K	180 – 320 K
TIR-1	10.3 to 11.3	4	0.35 K	300 K	180 – 340 K
TIR-2	11.5 to 12.5	4	0.35K	300 K	180 – 340 K

Note : Visible channel 100% Albedo: 52.4mW/cm²/Sr/ μm ; SWIR channel 100% Albedo: 6.7 mW/cm²/Sr/ μm

2. Development of sensor technology for observing weather

Indian space programme aims to address the requirement of synoptic observations of weather, by the combined use of Geo-synchronous satellites for communication as well as weather observations. Weather observations have been made by the INSAT-1 series of satellites since 1982, through procured satellites. Subsequently, a series of weather payloads have been indigenously developed and flown onboard, INSAT-2 & 3 series spacecrafts. This was followed by an exclusive weather satellite Kalpana-1 carrying VHRR. The most sophisticated third generation meteorological satellite, INSAT- 3D, carrying 6 band Imager and 19 channel Sounder was launched in 2013. The satellite is state of the art in terms of enhanced spectral, spatial, radiometric and temporal resolutions supporting enhanced application potential. A glimpse of ISRO's journey in meteorological observations from GEO platform is given in Figs. 1 (a-d). It is evident that the information content in terms of spectral bands, data rates and spatial resolution has significantly improved over last three decades.

Development and adaptation of critical technologies for realizing the meteorological payloads has been one of the key drivers for the program. Development of passive coolers for IR detectors was an important contribution. The cooler developed for a single IR detector element operating at 105 K for INSAT 2 VHRR was upgraded to accommodate up to four detector packages and twelve detector elements, operating at 90 K for INSAT 3D instruments. The forthcoming GISAT will use an Integrated Detector Cooler Assembly, cooling an IR area array detector to 50 K. For the detectors, ISRO has used Return Beam Vidicons (in Bhaskara I & II) to Silicon based photo diode arrays and CCDs; InGaAs arrays; InSb and HgCdTe sensors covering 0.4 to 15 μm spectral range. Semiconductor Laboratory (SCL), Chandigarh is geared up for the development and fabrication of linear and area array detectors for next generation payloads. The

Laboratory for Electro Optics (LEOS) develops the required refractive and reflective optics. Presently, LEOS is developing 1.2 meter primary mirror for space borne telescopes. ISRO Inertial System Unit is developing scan mechanisms required for VHRR and filter wheel drive assembly for Sounder. A number of satellites, both Geosynchronous Earth Orbit (GEO) and Low Earth Orbit (LEO), have been launched for observing the atmosphere.

2.1. GEO satellites for weather observations

2.1.1. Kalpana 1 VHRR

It provides three band VHRR images in Visible (VIS), Water Vapor (WV) and Thermal Infra Red (TIR) bands. It has three imaging modes, viz., Full Earth disk, Normal mode and Sector mode. The VHRR payload has 2 km ground resolution for the Visible channel and 8km for the WV and TIR channels.

2.1.2. INSAT 3A CCD

The CCD payload has three bands namely, Visible (0.62-0.68 μm), Near Infra Red (NIR) (0.77-0.86 μm) and Shortwave Infra Red (SWIR) (1.55-1.69 μm) and 1km spatial resolution. It has normal mode imaging of $10^\circ \times 10^\circ$ area or the program mode ($10^\circ \times 0.4^\circ$ N lines) ground coverage.

2.1.3. INSAT 3D

INSAT-3D is a three axis stabilized GEO satellite like the earlier, launched in July 2013 and parked at 82° E. It has following two payloads.

2.1.3.1. INSAT 3D imager

INSAT-3D Imager provides imaging capability of the Earth disk from geostationary altitude in one

TABLE 2
Sensor specifications for INSAT 3D Sounder

	Channel No.	Center wavelength (μm)	Bandwidth (μm)	NEDT (K) at 300 K scene
LWIR	1	14.71 \pm 0.05	0.281 \pm 0.04	<1.5
	2	14.37 \pm 0.05	0.268 \pm 0.04	<1
	3	14.06 \pm 0.05	0.256 \pm 0.04	<0.5
	4	13.64 \pm 0.05	0.298 \pm 0.04	<0.5
	5	13.37 \pm 0.1	0.286 \pm 0.04	<0.5
	6	12.66 \pm 0.05	0.481 \pm 0.04	<0.3
	7	12.02 \pm 0.1	0.723 \pm 0.05	<0.15
MWIR	8	11.03 \pm 0.06	0.608 \pm 0.04	<0.15
	9	9.71 \pm 0.02	0.235 \pm 0.02	<0.2
	10	7.43 \pm 0.02	0.304 \pm 0.02	<0.2
	11	7.02 \pm 0.02	0.394 \pm 0.03	<0.2
SWIR	12	6.51 \pm 0.065	0.255 \pm 0.02	<0.2
	13	4.57 \pm 0.008	0.048 \pm 0.015	<0.15
	14	4.52 \pm 0.008	0.047 \pm 0.015	<0.15
	15	4.45 \pm 0.055	0.0456 \pm 0.015	<0.15
	16	4.13 \pm 0.015	0.0683 \pm 0.016	<0.15
	17	3.98 \pm 0.05	0.0663 \pm 0.015	<0.15
	18	3.74 \pm 0.01	0.140 \pm 0.015	<0.15
VIS	19	0.695	0.050	SNR>150 @100% Albedo

visible (0.55 to 0.75 μm) and five Infrared channels, *viz.*, Short Wave IR (SWIR) in 1.55 to 1.68 μm , Mid IR (MIR) in 3.8 to 4 μm , Water Vapor IR (WV) in 6.5 to 7 μm , Thermal IR-1 (TIR-1) in 10.2 to 11.2 μm and Thermal IR-2 (TIR-2) in 11.5 to 12.5 μm range (Table 1). The ground resolution at nadir is nominally 1 km for VIS and SWIR channels, 4 km for MIR, TIR-1 & TIR-2 channels and 8 km for WV channel. It takes 26 minutes to scan the full Earth disc. It has a much higher performance of scan mechanism with servo non linearity as low as 25 μrad as against 150 μrad of VHRR. The program mode facilitates imaging of very small area in North-South direction. Thus, Imager can be called the enhanced version of VHRR with two fold improvements in spectral channels, six fold improvement in servo performance and 25% improvement in temporal resolution.

2.1.3.2. INSAT 3D sounder

INSAT-3D Sounder is a nineteen channel radiometer providing the sounding capability of the Earth from geo-

stationary altitude in one Visible and nineteen narrow band Infrared channels (Table 2). A set of dichroic beam splitters separate the visible spectrum and three coarse IR bands. The three IR bands are called the Long Wave IR (LWIR), Medium Wave IR (MWIR) and the SWIR. They pass through three concentric rings of a cold filter wheel maintained at a constant low temperature (\sim 190K) to limit the background radiation. Each ring is further divided into a number of sectors, each housing separate filter for individual channel. Detector array has four elements arranged in North-South direction for each band having 280 μrad IFOV. Hence the combined IFOV in North South direction is 1120 μrad .

The main improvements in INSAT-3D over INSAT-3A and KALPANA-1 are: (i) Imaging in MIR band to provide night time pictures of low clouds and fog, (ii) Imaging in two TIR bands for improved estimation of Sea Surface Temperature (SST), (iii) Higher Spatial Resolution in the VIS and TIR and (iv) Use of sounder sensor to generate vertical profile of temperature

(40 Levels from surface to ~70 km) and humidity (21 levels from surface to ~15 km) for better weather (Mid & Long Range) forecasting and disaster warning.

