Evolution of Satellite Meteorology and its Future Scope

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ABSTRACT. Satellite meteorology is the newest and fastest growing branch of meteorology. What satellite meteorology happens to be today, is the result of an interplay of science on one hand, and the technology of satellites, computers and communications on the other. Limitations of technology have been overcome by scientific ingenuity, and the requirements of science have driven technology to the cutting edge. INSAT is India's unique domestic multi-purpose satellite system which in 1982 ushered in a new era in communications, television and radio broadcasting, and meteorology, all at the same time. This paper traces the fascinating growth of satellite meteorology in India and discusses the use of INSAT imagery in operational meteorology and the use of satellite-derived products. It describes satellites like Oceansat-2 which has just been launched and INSAT-3D and Megha-Tropiques which will be launched in the very near future. It outlines India's plans to launch satellites with microwave sensors for monitoring rainfall and other surface parameters, and atmospheric aerosols which have a bearing on climate trends.

Keywords: Satellite meteorology, imagery, satellite derived products, INSAT, Kalpana.

1. Introduction

Fifty years ago, satellite meteorology did not exist except perhaps in science fiction. It was born on 1 April 1960 with the successful launch of the world's weather satellite TIROS-1 by the U. S. Since then there has been no looking back. What satellite meteorology happens to be today, is the result of an interplay of science on one hand, and the technology of satellites, computers and communications on the other. Limitations of technology have been overcome by scientific ingenuity, and the requirements of science have driven technology to the cutting edge. Satellite meteorology, although the newest branch of meteorology as a whole, has been the fastest growing one too. One wonders what the future will be like.

In the field of satellite meteorology, unlike many other areas in science and technology, India has been exceptionally different in that it has matched the global players, which are mainly the developed nations like the U. S. and Japan, in their strides. In 1982, India became the first developing country to have its own geostationary satellite INSAT-1A in orbit with a multi-purpose capability including meteorological remote sensing. Till then, Indian meteorologists were using analog imagery received from U. S. orbiting satellites from eight readout stations established over the country in the 1960s. But with launch of INSAT-1A, satellite meteorology in India truly came of age.

2. The INSAT System

The evolution of the Indian space programme and its meteorological component has been described in many reviews (Kelkar 1994, Pandey et al 1994, Joshi et al 2003, Kelkar 2006). In India, the need to have a national meteorological and remote sensing satellite programme to monitor its weather and vast natural resources was realized way back in the sixties by great pioneers and visionaries like Vikram Sarabhai and Satish Dhawan. The successful launches of the first Indian satellite Bhaskara-I in 1979 and its follow-on Bhaskara-II in 1981 were followed by the launch of INSAT-1A in 1982 and INSAT-1B in 1983. The first Indian remote sensing satellite IRS-1A was launched in 1988.

INSAT is India's unique domestic satellite system which was conceptualized to bring in satellite-based services in as many fields as possible in the quickest possible time. The multi-purpose concept of INSAT led to the realization of the full potential of the geostationary satellite system in one stroke. Thus while other countries had dedicated satellites for different purposes, INSAT-1A ushered in a new era in communications, television and radio broadcasting, and meteorology at the same time.

The Indian satellites INSAT-1A to -1D, and INSAT-2A and -2B carried a 2-channel Very High Resolution Radiometer (VHRR). The two channels were visible (VIS) 0.55-0.75 μ and thermal infra-red (TIR) 10.5-12.5 μ. Their resolutions at the sub-satellite point were 2.75 and 11 km respectively for INSAT-1A to -1D, and 2 and 8 km respectively for INSAT-2A and -2B. The INSAT-2E satellite, for the first time carried a 3-channel VHRR with a water vapour channel (WV) 5.7-7.1 μ added to the VIS and TIR channels. The ground resolution of the WV channel was 8 km.

Full details of the INSAT-2A and -2B VHRR instrument have been described by Joseph et al (1994) and subsequent improvements and additions made to the INSAT-2E VHRR have been discussed by Iyengar et al (1999). The VHRR optics assembly basically consists of a telescope, dichroic beam splitter, IR collimating lens, IR relay optics and VIS band optical elements. The incoming radiation is reflected onto an 8 inch (20.32 cm) diameter 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 VIS 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. For WV and TIR bands, the detector package contains two sets of dual mercury-cadmium-telluride (HgCdTe) photoconductive detector elements in close proximity to band defining filters. The IR detectors are operated nominally at a precisely controlled low temperature in the range of 105-115 ºK to limit thermally generated noise. A passive radiant cooler is used to cool the IR detector package. One of the detectors in each band is energized, while the other set provides the on-board redundancy. Both sets are identical in function and can be switched on or off from through ground command.

The image of the earth is generated by sweeping the instantaneous geometric field of view of the detectors by rotation of the scan mirror-gimbals in two orthogonal axes. For every east-west sweep of the mirror, four contiguous lines of VIS band and one line each of WV and TIR bands are generated. At the end of the sweep, the mirror is stepped south through an angle equivalent to 8 km on the ground and data collection is resumed in the reverse west-east sweep.

Three modes of operation are provided to allow trade-off between area and frequency of coverage. The full frame mode scans the entire earth disc and some space around (20º × 20º) in about 33 min. The normal frame mode coverage in the east-west direction is the same as in the full frame mode, but in the north-south direction, the scan is limited to only 14º, covering the region between 50 ºN and 40 ºS latitudes in 23 min. In the sector scan mode, the east-west coverage is the same as in the full frame and normal frame modes, but is further limited to a 4.5º scan in the north-south direction which can be completed in about 7 min. The sector can be positioned, through ground command, anywhere in the full scan field in steps of 0.5º in the north-south direction. This mode is particularly suited for rapid repetitive coverage during severe weather conditions.

The dark and cold space views at the east and west ends are used for establishing reference radiance for all the three bands. A full end-to-end calibration of WV and TIR bands is provided by swinging the mirror to view a black body cavity fitted on the inner side of north plate of the instrument. The physical temperature of the black body is accurately monitored by platinum resistance thermometers at five locations and is telemetered through the VHRR data stream. The system response for black body view is available in the video data slot.

The detector outputs of all the three channels are individually amplified, band limited and digitized to 1024 grey levels by A/D converters. The digitized data along with other housekeeping information and calibration data, are formatted, randomized and transmitted serially in extended C band to the INSAT Meteorological Data Processing System at the India Meteorological Department, New Delhi.

The design of the VHRR systems on the currently operational Indian satellites, INSAT-3A and Kalpana-1, are similar to the INSAT-2E VHRR.

Table 1 is a detailed chart of the milestones in the history of evolution of the

INSAT meteorological programme. While the INSAT-1 series consisted of multi-purpose satellites, some of the later satellites did not have a meteorological component. On the other hand, METSAT, launched in 2002, and later renamed Kalpana-1, is exclusively dedicated to meteorological services. INSAT-3D to be launched in very shortly, will be the first Indian satellite to carry a sounder.

Satellites in the INSAT-1 series were built in the U.S. as per Indian design and launched from abroad. Satellites in the INSAT-2 series were built indigenously but launched from abroad. INSAT-2C was India's first exclusive communications satellite. INSAT-2E was the first geostationary meteorological satellite to have a CCD payload. Metsat, India's first exclusive meteorological satellite, was launched from Sriharikota by ISRO's PSLV-C4. Metsat was renamed Kalpana-1 on 5 February 2003 in memory of Dr Kalpana Chawla, the India-born American astronaut who died in the U.S. space shuttle Columbia disaster on 1 February 2003. Kalpana-1 located at 74 °E and INSAT-3A located at 93.5 °E are the current operational satellites. INSAT-3D will be the first Indian meteorological satellite to have a sounder.

3, Satellite Imagery and its Interpretation

In the initial years of satellite meteorology, satellite imagery was available in analogue form and had to be interpreted by analysts. It was much later that satellite scanning radiometers began sending digital data that could be processed by computers. However, it became the practice to convert the digital data into image form so that it could still be interpreted visually. This practice continues even today. The most common method of image interpretation is to look for dominant cloud features, analyse their brightness and contrast, form and texture, and to see how these features change from one frame to another. Thunderstorms are the easiest to detect as they appear brightest in visible, infrared as well as water vapour images. Figure 1 shows the development of pre-monsoon afternoon thunderstorms over India and adjoining regions as spotted by Kalpana-1 satellite.

The arrival of the southwest monsoon over India is a much-awaited event for the Indian population, particularly the farmers who have to time their sowing operations in tune with it. As there is hardly any conventional meteorological data available to the south of India, the onset of the southwest monsoon over Kerala can best be monitored by INSAT and Kalpana satellites. Figures 2 and 3 are images of two different monsoon onset scenarios, a strong and early onset in 2006 and a weak and delayed onset in 2005. Satellite images are of great value in tracking the further progression of the southwest monsoon across the subcontinent. Of particular interest are the paths of monsoon lows and depressions as they determine the areas that are to receive copious monsoon rains. Figure 4 is an example of an active monsoon episode and shows a monsoon depression that has formed in the Bay of Bengal and is moving inland. The image clearly brings out the structure of the monsoon depression, including the curved cumulus cloud lines curving into its centre and the overcast southwestern sector which is the recipient of maximum rainfall.

During the winter season, a series of western disturbances enter the country, having originated over the Mediterranean Sea and traversing Iran, Afghanistan and Pakistan. The path of these disturbances can be followed by satellites like INSAT and Kalpana and an advance notice of their arrival obtained. Some of these western disturbances are only troughs or feeble lows, but many are stronger and their images show the typical comma-shaped cloud configuration as in Figure 5. In such cases, the mountain regions get heavy snowfall while the plains of northern India receive good rainfall. As the system move further eastwards, cold waves and fog follow in their wake, as seen in Figure 6.

By far the greatest benefit that meteorologists the world over have derived from satellite imagery has been in the monitoring of tropical cyclones. Satellites are the only source of information about tropical cyclones while they are far out as sea, and it is only when they come in the vicinity of the coast that radars can view them. Figure 7 shows the deadly Hurricane Rita that hit the U. S. coast in 2005 with full fury. Over the Bay of Bengal and the Arabian Sea too, INSAT and Kalpana satellites have been our watchdogs in space and allowed no cyclone go unnoticed.

4. **Quantitative Product Derivation from Satellite Data**

While early meteorological satellites had TV cameras they were soon replaced by scanning radiometers that sent back digital data. These could be converted into image displays but they could also be used for deriving quantitative products. Such derivations became possible in India only after digital data from the INSAT VHRR was first available in 1982 and could be processed at the Meteorological Data Utilization

Centre at New Delhi (Kelkar and Khanna 1986, Arkin, Rao and Kelkar 1989, Kelkar and Rao 1990, Kelkar, Rao and Bhatia 1993).

The extraction of meteorological products from VHRR radiance data is in principle simple and straightforward, although some products can be derived only from geostationary satellites and some only from orbiting satellites. By using successive half-hourly image triplets from geostationary satellites, cloud tracers can be identified and tracked across the three images. The positional displacement of the cloud divided by the image interval gives the wind speed and direction. In practice, numbers of issues arise, such as the level to which the wind is to be assigned or whether the cloud movement is truly representative of the wind at all. Then there a likelihood of a variety of errors vitiating the wind extraction arising from a change in the shape and size of the cloud tracer, vertical growth of the tracers, multiplicity of similar looking cloud elements and so on. Manual tracking is reliable but slow while automatic tracking is fast but error-prone. But most of all, when there are no clouds no winds can be derived. Again, low clouds can be best tracked in visible channel imagery but only during daytime, while high clouds are better tracked in infrared imagery. Water vapour imagery can be used at all times but only middle tropospheric winds can be derived.

When no clouds are present over the ocean, sea surface temperatures can be derived by inverting the radiance received by the satellite, in principle. However, in practice the main difficulty is to correct for the attenuation that the radiance leaving the sea surface is subjected to by the moisture intervening between the sea surface and the satellite. Again, in cloudy areas and at times like the monsoon, sea surface temperatures cannot be derived from infrared radiances just because the surface is not visible.

The broad band outgoing longwave radiation at the top of the atmosphere can be estimated rather easily from the narrow band infrared radiances reaching the satellite by applying statistical relationships. Like any statistical methods, this too has its own errors.

Large-scale precipitation can be estimated from geostationary brightness temperatures accumulated over a period of time by applying a statistically derived rain rate. Here again, the method is in principle simple but has several limitations. Monsoon rainfall is heavy and has characteristics that are different from the drizzle type rain the extra tropics. Spurious or incorrect rainfall values get estimated by this method over tall mountains and deserts.

As a result of all the errors and uncertainties that are entailed in quantitative product extraction from satellite data, the methods and algorithms used have to be constantly reviewed, modified and improved. As new sensors and new spectral channels become available, as spatial resolutions get better, as refined statistical methods and quality checks are devised, as there is more ground truth for comparison, the extraction process has to be modified to take advantage of them. In India particularly, and the world over, satellite-derived products have shown a steady improvement in accuracy and availability over the years. Figure 8 shows the prevailing high quality of tropospheric winds derived from Kalpana water vapour channel imagery. Figure 9 is a latitude-time diagram of daily OLR from 1 January 2009 through the latitude belt 15 S to 40 N. The OLR values are averaged over 50 E to 110 E for each latitude.

A unique feature of the INSAT-3A/Kalpana-1 satellites is the Charge Coupled Device (CCD) payload. This views the earth during daytime in the three bands: Visible 0.62–0.68 μ, Near IR band at 0.77–0.86 μ and Short wave IR band at 1.55–1.69 μ. The ground resolution at the sub-satellite point is nominally 1 km x 1 km and in the normal mode of operation the instrument is designed to scan a 10° x 10° field of view, which corresponds to a ground area of about 6300 x 6300 km. From geostationary altitude the CCD provides images of a very high quality although during daytime alone. However, the CCD data are being used for computing the Normalized Difference Vegetation Index (NDVI) an example of which is given in Figure 10.

5. Emerging Technologies

Many new technologies have already made an impact in the area of meteorological remote sensing and they are certain to be employed in a big way in the coming years. These are discussed in this section.

5.1 GPS-based Soundings of the Atmosphere

The Global Positioning System (GPS) of satellites was originally developed for meeting the requirements of high-precision navigation and positioning, and it consists of a constellation of satellites that transmit L-band radio signals. However, an exciting application of great potential has emerged in an area that the original GPS concept was never intended to serve. This has come to be known as the GPS radio occultation technique and it is now being used to retrieve temperature and humidity profiles in the atmosphere. Various aspects of the GPS radio occultation technique and data processing have been discussed in detail in many recent papers, but a concise explanation and description has been given by Anthes et al (2003).

The GPS radio occultation technique is based on the principle that radio waves while passing through the atmosphere undergo refraction, the nature of which is in turn determined by the gradients of temperature, water vapour and electron density. Refraction effects are most pronounced when the radio wave traverses a long atmospheric limb path, and measurements for a series of such paths at different tangent heights contain information on the vertical profile of refractivity. If the refraction effects can be measured, then the atmospheric temperature and humidity elements that produced them can, theoretically speaking, be retrieved.

In practice, the GPS radio occultation technique involves precise L-band dual-frequency phase measurements by a GPS receiver placed on a low earth orbiting (LEO) satellite which tracks a setting or rising GPS satellite on the horizon (Figure 11). The GPS receiver has to be suitably equipped to detect amplitude, pseudo-range and phase measurements for each of these signals. The LEO satellite uses the GPS signals both to determine its own precise location and to make signal occultation measurements. As the position and velocity of both the LEO and GPS satellites are known, the small increase in the phase path due to the atmospheric refraction during the occultation event can be derived. This information is then converted to the atmospheric bending angles. Assuming a spherically symmetric atmosphere, vertical profiles of refractive index can be determined and converted to lower tropospheric soundings of atmospheric parameters such as pressure, temperature and indirectly water vapour.

The main advantages of the GPS soundings are global coverage, high vertical resolution and all-weather capability combined with high accuracy which make them ideally suited for various applications in atmospheric and ionospheric research, weather forecasting and climate studies. While the GPS radio occultation technique is conceptually quite simple, the accuracy of the derived profiles depends on two major aspects of how the system actually operates. First is the calibration of the signal, which requires the atmospheric delay induced on the occulted signal to be isolated from all other effects such as geometrical motion of the satellites, clocks and ground troposphere. The other is the process of inversion of the atmospheric delay to obtain physical parameters such as refractivity and other derived products. There is a need for carrying out a proper calibration of the phase delays measured from GPS, correction of measurement errors due to data outages, proper smoothing of the data, and evaluation of errors due to Doppler shift and bending.