2.2. LEO satellites for weather observations

2.2.1. Megha-Tropiques

Megha-Tropiques (MT), an Indo-French satellite, was launched in 2011 to study the tropical atmosphere. The amount of precipitation in the tropics is influenced by surface evaporation, net radiation at the top of the atmosphere, integrated water vapour and the vertical profiles of temperature and humidity. Simultaneous measurement of these geophysical variables is required to understand the energy and moisture budget of tropical convective systems. Most of these parameters were being measured individually by satellites. The MT satellite provided such measurements simultaneously with four sensors *viz.*; Microwave Analysis and Detection of Rain and Atmospheric Structures (MADRAS), Sondeur Atmosphérique du Profil d'Humidité Intertropicale par Radiométrie (SAPHIR), Scanner for Radiation Budget (ScaRaB) and Radio Occultation Sensor for Atmosphere (ROSA) (www.cnes.fr/web/CNES-en/5503-megha-tropiques.php). Since diurnal variations in convection are large in the tropics, it is important to observe more frequently than twice daily, as in the case of polar orbiting satellites. MT satellite was placed in a highly inclined orbit (~20°) that allowed a latitudinal coverage of ~30° (up to 40° for ROSA) on both sides of the equator. The temporal sampling by MT is more frequent (3-6 visits per day depending on the latitude) but not at regular time intervals.

MADRAS is a 9-channel conical scanning passive microwave radiometer observing in 5-frequencies, *i.e.*, 18.7, 23.8, 36.5, 89 and 157 GHz, in V & H polarizations, except for 23.8 GHz (V only), with spatial resolution ranging from 6 to 40 km. The radiometer was designed to estimate rainfall, atmospheric water parameters and ocean surface winds in the equatorial belt over a swath of ~1700 km. SAPHIR instrument is used to study the vertical distribution of water vapour in the tropical troposphere (Mathur *et al.*, 2013). SAPHIR is multi-channel cross-track millimeter-wave humidity sounder for atmospheric profiling of humidity. The signal is detected and separated into 6 channels at 183.31 GHz. The narrow beam of the antenna provided a cross-track scanning within an angle of $\pm 42^\circ$, with respect to nadir. SAPHIR enables retrieving information in six atmospheric layers, from the Earth's surface up to ~12 km height. The horizontal resolution is 10 km and the swath is ~1700 km. ScaRaB is a 4-channel scanning radiometer dedicated to measure the earth's radiation

TABLE 3

Sensor specifications of the OSCAT instrument

Parameter	Inner beam	Outer beam
Frequency	13.515 GHz	(Ku-band)
Resolution	50 km × 50 km	
Polarization	HH	VV
Swath width	1400 km	1840 km
Scanning circle radius	700 km	920 km
Elevation angle (look angle)	42.62°	49.38°
Incidence angle	48.90°	57.60°
Footprint	26 × 46 km	31 × 65 km
Scanning rate	20.5 rpm	

budget (Sathiyamoorthy *et al.*, 2013). Among the four channels, two are main broadband channels and the remaining two are auxiliary narrowband channels. The two broad channels measure reflected solar (0.2 - 4 μm) and emitted terrestrial long wave (4-100 μm) radiances.

ROSA is a compact instrument consisting of a Global Navigation Satellite System (GNSS) receiver, a Precise Orbit Determination (POD) antenna for spacecraft position, velocity and time determination. It has two radio occultation antenna; one each in the velocity and the anti-velocity direction – for tracking the GPS GNSS dual frequency signals broadcast at 1.575GHz (L1) and 1.227GHz (L2) for extracting relevant atmospheric parameters (Shyam *et al.*, 2013). The occultation antenna are designed to keep the maximum gain lobe around the Earth limb elevation with a field of view of $\pm 45^\circ$ in order to acquire GPS signals in lower troposphere. The L1-CA and L2-P(Y) codeless GPS signals are processed by the onboard receiver unit after allocating each of the different possible combinations of GPS Spacecraft Vehicles (SVs) and POD or RO antennae to one of the 16 dual-frequency channels available in the receiver. A dedicated communication interface is used to exchange tele-command, telemetry and measurement data with onboard computer of the satellite.

2.2.2. Oceansat-2

Oceansat-2, is configured to cover global oceans and provide ocean colour data with global wind vector and characterization of lower atmosphere and ionosphere. Oceansat-2 carried three payloads: (a) Ocean Colour Monitor (OCM2), having 8-bands with 360 m spatial resolution; (b) Ku-band Scatterometer (OSCAT) with a

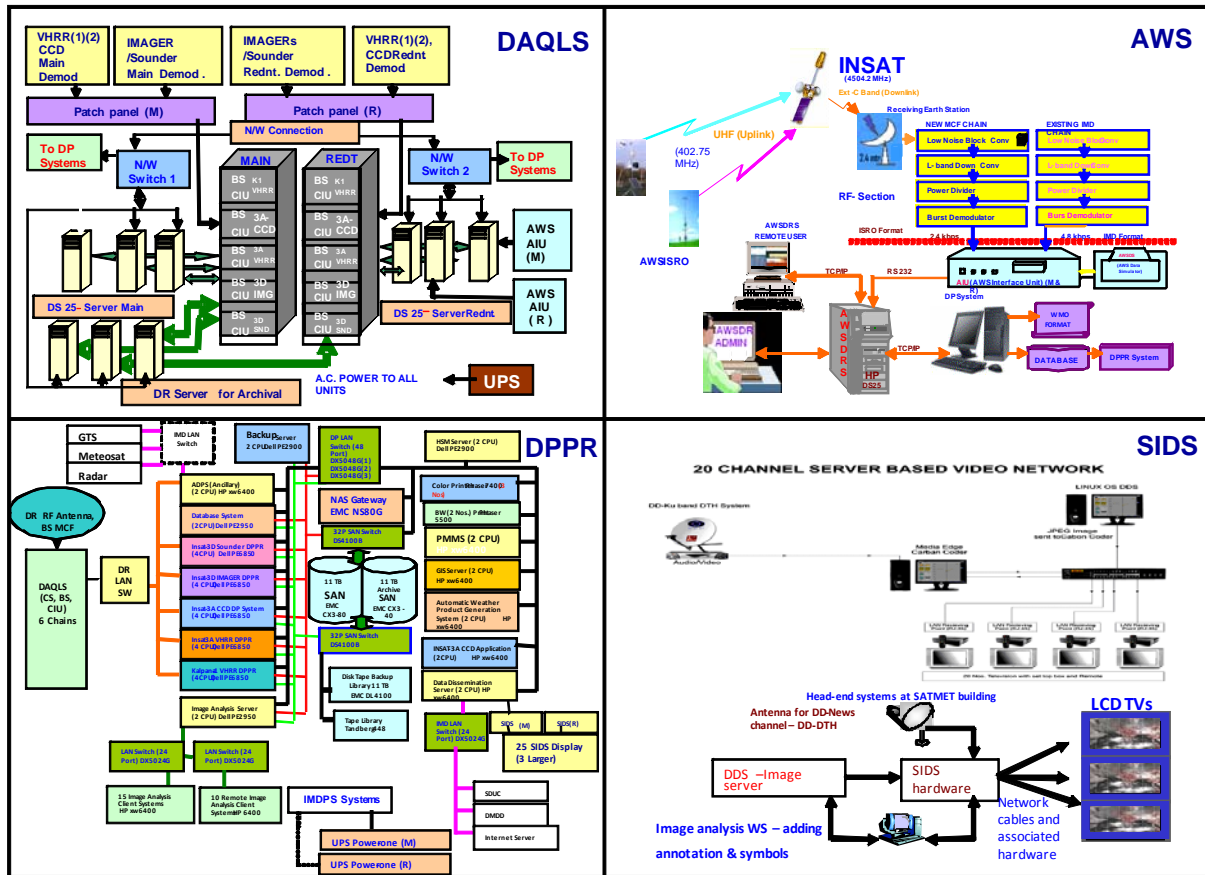


Fig. 2. INSAT 3D Meteorological Data Processing System (IMDPS) showing the Data Acquisition and Quick Look (DAQLS), Data Processing & Parameter Retrieval (DPPR), Automatic Weather Station (AWS) data processing, and Satellite Image Display System (SIDS)

ground resolution of $50 \text{ km} \times 50 \text{ km}$; and (c) ROSA (developed by the Italian Space Agency, ASI). It has significantly contributed to early detection and forecasting of EWEs. The Oceansat-2 Scatterometer (OSCAT) is described here.