5.2 Hyperspectral Imaging

The spectral resolution of a satellite sensor is inversely related to the spectral range covered by it. A higher spectral resolution and an accurate spectral signature can be obtained by having a large number of narrow bands, rather than one continuous broad band. Further, the spectral resolution and spatial resolution are also inversely related, since for registering the small amount of radiance contained in a very narrow spectral band, the sensor must dwell on the ground area for a longer time. However, if the satellite sensors are made to scan the earth at a slow speed they will take longer to complete the scan, thus reducing the temporal resolution or repetivity of observations as well. Remote sensing satellites can have a long repeat cycle of 10-20 days and can therefore make measurements in narrow spectral channels. Meteorological satellites cannot do this and in order to accomplish fast earth scans, they acquire stronger radiances from wider spectral bands such as VIS 0.55-0.75 μ or TIR 10.5-12.5 μ. The sensor response is, however, not uniform over the entire width of the channel and even if many satellite radiometers have nominally the same spectral bandwidths, their spectral response functions across the band are not identical. This is the reason why images of the same region obtained from different satellites look a little different from each other.

Hyperspectral imaging is a new and powerful means for reducing the spectral channels to extremely small widths, even as small as 0.01 μ. With such narrow widths, the spectral range from 0.38 to 2.55 μ for example, can be divided into as many as 217 intervals. This is made possible by the use of silicon microchips as detectors for the very near IR region, and Indium-Antimony (In-Sb) alloy detectors for the shortwave SWIR region. The radiance values measured by the CCDs for each such narrow interval are plotted as a graph of intensity versus wavelength, that provides a sufficient number of points through which we a meaningful continuous spectral curve can be drawn. Hyperspectral imaging is in principle far superior to multi-spectral imaging, as it provides much more detail about the spectral properties of the features to be identified. The hyperspectral data yields continuous spectral signatures rather than the band histogram plots.

Two recent satellites have been able to demonstrate the capability of hyperspectral imaging. An instrument called Hyperion, is part of EO-1, the first satellite in NASA's New Millenium series, launched in December 2000. It was inserted into an orbit that positions it just about 50 km behind Landsat-7, which allows both satellites to view almost the same scene for making comparative evaluations. ESA has launched in 2001, as part of the MicroSat program, a satellite called Project for On-Board Autonomy (PROBA). This small satellite of dimensions 40 × 60 × 80 cm and a weight of 94 kg with solar panel collectors mounted on its surface, also has a hyperspectral imaging system with 200 narrow bands.

5.3 Lightning Detection

Lightning is a phenomenon that is far more deadly than other severe hazards like hail, squalls and heavy rain associated with a thunderstorm. Hundreds of people lose their life every year across India to lightning strikes particularly in the pre-monsoon summer months. Meteorological satellites are able to monitor thunderstorms but not lightning per se. By definition, lightning is a high-energy luminous electrical discharge from a cumulonimbus (Cb) cloud to the ground which is accompanied by thunder. Electrical discharges can also occur in the atmosphere in two other ways. Intra-cloud lightning occurs within a Cb cloud and inter-cloud lightning is between two different Cb clouds.
The top of the Cb cloud develops a positive electric charge while its base has a negative charge. As air is a poor conductor of electricity, positive charge accumulates on all objects below the Cb cloud, and tends to concentrate on the highest object in the area. When the potential difference between this positive charge and the negative charge on the cloud becomes large enough to overcome the electrical resistance of the air, lightning occurs. The heavy electrical discharge of 100 million volts leaves the air heated to about 30,000 ºC in a few milliseconds. This generates shock waves whose propagation is heard as thunder.

Since lightning can occur only when there is a thundercloud, data on lightning occurrence can serve as proxy for convective precipitation. Estimates of the frequency of lightning flashes were first made from space in the early 1980’s with optical detectors on the DMSP and ISS-b satellites by observing the atmospherics from lightning discharges at frequencies of 2.5, 5, 10 and 25 MHz. An instrument called the NASA Optical Transient Detector (OTD) was launched on 3 April 1995 aboard the MicroLab-1 satellite into a 70º inclination orbit at an altitude of 740 km. At any given instant it viewed a 1300 × 1300 km region of the earth at 128 × 128 pixels. The instrument had a spatial resolution of 10 km and a temporal resolution of 2 ms. From an analysis of OTD data it has been found that over 1.2 billion lightning flashes, including both intra-cloud and cloud-to-ground strikes, occur around the world every year (Christian et al 1999, 2003). The highest number is over the land portion of the Inter-Tropical Convergence Zone (ITCZ), and there is generally far more lightning over the continents than over the oceans. This results from the stronger vertical motions that occur in continental clouds than in oceanic clouds.

The TRMM satellite launched in 1987, carried another lightning detection instrument called the Lightning Imaging Sensor (LIS). While the primary mission of TRMM is to measure rainfall, lightning data can be used to corroborate the rainfall data. LIS has been used to detect lightning in all its three forms, cloud-to-cloud, intra-cloud, and cloud-to-ground, and it has been possible to map out their frequency and distribution over the tropical regions. LIS consists of a staring imager which is optimized to locate and detect lightning with storm-scale resolution (4 to 7 km) over a large region (600 x 600 km) of the earth's surface. In spite of the fact that the TRMM satellite moves at a speed of 7 km/sec, LIS has an observation time of 90 seconds over any place, which is long enough to estimate the flashing rate of most storms. The instrument records the time of occurrence, measures the radiant energy and determines the location of lightning events within its field of view. LIS uses a wide field of view optics, a narrow band filter and a matrix of highly sensitive CCDs for the detection of the transient lightning signals. Even in the presence of bright sunlit clouds or high background illumination, the lightning signal can be extracted at 90 % efficiency by adopting appropriate filtering and data processing techniques.

Because of the small dwell time of orbiting satellites over a given place and the long time interval between their successive passes, efforts are now under way to place a lightning detector on geostationary platforms. The GEO Lightning Mapper (GLM) proposed to fly on the GOES-R satellite in 2012, is a sensor capable of continuously mapping lightning discharges at all times. From this orbit, the sensor will be capable of detecting all forms of lightning with a high spatial resolution and detection efficiency.

5.4 Polarimetric Radiometry

The emissivity of the sea surface can be assumed to be close to 1 in the IR region, but in the microwave region of the spectrum, it is a highly variable function of various factors particularly the roughness of the sea surface and its temperature and salinity. When the sea is calm, it has a smooth surface and the microwave emissivity is low. When the winds blowing over the sea surface are strong, the sea surface roughness increases and the microwave emissivity also increases. A finer feature of this situation, however, is that the waves on the ocean surface driven by the winds are not isotropic and their distribution varies with the wind direction. The result is that the intensity of the microwave emission from the seas surface is determined not only by the characteristics of the wave structure, but also by the directional orientation of the wind-driven waves. Again, while the visible solar radiation coming from the sun is not polarized, certain physical processes on earth result in generating polarized light. Satellites like POLDER are able to measure this polarization and derive properties of clouds and aerosols which cause the polarization.

A similar principle is made use of in the design of polarimetric radiometers working in the microwave region of the spectrum. A microwave polarimetric radiometer measures both vertical and horizontal polarizations of the radiation reaching the satellite, and in addition measures the cross-correlation between the two. The cross-correlation terms are derived from the microwave radiances at vertical, horizontal, and 45° left hand circular and right hand circular polarizations. The Stokes vector provides a full characterization of the spectral signature of the ocean surface in the microwave region and yields all the independent information that is needed to uniquely determine the wind direction over the ocean.

Wind retrievals from polarimetric radiometers are best made when there is no rain, and the data can also be used to obtain additional information on parameters such as sea surface temperature, rain rate, ice and snow characteristics, water vapour and soil moisture over land. The first space-borne polarimetric radiometer, with a 1.9 m diameter reflector, was flown on the Coriolis/WindSat satellite, which was launched by the U. S. on 6 January 2003 in a 830 km altitude polar orbit. The satellite has an expected life of three years. This instrument was designed to measure the ocean surface wind field at a 25 km spatial resolution. The Coriolis/WindSat instrument operates in 6.8, 10.7, 18.7, 23.8 and 37.0 GHz microwave bands. The 10.7, 18.7 and 37.0 GHz channels are fully polarimetric. The 6.8 GHz channel has dual-polarization and is more sensitive to SST than to winds. It is therefore useful for removing measurement noise due to variations in SST. The 23.8 GHz channel also has dual-polarization. This is more sensitive to water vapour absorption, and is used for removing the attenuating effects of atmospheric water vapour on the signal. The horizontal spatial resolution of the different channels varies between 40 × 60 km at 6.8 GHz to 8 × 13 km at 37.0 GHz.