OSCAT is an active microwave payload designed and developed at the Space Applications Centre (SAC). Operating at 13.515 GHz (Ku-band) it has ground resolution of 50 km (Table 3). This system has a 1-m parabolic dish antenna and a dual feed assembly to generate two pencil beams with a scanning rate of 20.5 rpm. The antenna is continuously rotated using a scan mechanism with the scan axis along the +ve Y axis. By using two offset feeds at the focal plane of the antenna, two beams are generated which conically scan the ground surface. The backscattered power in each beam from the ocean surface is measured to derive wind vector. It covers a swath of 1400 km by inner beam and 1840 km for outer beam, respectively. It has provided global ocean surface wind vector with a revisit time of 2 days.

3. Data processing systems

Data processing system for INSAT-3D (Imager and Sounder) and Oceansat-2 Scatterometer is described in the following section:

3.1. INSAT-3D system and products

INSAT-3D Meteorological Data Processing System (IMDPS) consists of real time Data Acquisition and Quick Look Processing (DAQLS), near real time Data Processing (DP) and Geo-Physical Parameter Retrieval (PR) of all data transmitted by the Imager and Sounder payloads of INSAT-3D (Ramakrishnan *et al.*, 2010). It has a Satellite Image Display System (SIDS), which is used for display of images and products. IMDPS also includes the Image Analysis System, Ancillary Data Processing, Data Dissemination, Automatic Weather Station (AWS) data processing, archival and retrieval. A schematic diagram is given in Fig. 2.

TABLE 4
List of Geo-physical products from INSAT-3D

Sensor (No. of products)	Product description (No.)	Sub-product list
IMAGER Products (10)	Atmospheric Motion Vector (4)	Water Vapour, IR, VIS and MIR winds
	Outgoing Longwave Radiation	-
	Rain (3)	Quantitative Precipitation Estimation (QPE - PI); IMSRA & HE
	Snow Cover	-
	Upper Troposphere Humidity	-
	Fog Identification	-
	Smoke	-
	Fire	-
	Sea Surface Temperature	-
	Aerosol	-
SOUNDER Products (02)	Profiles (3)	Temperature, Water Vapour and Ozone
	Derived (8)	Total Ozone, Surface Skin Temperature, Geopotential Height, Layered Precipitable Water (3); Lifted Index, Wind Index, Max. Vertical Theta-e & Dry Micro-burst Index

IMDPS software has been indigenously designed, developed, installed and commissioned at IMD, New Delhi with Mirror Site at SAC – Bopal Earth Station (BES), Ahmedabad. It is operational 24 × 7 and caters to INSAT-3D Imager and Sounder, INSAT-3A and Kalpana-1 data processing and product generation. Various types of Data Products generated are: LEVEL - 0 (Raw) – for internal use and archival; LEVEL - 1 (Full Globe); LEVEL - 2 (Sector); LEVEL - 3 (Geo-Physical). The DP Software has the capability for generating the products on user requested media in HDF and /or generic binary formats. Several Geophysical products are generated as shown in Table 4. The data archival and dissemination is through IMD Delhi (www.imd.gov.in/section/satmet/dynamic/insat.htm) and SAC – MOSDAC (www.mosdac.gov.in) websites.

3.1.1.1. Data products software

INSAT-3D processor indigenously designed and developed is based on service oriented architecture to cater to multiprocessing. The core Data Processing consists of Algorithms for radiometric correction including black body calibration, geometric correction to generate per pixel geo-location (for navigation) information including, servo correction and image motion compensation. Geophysical Parameters are generated using standard products as input. Sample products from Imager (sector, full disk view; OLR and UTH) and

sounder (Ozone and skin surface temperature) are shown in Fig. 3.

3.1.1.1.1. Radiometric corrections

The response of the different detectors in the array needs to be normalized. This is done by generating a calibration Lookup table. Before launch, the calibration lookup table is generated in the laboratory. The radiometric calibration pre-processing is carried out based on the extensive ground calibration data and on-board calibration techniques, which track the changes in the instrument response, due to in-orbit thermo-mechanical environment, radiation effects, aging etc. This process also takes into account Global Space-based Inter-Calibration System (GSICS) observations requirements. The new calibration look up table is generated and provided with every product to users.

3.1.1.1.2. Geometric corrections

Resampling is performed on the radiometrically corrected pixel-data based on static and dynamic models of the instrument and satellite. Orbit and attitude parameters recorded simultaneously with the image data are used. High accuracy for a product is achieved by registering the image-pixels on fixed lat-long grids. This is achieved through image navigation and registration algorithm with an automatic approach.