5.5 Lidar-based Humidity Profiling

Satellite soundings of atmospheric humidity are currently obtained from instruments that measure either IR or microwave radiances. In the proposed Megha-Tropiques satellite an instrument called SAPHIR will provide humidity soundings, while the INSAT-3D satellite will carry a sounder that will operate in the water vapour absorption bands. Passive microwave sensors are less sensitive to clouds than IR but the surface emissivity problem still has to be taken care of.

In recent times, ground-based and airborne Differential Absorption Lidar (DIAL) systems have been coming into increasing use as an alternative means for atmospheric humidity measurements because of their good vertical resolution, high precision and low bias. The success of these measurements have prompted the use of the DIAL technique in space-based systems. In other words, an attempt is being made to have the first humidity profiling system in space using active remote sensing technique. The initiative towards this goal has come from the European Space Agency (ESA) and has been named the Water Vapour Lidar Experiment in Space (WALES). The project aims at achieving unsurpassed data quality. WALES is intended to profile the atmosphere in a nadir-viewing configuration. The use of the DIAL technique for humidity profiling basically consists of a comparison of the attenuation of two laser pulses emitted at a pair of closely spaced wavelengths in the 925-940 nm region. The on-line wavelength falls on the centre of a water vapour absorption line, and the off-line wavelength falls on the line wing, where absorption is significantly reduced. The water vapour number density as a function of height is directly derived from these two measurements.

The high vertical resolution of WALES can be regarded as a major advance over present humidity profiling techniques. A further possible extension of the space-based DIAL technique is to use three pairs of wavelengths: the strongest absorption line pair will measure the humidity in the upper troposphere, lower stratosphere and tropopause region, and the weakest pair will probe the lower troposphere. The proposed WALES instrument is of the non-scanning type. As the satellite moves in its orbit, backscatter signals from consecutive laser shots with a footprint of 40 m, will be averaged over a distance of 50-100 km, but the data down linked to ground is expected to be supplied at around 1 km horizontal resolution. Assuming an integration length of 100 km, this means that about 6000 profiles would be collected daily. The DIAL technique used by WALES allows for trade-offs between horizontal as well as vertical resolution and precision for serving different types of applications. An advantage of DIAL systems is that they can make precise measurements of cloud tops, and profiling above the cloud tops causes no significant difference in instrument performance.

5.6 Direct Assimilation of Satellite Radiances

When global retrievals of temperature and moisture profiles from polar orbiting satellites first became available there was considerable excitement about their use in numerical weather prediction models and the results were promising. However, as both numerical models and data assimilation techniques themselves improved in the 1980s, the positive impacts due to the assimilation of the satellite retrievals over Northern Hemisphere began to fade out in comparison, and in some cases the impact even appeared to be on the negative side. Research investigations revealed that the procedures that had been adopted for retrieval of various parameters from satellite observations were such that the results had inherent errors, biases and uncertainties, which could not be removed by applying a simple quality control.

Further, satellite retrievals of vertical temperature and humidity profiles have a relatively poor vertical resolution due to the broad and overlapping nature of the weighting functions used in the retrieval process, and it is not possible to derive a unique profile. Iterative procedures are used which require a realistic first guess that is not always available. This implies that the small-scale features of the vertical structure in the retrieval must come from the prior information and not the sounding instrument. The contribution of errors in the first guess to the final retrieval can turn out to be significant.

All these limitations of satellite data did not really matter when they were used for synoptic analysis in a manner that just conformed to and complemented the available ground-based observations. However, the implications of assimilating them for initialization of numerical models were found to be more serious, and led to the new thinking that it might be better to assimilate the basic satellite radiances themselves rather than products derived indirectly from them.

The process of direct radiance assimilation essentially involves a simulation of the satellite radiances through a forward solution of the radiative transfer equation, assuming a knowledge of the vertical profiles of temperature and absorbing gases, through a series of iterations. The vertical profiles are adjusted until convergence is reached. As a first step towards direct radiance assimilation, a stand-alone one-dimensional variational analysis or 1D-Var scheme is used for the retrieval of different atmospheric variables from the satellite radiances in the vertical direction alone. In the more advanced 3D-Var scheme, the final retrieval step is not performed for single profiles but all available observations and radiances are used together with the background fields and associated error covariances. Arrangements have to made by the operational NWP centres to receive the satellite radiance data of various satellites in near real time from the concerned satellite agencies. The radiance data is voluminous, considering that a single full disc image of a geostationary satellite in one channel may consist of 10 to 100 million pixels or more and an appropriate processing software package is required for handling such data.

The main advantage of 3-D Var assimilation of satellite radiances is that the errors in radiances are much easier to characterize than the errors in the retrievals. However, errors in the background fields will also strongly affect the retrieval solution necessitating quality control and data screening.

6. Very Récent and Future Indian Space Missions

Since 1982, the Indian Space Research Organisation has launched a series of geostationary satellites that have provided a continuous meteorological coverage of the Indian region and the surrounding land and Indian Ocean regions. Four satellites in the INSAT-1 series, three in the INSAT-2 series, the dedicated Kalpana-1 satellite, and the current INSAT-3A satellite, have carried a total of nine VHRR instruments so far, besides the CCD cameras on the more recent satellites. The next satellite, INSAT-3D, to be launched very shortly will have an advanced 6-channel imager and a 19-channel sounder. These will offer new capabilities for obtaining high resolution images in new channels and deriving vertical profiles of temperature and moisture.

India has an ambitious space programme that includes lunar and planetary missions. While the emphasis of the INSAT programme has always been on meeting the requirements of operational meteorology, India is now planning to go in a big way in several new directions towards making systematic observations of parameters related to climate studies. This will also involve the use of microwave sensors, both passive and active, and the placement of satellites in non-geostationary orbits, as described in the following sections.

6.*1 Oceansat-2*

The Oceansat-2 satellite was launched by ISRO in September 2009. This satellite carries an 8-channel (VIS and NIR) Ocean Colour Monitor that has a swath of 1420 km and a resolution of 360 m. What is more important for meteorological and oceanographic applications, however, is its Ku-band Scatterometer having a 1 m diameter antenna that rotates at a speed of 20 rpm and generates two beams at a frequency of 13.5 GHz. The Scatterometer from an altitude of 720 km covers a swath of 1400 km and operates continuously. Oceansat-2 surface wind vectors will be generated in cells of 50 x 50 km size. The wind speed accuracy is expected to be 2 m/sec and the wind direction is expected to be 20 degrees. Scatterometer surface wind data are going to be crucial in the early detection of tropical cyclones over the Bay of Bengal and Arabian Sea and in their subsequent monitoring.

6.2 INSAT-3D Sounder and Imager

The INSAT-3D satellite which is likely to be launched in the 2009-2010 time frame, will carry an advanced imager and for the first time a sounder payload. This will make it much easier to get the data in real time and process it faster, enabling its quick assimilation by numerical models. Since INSAT-3D will be a geostationary satellite, many soundings can be made at small time intervals over the region covered by the INSAT full disc than what are currently available from other means.

The INSAT-3D sounder instrument will be capable of making soundings at 10 km ground resolution every 3 hours for a full frame scan. Derivation of vertical profiles of temperature and humidity over 30 x 30 km areas will be possible. Besides these vertical profiles, there are many other parameters than can be derived such as atmospheric stability indices, total precipitable water, and total column ozone. The INSAT-3D 6-channel imager specifications are given in Table 1 and the characteristics of the 19-channel sounder in Table 2.

6.3 Megha-Tropiques Mission

Geostationary and polar orbiting satellites have their own relative merits and demerits in various aspects. Geostationary satellites provide images every half-hour or even faster for small sectors. However, because of their height, they are not suited for microwave remote sensing as the radiance reaching them is very weak. Orbiting satellites either in polar orbits or tropical orbits like TRMM, can provide a higher spatial resolution but they have a repeat cycle of one or two days and hence many atmospheric developments are lost between scans. The proposed Megha-Tropiques satellite strikes a trade-off among these conflicting requirements by placing passive microwave sensors in a low altitude orbit also having a low inclination with respect to the equatorial plane.

Megha-Tropiques is a joint India-France (ISRO-CNES) mission with a shared responsibility for development of payloads which would be flown on an ISRO IRS bus. A PSLV launcher will launch the satellite from Sriharikota in an orbit with 867 km altitude and a unique 20^{o} inclination in 2009-2010. The expected mission life is 3 years. The main scientific objectives of the Megha-Tropiques mission are: (a) to collect a long-term set of measurements with a good sampling and coverage over tropical latitudes to understand better the processes related to tropical convective systems and their life cycle, (b) to improve the determination of atmospheric energy and water budget in the tropical region on various time and space scales, (c) to study tropical weather and climate events like monsoon variability, droughts, floods, and tropical cyclones, and their predictability. Megha-Tropiques will carry a rare combination of three state-of-art payloads, MADRAS, SAPHIR and ScaRaB designed for measurements of radiative fluxes, precipitation, humidity profiles and cloud properties, which are described below.

MADRAS (Microwave Analysis and Detection of Rain and Atmospheric Structures), will be a passive imaging radiometer operating at five frequencies of 18.7, 23.8, 36.5, 89 and 157 GHz in both H and V polarizations except the 23.8 GHz which will have only V polarization. Data from the first three channels will have applications in the retrieval of rain over oceanic regions, liquid water content in clouds and vertical integrated water vapour. Their spatial resolution is expected to be better than 40 km. The 89 GHz channel will be useful in retrieving convective rainfall over both land and ocean at a still better resolution of less than 10 km. The 157 GHz channel will measure the concentration of ice particles in clouds at a resolution as high as 6 km.

SAPHIR (Sounder for Atmospheric Profiling of Humidity in the Inter-tropics by Radiometry) is a microwave sounding instrument. It will have six channels in the frequency region of 183 GHz, having 10 km ground resolution. SAPHIR soundings will complement the temperature and humidity profiles that will be derived from the INSAT-3D sounder that is to be launched soon.

The third Megha-Tropiques payload, is a radiation budget instrument. ScaRaB (Scanner for Radiation Budget Measurement) will have four channels: Sc1 - Visible 0.5 to 0.7 µ, Sc2 - Solar 0.2 to 4.0 µ, Sc3 - Total 0.2 to 100 µ, and Sc4 - IR window 10.5 to 12.5 µ. Sc2 and Sc3 are the main channels of the ScaRaB instrument. Longwave irradiance can be calculated from the difference between Sc3 and Sc2 measurements. Images from Sc1 and Sc4 channels will be used for scene identification and will provide the necessary compatibility with operational satellites like INSAT which have radiometers with similar spectral channels.

The three Indian satellites, Oceansat-2 which has already been launched and INSAT-3D and Megha-Tropiques which are due for an early launch, is expected to result in a synergistic utilization of the diverse but complementary data gathered from them. This is certainly going to lead to a great advancement of the current knowledge of the role of the tropical atmosphere and oceans in the global weather and climate besides an improvement in the forecasting capability on the shorter time scale.

6.4 Satellites for Aerosol Measurements

While currently available satellite sensors can provide information on the aerosol optical depth (AOD) and can distinguish between coarse and fine mode particles, their limitation is that they cannot differentiate whether the aerosols are of the absorbing and scattering type, which is important from the standpoint of their impact on climate. It is also not possible for the sensors to delineate unambiguously the contribution from naturally produced particles and anthropogenic aerosols to the total aerosol optical depth.

India is therefore considering making space-borne measurements that will focus on the source apportionment of aerosols and differentiation between natural and anthropogenic, and absorbing and non-absorbing aerosols. The objective is also to get their vertical distributions of aerosols, ozone, water vapour and carbon monoxide, and their regional and seasonal variation. Measurements of cloud top height and its spatial and seasonal variations will additionally help in estimating the radiative forcings at the top of the atmosphere and within it.

There are proposals for launching two small satellites carrying three major scientific payloads: (a) a nadir-viewing multi-angle polarisation and multi-spectral sensor in the wavelength bands 0.4-1.2, 2-4 and 10.5-12.5 μ, (b) an instrument for measurements along the earth's limb to obtain the vertical distribution and extinction properties of aerosols in the stratosphere and troposphere, (c) an IR spectrometer for measurement of concentrations of atmospheric gases in the 2-5 μ range using a Cassegrain telescope and a linear 256 pixel In-Sb detector.

6.5 Satellites for Precipitation Measurements

There is another proposal for a launching a comprehensive Indian mission carrying the complement of sensors listed below using a low altitude, low latitude earth orbiting satellite for more frequent coverage of the tropical regions: (a) Scanning radiometer and a Polarimetric Radiometer operating at 6.6, 10.6, 18, 23, 37, 89 GHz and 150 GHz with a combination of vertical and horizontal polarisations. These instruments would help to retrieve various parameters such as atmospheric water vapour, liquid water content and rain, (b) Synthetic Aperture Radiometer operating at 1.4 GHz in the L-Band for measuring moisture with a high spatial resolution, (c) Precipitation radars in Ku and Ka bands similar to those in the GPM mission for measurement of rain and rain rate.

Ultimately, the development of the above payloads is expected to converge into the design of a single combined passive microwave imager/sounder. These are exciting proposals and the Indian weather and climate community is looking forward to their realization.

7. Concluding Remarks

Over the last fifty years, satellite meteorology has made a tremendous impact in operational meteorology and weather forecasting. The INSAT and Kalpana satellites have provided an uninterrupted monitoring of the atmosphere over India and the surrounding land and ocean, leading to an improved understanding of the processes that govern the Indian monsoon and tropical cyclones in particular. INSAT-derived products are being used for initialization purposes in numerical models.

Several new satellites are scheduled for launch shortly and will provide high resolution imagery and data for deriving vertical profiles of temperature and humidity, radiation budget parameters. Many new initiatives are in the pipeline or are under consideration for deploying satellites with new types of sensors, and in new types of orbits. The future of satellite meteorology is indeed bright and promising.

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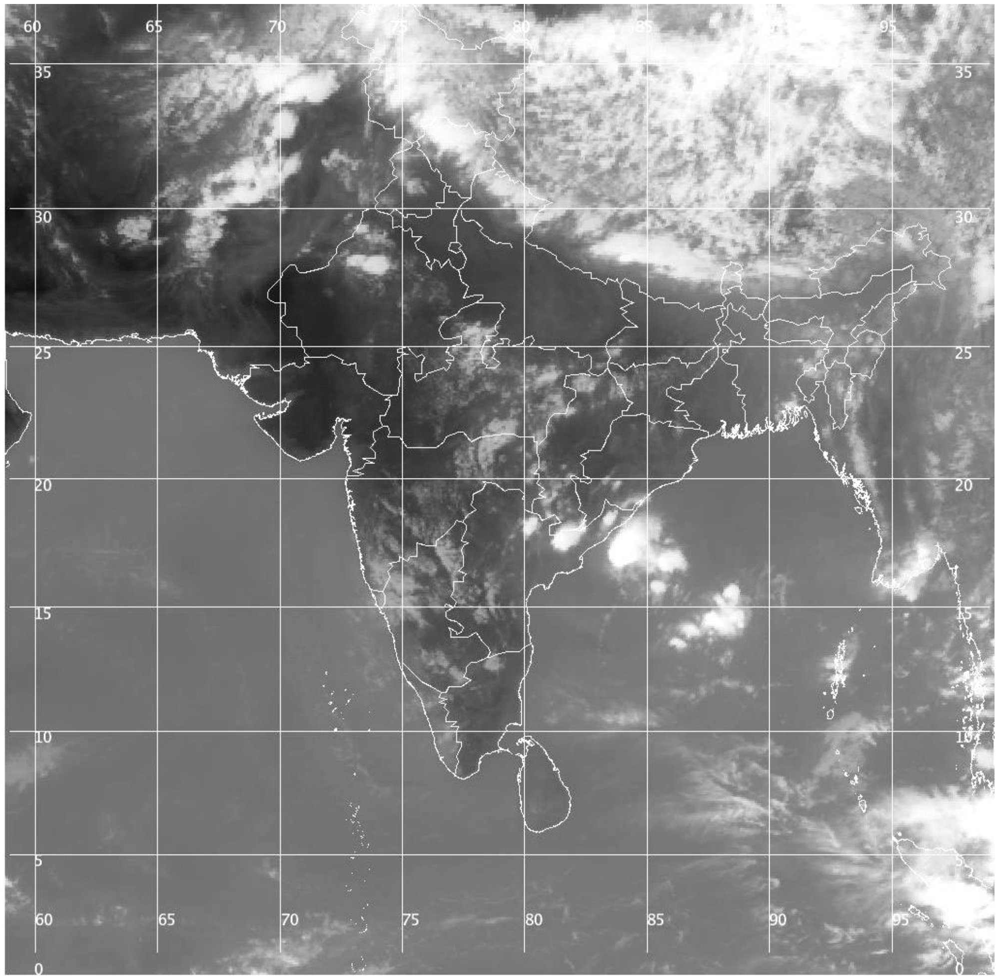

Figure 1. Kalpana-1 IR image of 1 May 2006 showing the development of afternoon thunderstorms.