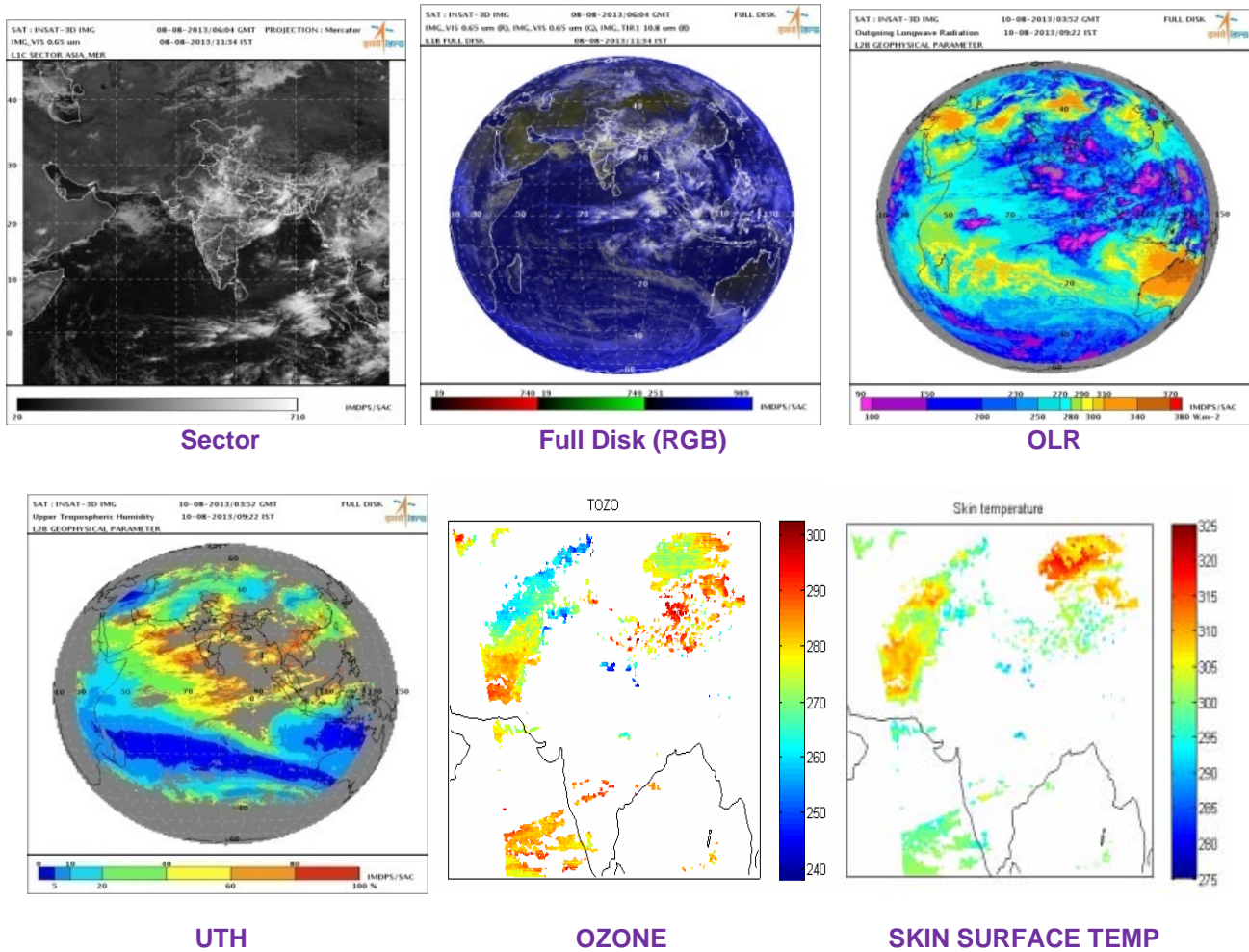


Fig. 3. Sample data products from INSAT-3D imager and sounder

3.1.2. Geophysical parameters retrieval

There are two types of products generated from INSAT-3D viz., (i) Imager based and (ii) Sounder based. Algorithms are implemented in DP chain using INSAT-3D standard data products of full globe or sectors. Products are calibrated using online/lab calibration with GSICS observations and bias-correction is applied. Different visualization techniques for re-projection have been developed for the Earth Observation data received from geo-stationary satellites. The advantage of such a projection is that the data can be visualized from different view angles by RAPID Package.

3.2. Calibration/validation of satellite data

GSICS is an initiative to generate satellite data and products according to well laid procedures and international standard. The main objective of GSICS is to

establish objective scientific procedures that can quantitatively compare, bring out the uncertainties and provide necessary corrections in the measurements taken by different instruments, at different times, over different geographical regions (Goldberg *et al.*, 2011). GSICS corrections are necessary for applications encompassing products taken from multiple satellites platforms, over a large time scale. GSICS activity in ISRO have been taken up for inter-calibration of infrared (IR) channels onboard Indian geostationary satellites; Kalpana, INSAT-3A and INSAT-3D (Shukla *et al.*, 2012). In this exercise data from hyperspectral IR sounders, such as IASI (onboard Metop-A/B) and AIRS (onboard Aqua) with Simultaneous Nadir looking Overpass (SNO) of India geostationary satellites was collected in space and time. The spectra of IASI/AIRS from collocated pixels are convolved over SRFs of Indian Geostationary IR channels. These convolved values are used for further analysis. The inter comparison of Kalpana and INSAT-3D IR imager

channels and INSAT-3D sounder channels show diurnal and seasonal biases. The diurnal biases of IR channels of Indian geostationary satellites reflect the mid-night sun problem in three axis stabilized geostationary satellites. ISRO has also initiated GSICS exercise for calibrating visible channel onboard INSAT-3D imager using lunar calibration method.

4. Applications of space based observations

Space based observations are used to derive weather parameters and also to forecast weather events using the data and products derived from such observations.

4.1. *Deriving the weather products from space observations*

Some of the basic meteorological parameters being estimated from space platform are rainfall, wind, temperature and humidity. There are other parameters such as, vegetation index and Digital Elevation Model (DEM) which help to improve forecast as well as assessing the damage due to EWEs.

4.1.1. *Rain estimation*

Rain-rate estimation from space observation is typically done by Hydro-Estimator (H-E) method (Scofield and Kuligowski, 2003). This method uses thermal infrared observations at 10.7 μm along with environmental parameters to make a quantitative assessment of precipitation. The rain rate is determined by the cloud growth at the given pixel relative to the surrounding pixels. Cloudy pixels having brightness temperature (BT) higher than surrounding are considered non-active, whereas those which are colder are considered raining with rain coming from core, non-core or mixed part of the storm, depending upon value of change in BT. The relationship between core-rain and BT is exponential in nature. Further corrections for orography induced rain and rain from warm clouds are also applied. The orographic correction is carried out by determining gradient of the elevations in the direction of the prevailing 850 hPa level winds (Vicente *et al.*, 2002), whereas correction for the warm clouds is determined by locating the Level of Neutral Buoyancy (LNB) in the atmosphere (Scofield and Kuligowski, 2003).

4.1.2. *Wind estimation*

Winds at different pressure levels are estimated by atmospheric motion vector (AMV) method. In this method, a sequence of geometrically registered imageries from geostationary satellites is used. The “tracers” are identified in the reference image and their location is

monitored over short period of time, typically better than 1 hour. The tracers are followed in the subsequent image in their neighbourhood (Menzel, 2001 and Kishtawal *et al.*, 2009; Källén *et al.*, 2010). Ocean surface winds are also derived using measurements in microwave region by Scatterometer, Altimeter, SAR and Radiometer. Wind vectors are obtained from Scatterometers due to its sensitivity to the ocean surface roughness, primarily generated by wind. Scatterometer offers the possibility of measurements under all weather conditions except during heavy precipitation. Ocean surface wind speed estimation by radar altimetry is also done using the normalized backscatter coefficient, sigma-0. Only single radar backscatter measurements are made at nadir direction for Altimeter. Due to only one measurement, it provides only wind speed. Synthetic Aperture Radar (SAR) provides a unique opportunity to extract ocean surface winds in finer spatial resolution. The wind retrieval from SAR mainly relies on the theory of sensitivity of radar backscatter to the ocean surface roughness. Similar to the case of altimeter, SAR measurements are taken at one azimuth angle, so it requires ancillary information to determine wind direction.

4.1.3. *Land surface temperature*

Land surface temperature (LST) is estimated by measurements in Thermal IR region of electromagnetic spectrum. The LST is basically coupled with two factors: the surface emissivity and the atmospheric absorptions. LST is obtained by correcting the atmospheric and emissivity effects and then by inversion of the Planck's law. Satellite based Sounder observations also provide vertical profiles of temperature under clear-sky conditions. Atmospheric profile retrieval algorithm for Sounder is a two-step approach. The first step includes generation of accurate hybrid first guess profiles using combination of statistical regression retrieved profiles and model forecast profiles. The second step is the physical retrieval based on radiative transfer model (Ajil *et al.*, 2010).

4.1.4. *Atmospheric humidity*

Algorithms for the estimation of Upper Tropospheric Humidity (UTH) use measurements in the water vapor channel onboard satellites (Thapliyal *et al.*, 2011). Corrections need to be incorporated for view zenith angle and atmosphere. A look-up table is derived from radiative transfer calculations for a set of fixed relative humidity (RH) values that interrelates thermal infrared window (IR) and water vapor (WV) channel radiances with the RH. Empirical equations are derived and used to estimate RH. Similar to temperature, satellite based sounder observations also provide vertical profiles of humidity in clear-sky conditions (Thapliyal *et al.*, 2012).