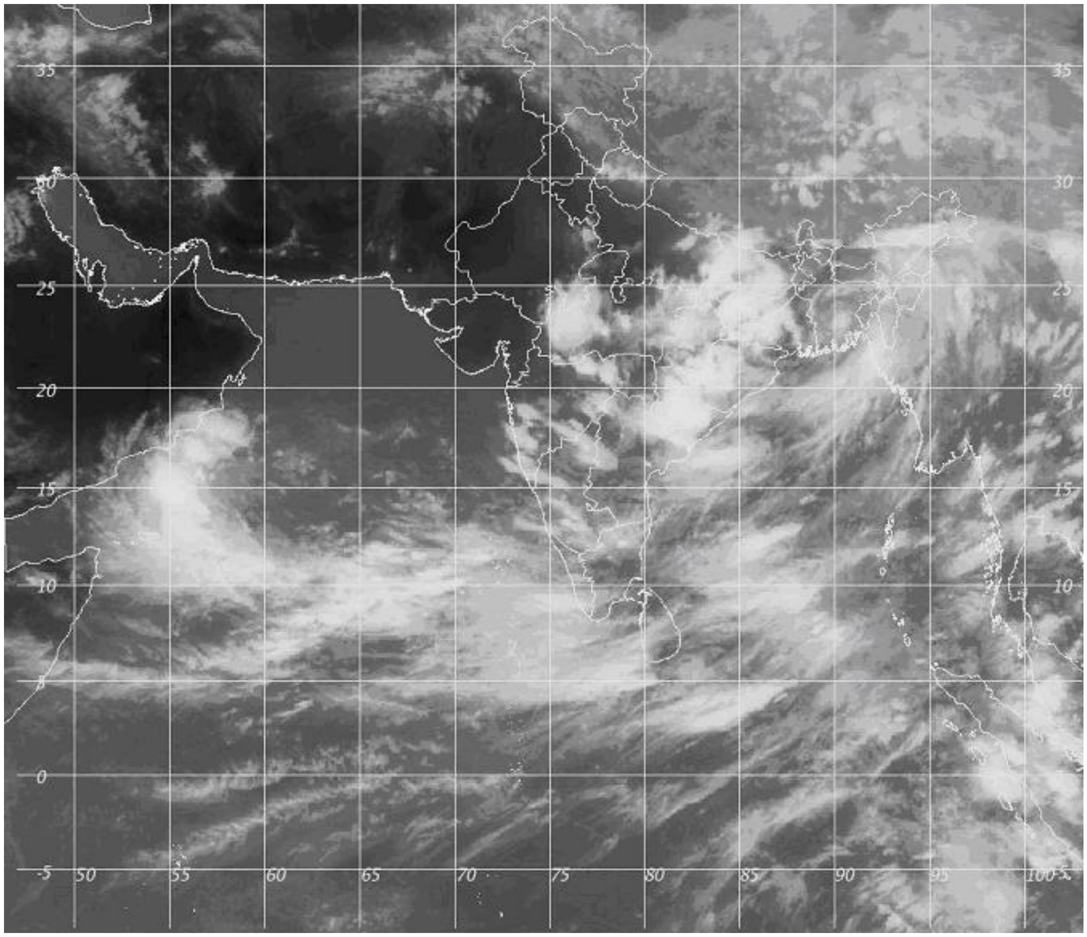

Figure 2. Kalpana-1 infra-red channel image of 26 May 2006 showing an early and strong onset of the southwest monsoon over Kerala.

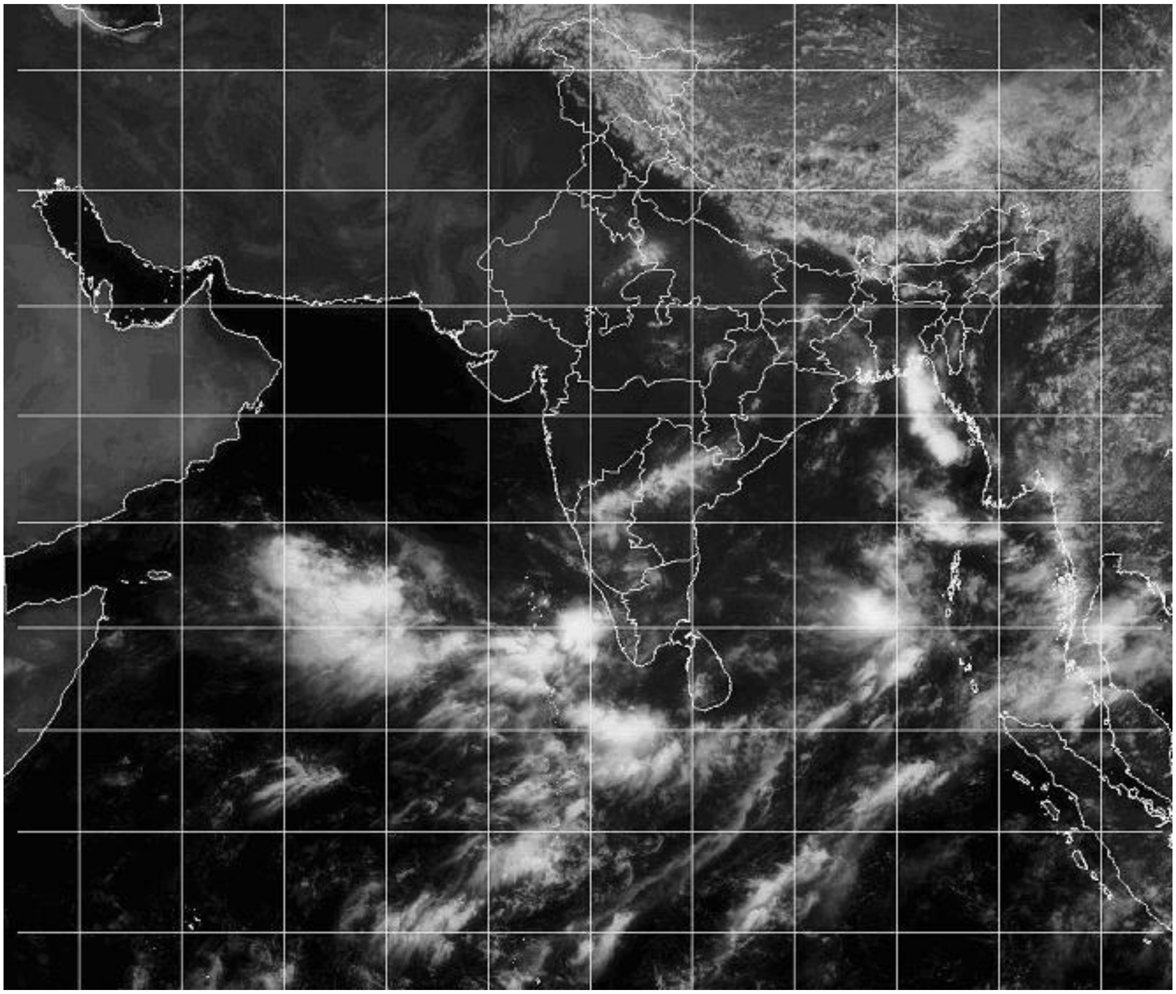

Figure 3. Kalpana-1 visible channel image of 5 June 2005 showing a weak and delayed onset of the southwest monsoon over Kerala.