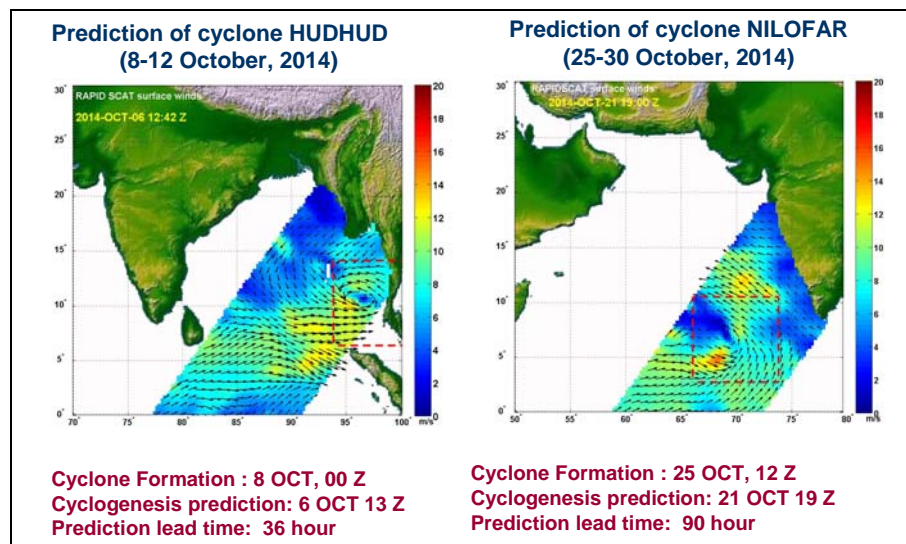


Fig. 4. Prediction of cyclogenesis using wind vector observations

4.1.5. Land cover

Multispectral images, typically from low earth orbiting satellites, acquired at appropriate period are used for land cover classification. They are processed to correct for distortions and noise induced in the imaging process. The output is a corrected image that is as close as possible, both geometrically and radiometrically, to the original object radiant energy distribution. Knowing the spectral behaviour of the land cover class, the data are transformed in such a way that information can be meaningfully interpreted. Based on information about spatial locations of various land covers on ground, their spectral signatures (statistical properties of the land cover class) are generated. These signatures are subjected to separability analysis and checking their distribution in the spectral space. The class assignment is based on similarity measures, typically, a function of weighted distance. The choice of sensor depends upon level of details required for an application. With proper choice of sensor, duration of acquisition and method of classification, information on land cover is generated (Roy and Giriraj, 2008; NRSA 2007 and Roy *et al.*, 2015).

4.2. Satellite data in predicting the EWEs

The ability to predict EWEs is a challenge because of the contribution of fine-scale processes and their nonlinear interactions with the larger-scale forcing. High resolution Numerical Weather Prediction (NWP) model with accurate representation of fine-scale features and explicit representation of convection is required, to improve the prediction of EWEs. Forecasts of NWP model depend on the accuracy of the initial data

describing the current state of atmospheric variables such as winds, pressure, temperature and humidity. Instruments on geostationary platform due to their high spatial and temporal resolutions provide almost continuous information about the evolution of the weather systems over the observing domain. Some of the recent developments in use of space observation and improved analysis techniques in forecasting EWEs such as (i) Tropical Cyclone; (ii) High rainfall events; (iii) heat and cold wave; (iv) Fog and (v) Flood and drought are illustrated in this sub-section.

4.2.1. Tropical cyclone

Satellite data from infra red, visible and microwave channels play an important role in real-time monitoring and forecasting of tropical cyclones. Technique has been developed at SAC for 24 to 96 hours advance prediction of tropical cyclogenesis (Jaiswal and Kishtawal, 2011; Jaiswal *et al.*, 2013). It is based on the wind pattern matching approach in which the ocean surface wind estimated using Scatterometer data is used (Fig. 4). The mean lead prediction time of this approach for the cyclogenesis prediction in the north Indian Ocean is 76 hours (2010-2014).

Thermal Infra Red (TIR) and visible channel data from the geostationary satellites, *viz.*, INSAT-3D and Kalpana are used to estimate the intensity of cyclone using the Advanced Dvorak Technique (ADT) (Fig. 5). High resolution satellite images are useful for the structural analysis of the cyclone as they result in better determination of cyclone center, radius of maximum winds estimation and examining the multiple eye-wall.

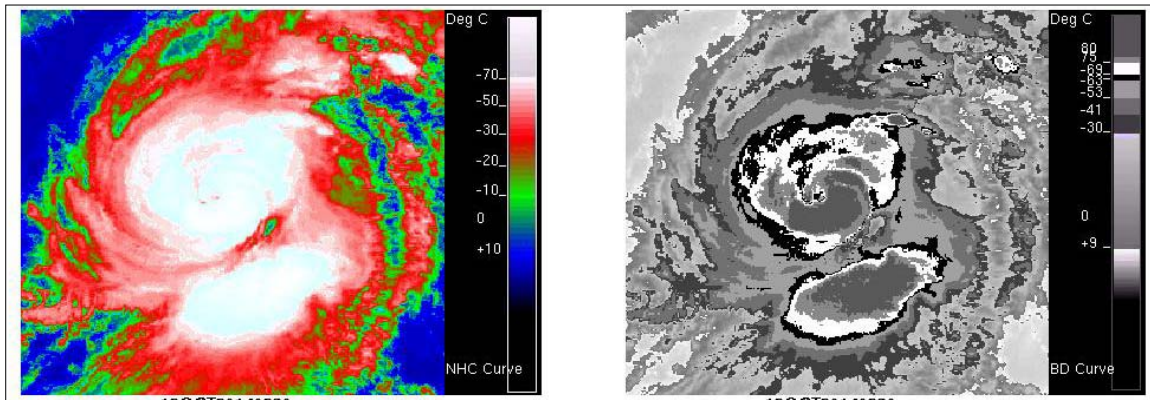


Fig. 5. Structural analysis of cyclone HUDHUD using NHC colour enhanced (left) and BD curve enhanced TIR-1 image from INSAT-3D satellite (0230 UTC, 12 OCT-2014) (right)

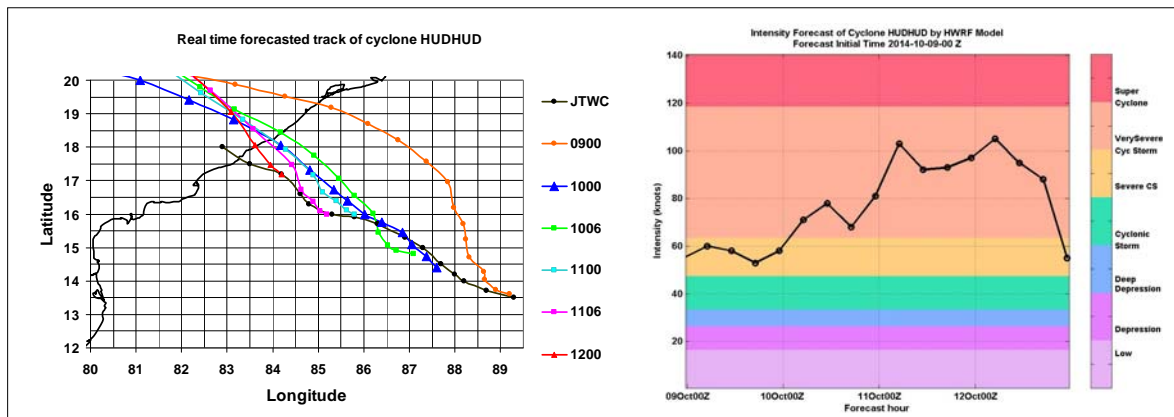


Fig. 6. Real-time forecasted track of cyclone HUDHUD at different initial time by SAC-Lagrangian advection model (left) and Real-time cyclone intensity prediction using HWRF model (right)

Cyclones move along the direction of net environmental steering flow, which is determined by analysing the vertical structure of the atmosphere. A real-time cyclone track prediction model (Lagrangian advection model) has been developed by ISRO, which involves the computation of net environmental steering flow, based on the potential vorticity approach (Singh *et al.*, 2012a & b). The atmospheric-ocean coupled model HWRF developed at NCEP has been customized at ISRO for North Indian Ocean and is being used for cyclone track, intensity and rainfall prediction in the real-time (Fig. 6).

Accuracy of cyclone track prediction using NWP models has increased since the inception of satellite data assimilation in the numerical models. Running the model at cloud resolving scale (fine resolution ~ 3m) has led to improvement in track forecasting. To improve cyclone intensity prediction in WRF/HWRF, a methodology based on Dynamic time wrapping technique along with histogram matching has been developed for inner-core

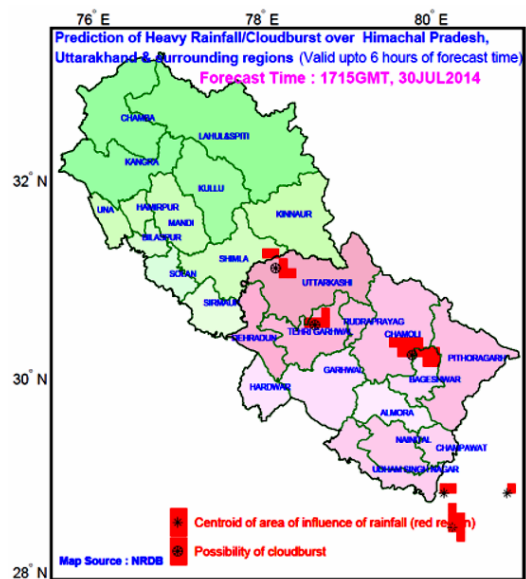


Fig. 7. Half hourly heavy rainfall alerts over Uttarakhand and Himachal Pradesh

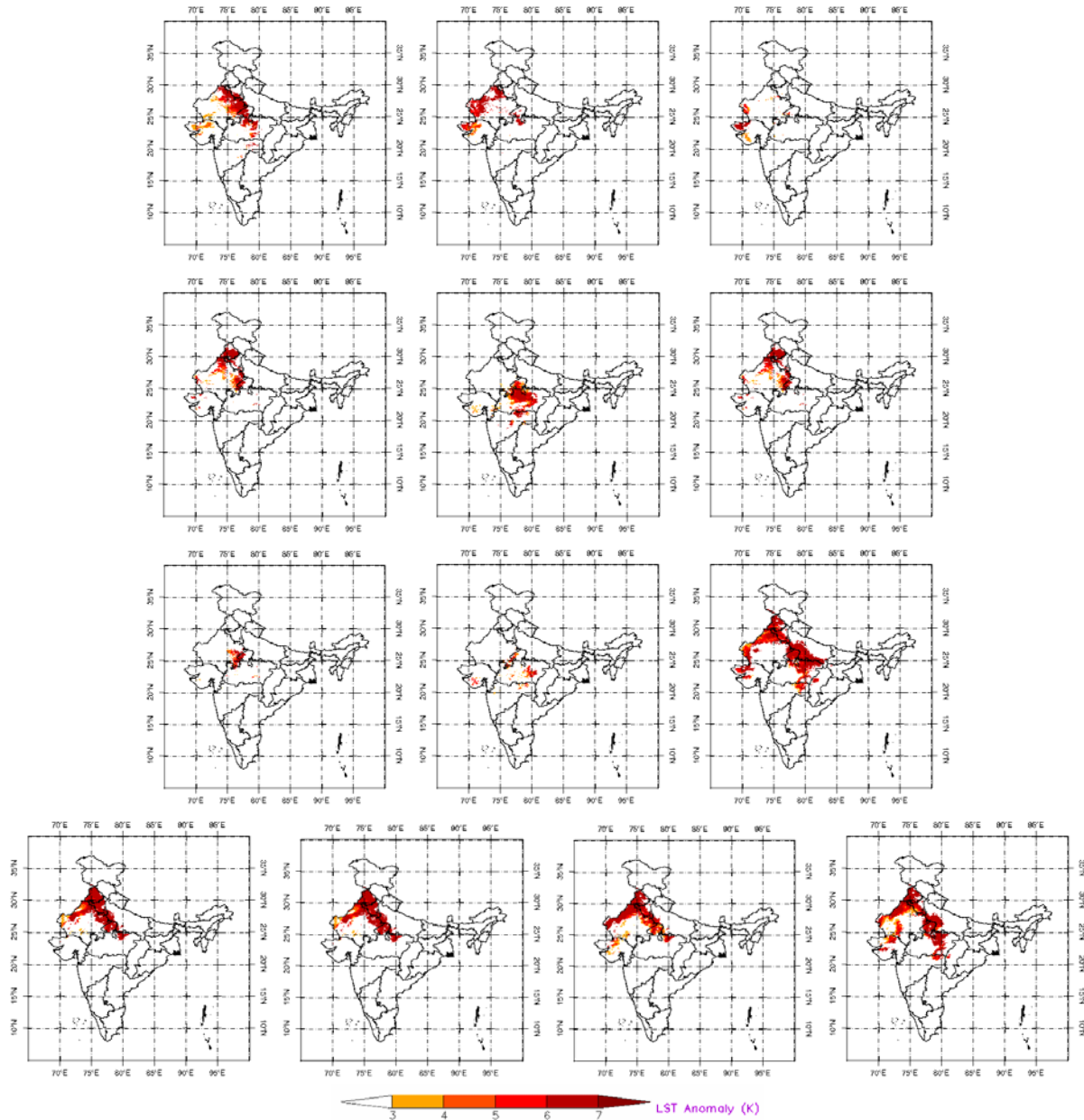
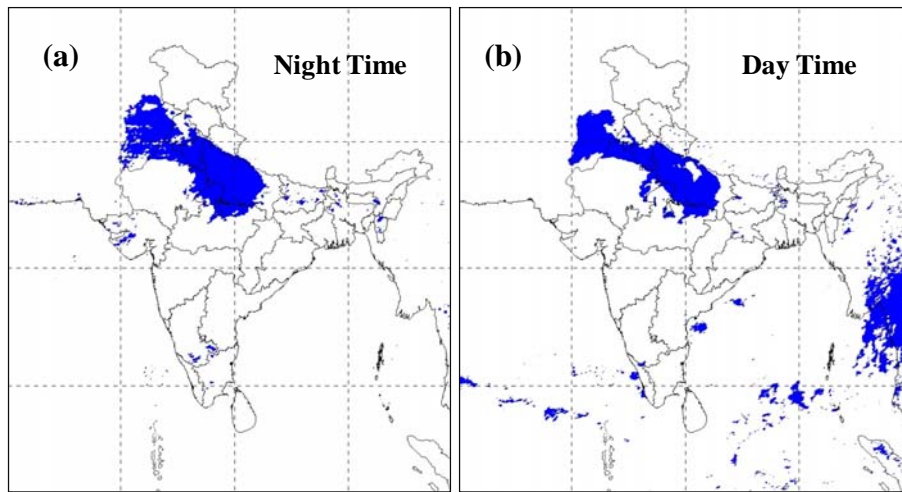


Fig. 8. Heat wave affected regions detected through the use of Kalpana-1 derived LST images shown for a period of 27 May to 10 June, 2014

cyclone data assimilation. Cyclone prediction in terms of cyclogenesis and intensification can be further enhanced by incorporating information on vertical wind shear and oceanic heat content in the models. High resolution satellite observations will enable detailed structural analysis of cyclone (like multiple eye-wall formation which is responsible for rapid intensification) that may improve the prediction of cyclone intensification.

4.2.2. High rainfall events

An algorithm for Nowcasting of ExTreme orographic RAIN events (NETRA) has been developed (Shukla and Pal, 2012; Shukla *et al.*, 2014) for predicting intense convection and precipitation using half hourly INSAT-3D and Kalpana satellite data. It is based on the premise that low BT values represent high cloud cells



Figs. 9(a&b). Sample fog product generated using INSAT-3D data for (a) night time (Jan 07, 2015 2330 UTC) and (b) day time (Jan 08, 2015 0530 UTC). Blue colour represents area covered with fog

TABLE 5

Some extreme weather events and their assessment / forecast using space observations

Event	Spectral region	General principle / method / process	Requirements for improvement
Cyclone	IR & Microwave	Intensity is proportional to pressure gradients; track based on Advanced Dvorak Technique and structure as derived from NWP	High spatial and temporal resolution; improved pressure retrievals; Dual Polarised Rain Radars
Heavy rainfall	TIR, WV	(i) Cloud tops cold enough to support super cooled water and ice mass growth are indicative of heavy precipitation; (ii) The positive water vapour and thermal channel difference is related to deep convection (iii) The rate of change of BT is an indicator of cloud growth rate and provides crucial information in hilly regions	(i) Improved temporal and spatial resolution; (ii) Wind from NWP to be used in conjunction with topography; (iii) Global Navigation Satellite System (GNSS) based now-casting
Heat and cold wave	TIR	Monitoring LST in time	Improving estimation of surface emissivity and better characterisation of atmosphere
Fog	Optical, water vapour, IR	Fog occurs in stable atmospheric conditions (temperature, moisture and wind) where temperature inversion takes place	Hyperspectral measurements from geostationary platform; Improved sensing of atmospheric constituents and boundary layer processes
Flash flood	Optical, IR, Microwave	Water level in lakes and dams, amount of rain upstream, hydrological processes in the stream track and DEM are used to predict the consequences	Improved temporal resolution; real-time information on water level in reservoirs ; integrated information in GIS framework

and marked increase in number of contiguous pixels having cold BT values indicate development of deep convective zones. The alerts in experimental mode from NETRA model are provided for the states of Uttarakhand and Himachal Pradesh with half hourly update through Meteorology and Oceanography Data Archival Centre (MOSDAC; www.mosdac.gov.in) web portal (Fig. 7).