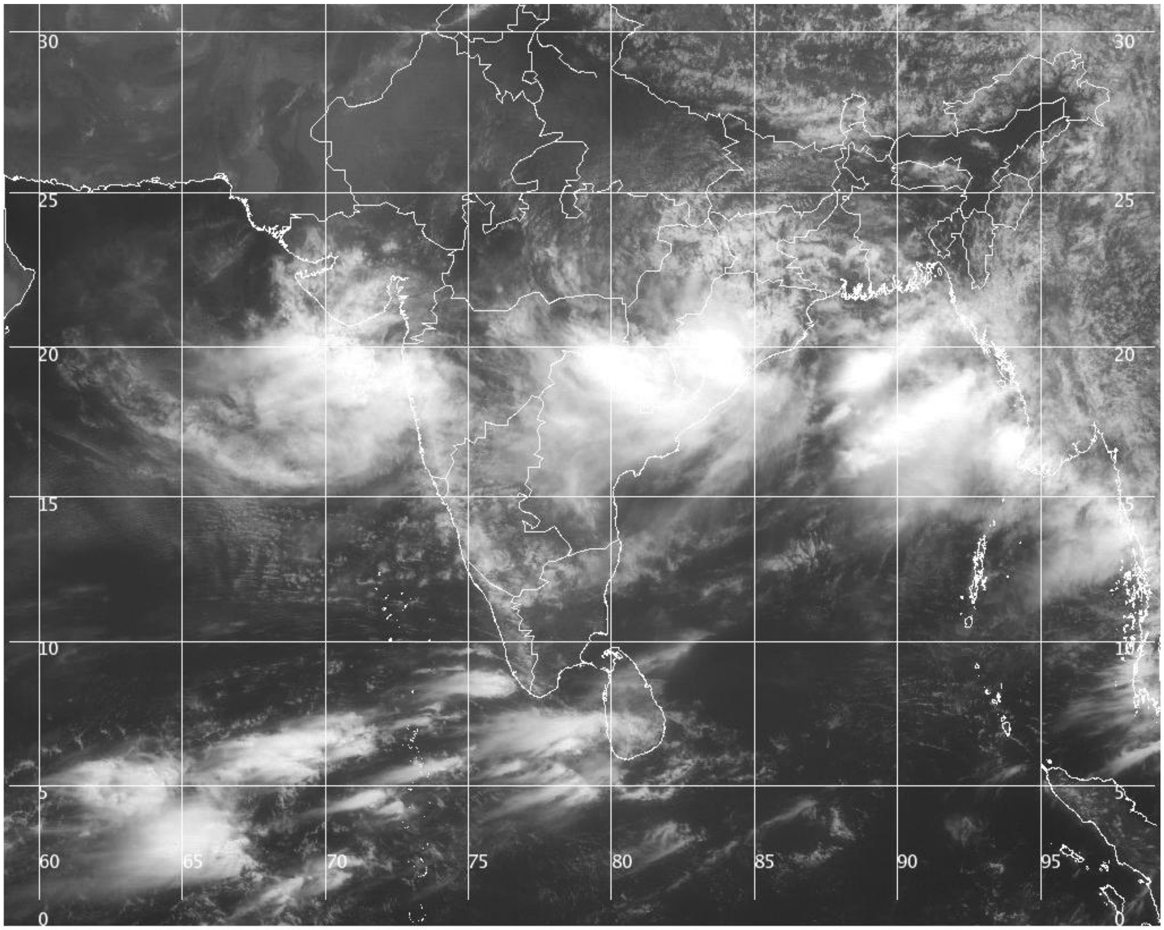

Figure 4. Kalpana-1 visible channel image of 3 July 2006 showing a monsoon depression which has crossed from the Bay of Bengal into Orissa. The curved cumulus lines are seen. The lower portion shows the cirrus blow-off due the strong winds of the tropical easterly jet.

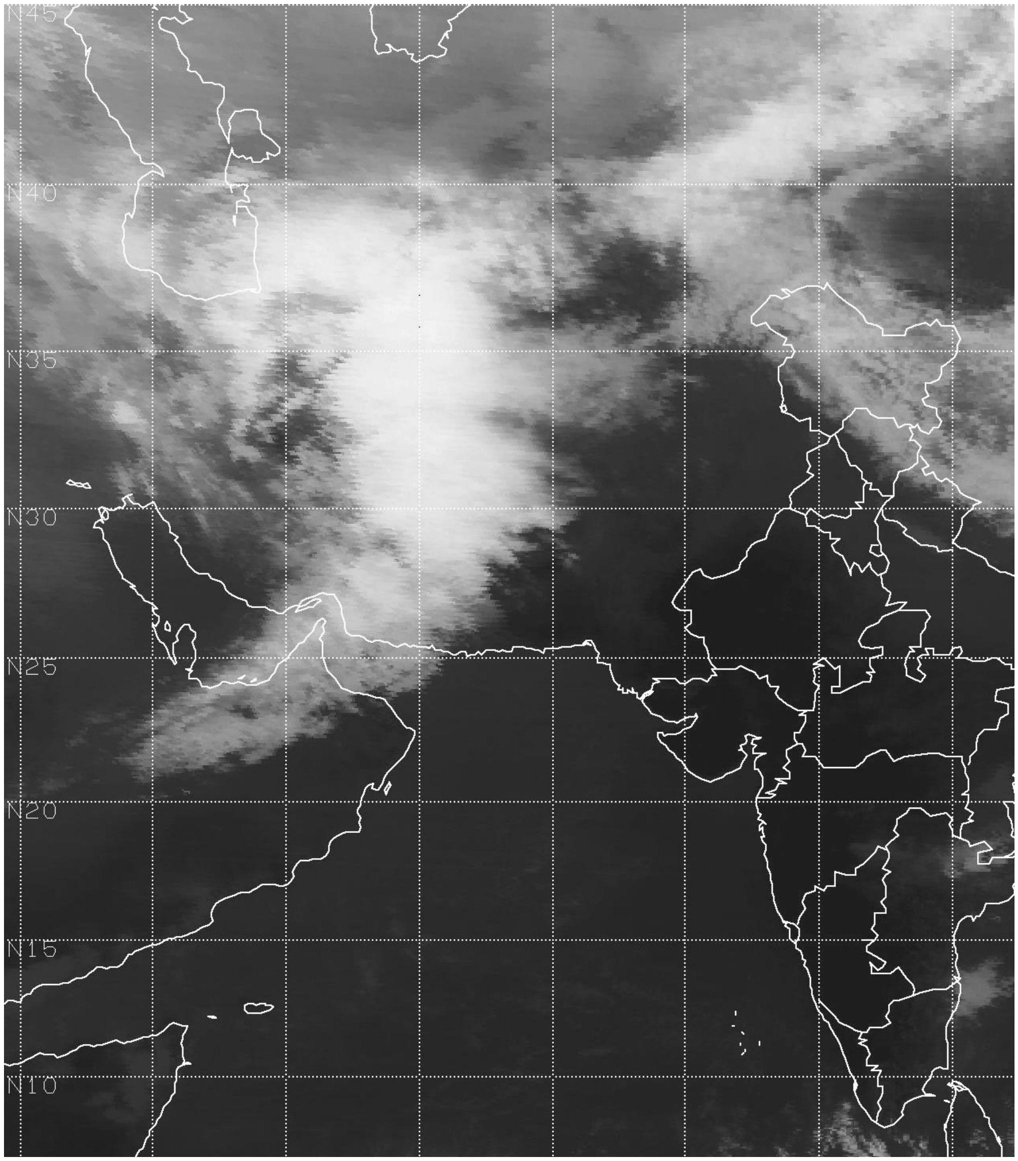

Figure 5. INSAT-3A IR image of 27 January 2004 showing comma-shaped cloud and vortex associated with an intense western disturbance approaching north India.

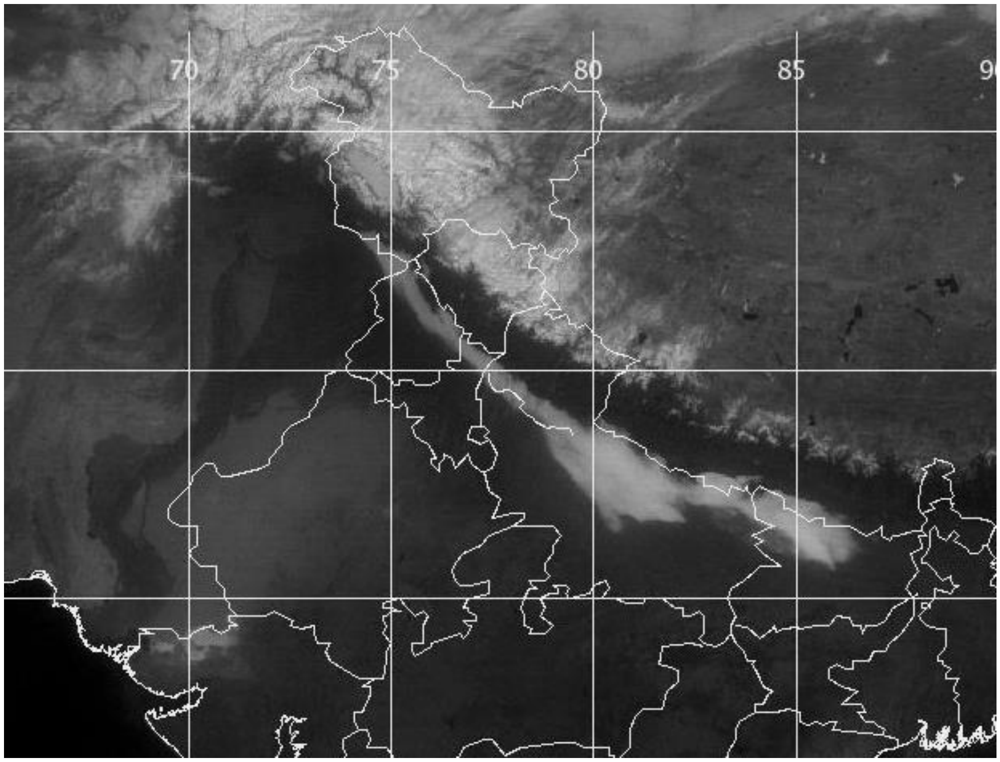

Figure 6. Kalpana-1 VIS image of 5 January 2006 showing Himalayan snow cover and extensive morning fog over the plains of northern India south of the Himalayan foothills.