4.2.3. Heat and cold wave

Satellite observations have been used to detect the heat wave conditions prevailing over India (Pandya *et al.*, 2014a). The Kalpana-1 VHRR derived LST products (Pandya *et al.*, 2014b) available from the MOSDAC (www.mosdac.gov.in) were used in the analysis to detect

TABLE 6
Proposed sensor specifications for GISAT

S. No.	Parameter	Goal value			
1.	Satellite altitude (km) Position	35786 (GEO) Equator, 93.5 °E Longitude			
2.	Clear aperture (mm)	700			
3.	Number of bands	4 MX-VNIR HyS-VNIR HyS-SWIR MX-LWIR Each band realized as separate instrument within common telescope			
4.	Spectral channels	Instrument	# Channels	Range (μm)	Channels (μm)
		MX-VNIR	6	0.45 – 0.875	B1 : 0.45 – 0.52 B2 : 0.52 – 0.59 B3 : 0.62 – 0.68 B4 : 0.77 – 0.86 B5N : 0.71 – 0.74 B6N : 0.845 – 0.875
		HyS-VNIR	158	0.375 – 1.0	$\Delta\lambda = 4 \text{ nm}$
		HyS-SWIR	256	0.9 – 2.5	$\Delta\lambda = 7 \text{ nm}$
		MX-LWIR	6	7.1 – 13.5	T1 : 7.1 – 7.6 T2 : 8.3 – 8.7 T3 : 9.4 – 9.8 T4 : 10.3 – 11.3 T5 : 11.5 – 12.5 T6 : 13.0 – 13.5
5.	IGFOV (m) and N-S swath (km) at sub- satellite point	Instrument	IGFOV (m)	N-S Swath (km)	
		MX-VNIR	42	495	
		HyS-VNIR	320	163	
		HyS-SWIR	191	191	
		MX-LWIR	1180	378	

the heat wave regions over India. Images showing area under heat wave conditions and LST anomaly products for of the period May 27 to June 10, 2014 is shown in Fig. 8, where heat wave condition in the north-west-central India are clearly seen.

4.2.4. Fog

Fog is a meteorological phenomenon with temperature inversion, high relative humidity, calm wind condition at surface. The fog is formed when water vapour in the lower atmosphere condenses in cold conditions. The fog droplets are much smaller than the cloud droplet. The small droplets found in fog are less emissive at $3.9 \mu\text{m}$ than at $\sim 11 \mu\text{m}$, whereas emissivity for larger droplets is similar in both the wavelength (Hunt, 1973). The difference between BT measured at these wavelengths is

used to detect the fog (Cermak and Bendix, 2008; Chaurasia *et al.*, 2011). The night time fog and its persistence till the next day morning are illustrated in Fig. 9.

The most useful spectral regions, the general principles / methodology used in observing and predicting the above mentioned EWEs and their assessment/forecast using space observations is listed in Table 5. The factors which are likely to improve the forecasting and / or assessment of EWEs are also listed.

5. Future plan

Forthcoming GEO missions will be INSAT-3DR (R for repeat) and 3DS (S for spare) to ensure continuity of INSAT-3D services till 2027. Oceansat-2 Scatterometer derived product has been found useful, its continuity will

be provided by SCATSAT-1 Scatterometer to be launched in the last quarter of 2015. Similar to the INSAT series of satellites for weather monitoring, series of scatterometers are also being planned to facilitate continuous observation of ocean surface winds in future. In continuation to RISAT-1 SAR, missions with higher imaging capabilities are also planned. A dual frequency SAR is planned to monitor weather, ocean and cryosphere.

While ensuring the continuity of data similar to INSAT-3D and Scatterometer, some new system, viz., Nanosatellite for Earth Monitoring and Observation – Aerosol Monitoring (NEMO-AM) and GISAT (Table 6) are under development to meet the requirements of applications in atmosphere and oceanography. NEMO-AM satellite will be launched in 2015-16. It will carry an optical instrument capable of observing in 3 bands (0.480-0.500 μm , 0.650-0.675 μm and 0.860-0.880 μm) in two polarizations and from multiple angles. It will have ground resolution of ~ 200 m. NEMO-AM will have an in-track look capability of slightly less than 90° and an off-track look capability of 30° . The data from this satellite will provide information on atmospheric aerosols.

GISAT with high spatial resolution in Visible and Near Infrared (VNIR) region is planned for launch in near future. Improved spatial resolution from GISAT, in long wave infrared region will enable precision of meteorological products. GISAT will have capability of providing rapid observations (temporal resolution ~ 10 to 30 minutes) over the Indian land mass and adjoining sea. Such a system will have unique potential for the now-casting and short range weather prediction. Split window thermal IR channels at high resolution will be useful in resolving the SST fronts that has applicability in prediction of convective weather developments and accurate detection of structural features of tropical cyclones. The high resolution radiances, particularly water vapour radiances, will be useful for initializing the convective scale NWP models. Hyperspectral VNIR and short wave infrared instruments, due to availability of channels with small/negligible water vapor absorption for interaction with cloud droplets, will enable retrieval of temperature and humidity profiles.

6. Summary

A number of Indian satellites for observation of land, ocean and atmosphere have been launched. These have carried payloads ranging from VHRR, CCD, Sounder, Imager, Scatterometer, SAR etc. Software developed for generation of products for applications in weather and atmosphere has been deployed at IMD for operational use. Data products are regularly available to users in near real-time. Using the products from Indian satellites it has been

possible to monitor and forecast a large number of EWEs. The 3D coverage of earth surface as well as atmosphere, coupled with NWP models has enhanced the ability of detecting, monitoring and forecasting the events more accurately. In order to further enhance the capability new systems such as NEMO-AM and GISAT are planned in future.

References

- Ajil, K. S., Thapliyal, P. K., Shukla, M. V., Pal, P. K., Joshi, P. C. and Navalgund, R. R., 2010, "A new technique for temperature and humidity profile retrieval from infrared-sounder observations using Adaptive Neuro-Fuzzy Inference System", *IEEE Trans. Geosci. Rem. Sens.*, **48**, 4, 1650-1659.
- Cermak, J. and Bendix, J., 2008, "A novel approach to fog/low stratus detection using Meteosat 8 data", *Atmospheric Research*, **87**, 279-292.
- Chaurasia, S., Sathiyamoorthy, V., Paul Shukla, B., Simon, B., Joshi, P. C. and Pal, P. K., 2011, "Night time fog detection using MODIS data over Northern India", *Meteorological Applications*, **18**, 4, 483-494.
- Goldberg, M., Ohring, G., Butler, J., Cao, C., Datla, R., Doelling, D., Gärtner, V., Hewison, T., Iacovazzi, B., Kim, D., Kurino, T., Lafeuille, J., Minnis, P., Renaut, D., Schmetz, J., Tobin, D., Wang, L., Weng, F., Wu, X., Yu, F., Zhang, P. and Zhu, T., 2011, "The global space-based inter-calibration system", *Bull. Amer. Meteorol. Soc.*, **92**, 4, 467-475.
- Hunt, G. E., 1973, "Radiative properties of terrestrial clouds at visible and infra-red thermal window wavelengths", *Quarterly Journal of the Royal Meteorological Society*, **99**, 346-369.
- IPCC, 2011, "Intergovernmental Panel on Climate Change", 2.7 Has Climate Variability, or have Climate Extremes, Changed?, www.ipcc.ch/ipccreports/tar/wg1/088.htm.
- Jaiswal, N. and Kishtawal, C. M., 2011, "Prediction of tropical cyclogenesis using scatterometer data", *IEEE Transaction on Geoscience and Remote Sensing*, **49**, 12, 4904-4909.
- Jaiswal, N., Kishtawal, C. M. and Pal, P. K., 2013, "Prediction of tropical cyclogenesis in North Indian Ocean using Oceansat-2 scatterometer (OSCAT) winds", *Meteorology and Atmospheric Physics*, **119**, 137-149.
- Källén, E., Tan, D., Cardinali, C. and Berrisford, P., 2010, "Spaceborne doppler wind lidars - Scientific Motivation and Impact Studies for ADM/Aeolus", 33rd meeting of the working group on space-based lidar winds, Destin, FL, CIRES. [Available online at <http://cires.colorado.edu/events/lidarworkshop/LWG/Feb10/Papers.feb10/Kallen.feb10.ppt>].
- Kishtawal, C. M., Deb, S. K., Pal, P. K. and Joshi, P. C., 2009, "Estimation of atmospheric motion vectors from Kalpana-1 imagers", *Jour. Appl. Meteor. Clim.*, **48**, 11, 2410-2421.
- Mathur, A. K., Gangwar, R. K., Gohil, B. S., Deb, S. K., Prashant Kumar, Shukla, M. V., Simon, B. and Pal, P. K., 2013, "Humidity profile retrieval from SAPHIR on-board the Megha-Tropiques", *Current Science*, Special section: Megha-Tropiques, **104**, 12, p25 2010JD014291.

- Menzel, W. P., 2001, "Cloud tracking with satellite imagery : From the pioneering work of Ted Fujita to the present", *Bull. Amer. Meteor. Soc.*, **82**, 33-47.
- NRSA, 2007, "Natural resource census: National land use land cover mapping using multi-temporal AWiFS data", Project Report NRSA/LULC/1:250K/2007-1. National Remote Sensing Agency - Hyderabad, India.
- Pandya, M. R., Shah, D. B. and Darji, N. P., 2014a, "Detection of heatwave from the satellite derived land surface temperature products", Scientific Note : Space Applications Centre - Ahmedabad: Scientific Note. SAC/EPISA/BPSG/EHD/SN/01/JUNE/2014.
- Pandya, M. R., Shah, D. B., Trivedi, H. J., Darji, N. P., Ramakrishnan, R., Panigrahy, S., Parihar, J. S. and Kirankumar, A. S., 2014b, "Retrieval of land surface temperature from the Kalpana-1 VHRR data using a single-channel algorithm and its validation over western India", *ISPRS Journal of Photogrammetry & Remote Sensing*, **94**, 160-168.
- Ramakrishnan, R., Goswami, D. R., Padmanabhan, N., Dube, N., Darji, N. Mahammad, S. and Pandya, K. S., 2010, "Near real time data processing of INSAT data and dissemination of data products", In Proc. of the Coordination Group for Meteorological Satellites, New Delhi, (CGMS-38).
- Roy, P. S. and Giriraj, A., 2008, "Land use and land cover analysis in Indian context", *J. of Appl. Sci.*, **8**, 8, 1346-1353.
- Roy, P. S., Roy, Arijit, Joshi, P. K., Kale, M. P., Srivastava, V. K., Srivastava, S. K., Dwivedi, R. S., Joshi, C., Behera, M. D., Meiyappan, P., Sharma, Y., Jain, A. K., Singh, J. S., Palchowdhuri, Y., Ramachandran, R. M., Pinjarla, B., Chakravarthi, V., Babu, N., Gowsalya, M. S., Thirunevgadam, P., Kotteeswaran, M., Priya, V., Krishnamurthy, Y. V. N., Maithani, S., Talukdar, G., Mondal, I., Rajan, K. S., Narendra, P. S., Biswal, S., Chakraborty, A., Padalia, H., Chavan, M., Pardeshi, S. N., Chaudhari, S. A., Anand, A., Vyas, A., Reddy, M. K., Ramlingam, M., Manonmani, R., Behera, P., Das, P., Tripathi, P., Matin, S., Khan, M. L., Tripathi, O. P., Deka, J., Kumar, P. and Kushawaha, D., 2015, "Development of decadal (1985-1995-2005) land use and land cover database for India", *Remote Sensing*, **7**, 2401-2430; doi:10.3390/rs70302401.
- Sathiyamoorthy, V., Shukla, Bipasha Paul, Sikhakolli, R., Chaurasia, S., Simon, B., Gohil, B. S. and Pal, P. K., 2013, "Top of atmosphere flux from the Megha-Tropiques ScaRaB", *Current Science*, Special section: Megha-Tropiques, **104**, 12, 1656-1661.
- Shyam, A., Gohil, B. S. and Basu, S., 2013, "Retrieval of water vapour profiles from radio occultation refractivity using artificial neural network", *Indian Journal of Radio and Space Physics*, **42**, 411-419.
- Scofield, R. A. and Kuligowski, R. J., 2003, "Status and outlook of operational satellite precipitation algorithms for extreme-precipitation events", *Weather and Forecasting*, **18**, 1037-1051.
- Shukla Bipasha, P. and Pal, P. K., 2012, "A source apportionment approach to study the evolution of convective cells: An application to the nowcasting of convective weather systems", *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **5**, 1, 242-247.
- Shukla Bipasha, P., Kishtawal, C. M. and Pal, P. K., 2014, "Nowcasting of ExTreme orographic RAin (NETRA)", Space Applications Centre - Ahmedabad: Scientific Report. SAC/EPISA/AOSG/SR/12/2014.
- Shukla, M. V., Thapliyal, P. K., Bisht, J. H., Mankad, K. N., Pal, P. K. and Navalgund, R. R., 2012, "Intersatellite Calibration of Kalpana Thermal Infrared Channel Using AIRS Hyperspectral Observation", *Geoscience and Remote Sensing Letters*, IEEE, **9**, 4, 687-689. doi: 10.1109/LGRS.2011.2178813.
- Singh, S. K., Kishtawal, C. M. and Pal, P. K., 2012a, "Track prediction of Indian Ocean cyclones using Lagrangian advection model", *Nat. Hazards*, **62**, 745-778.
- Singh, S. K., Kishtawal, C. M., Jaiswal, N., Singh, R. and Pal, P. K., 2012b, "Impact of vortex-removal from environmental flow in cyclone track prediction using Lagrangian advection model", *Meteorology and Atmospheric Physics*, **117**, 103-120.
- Thapliyal, P. K., Shukla, M. V., Shah, S., Joshi, P. C., Pal, P. K. and Ajil, K. S., 2011, "An algorithm for the estimation of upper tropospheric humidity from Kalpana observations: Methodology and validation", *J. Geophys. Res.*, **116**, D01108, doi:10.1029/2010JD014291.
- Thapliyal, P. K., Shukla, M. V., Bisht, J. H., Pal, P. K. and Navalgund, R. R., 2012, "Improvement in the retrieval of humidity profiles using hybrid regression technique from infrared sounder data – A simulation study", *Meteorological Applications*, (Doi: 10.1002/met.1330).
- Vicente, G. A., Davenport, J. C. and Scofield, R. A., 2002, "The role of orographic and parallax corrections on real time high resolution satellite rainfall estimation", *International Journal of Remote Sensing*, **23**, 221-230.
- www.cnes.fr/web/CNES-en/5503-megha-tropiques.php
- www.imd.gov.in
- www.isro.gov.in/applications
- www.mosdac.gov.in