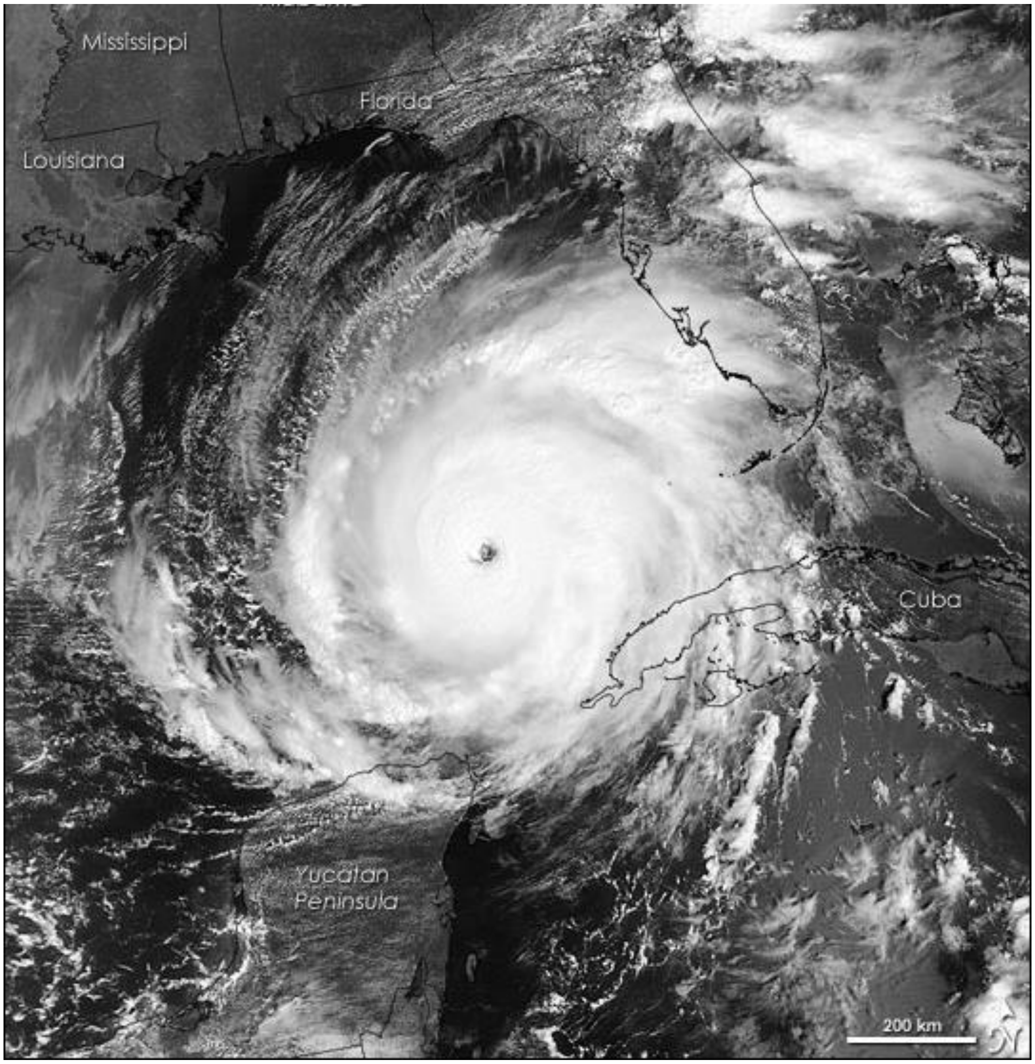

Figure 7. MODIS image of Hurricane Rita taken on 21 September 2005, when the storm was out at sea and in its full fury (Source: http://earthobservatory.nasa.gov/)

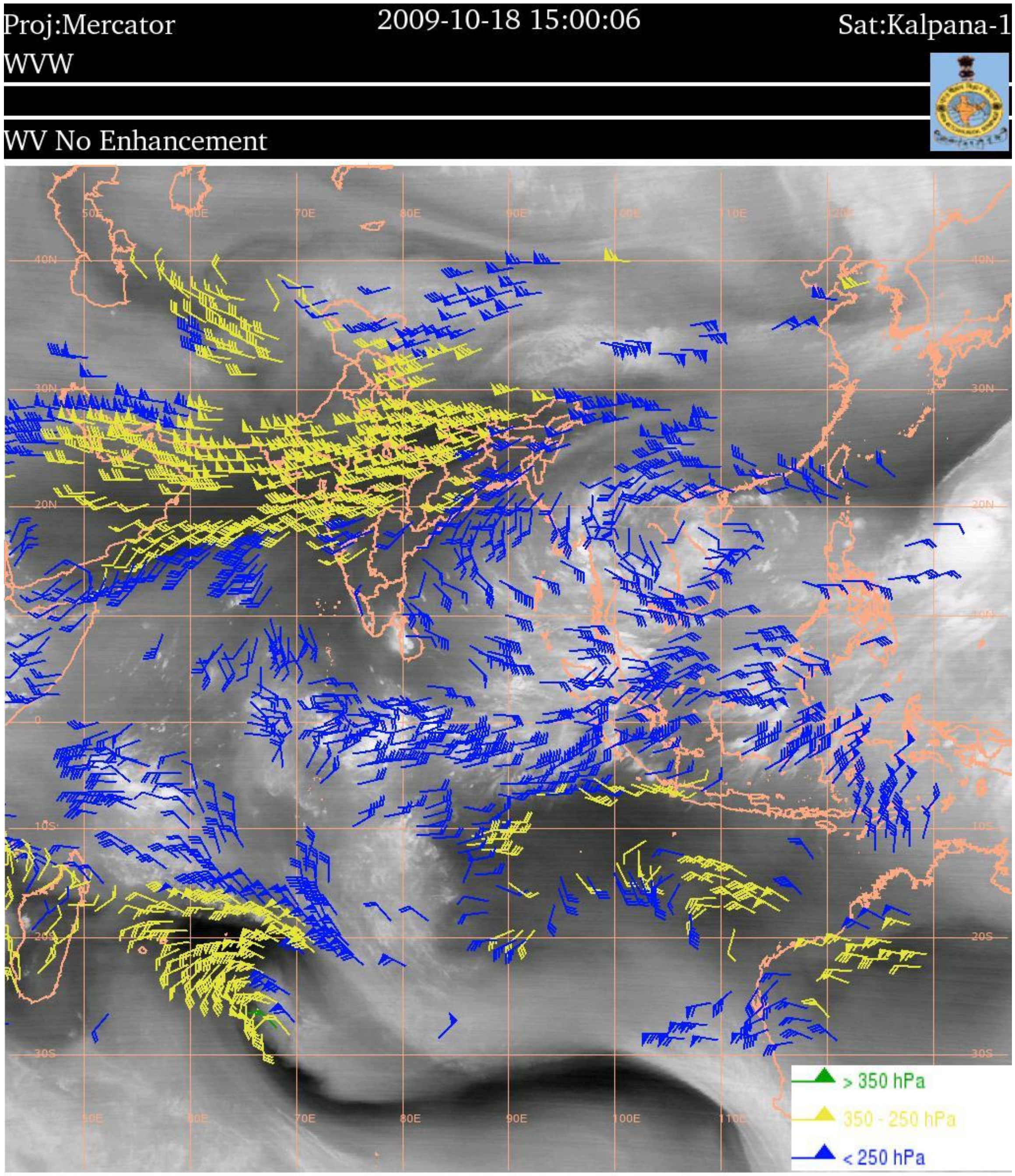

Figure 8. An example of water vapour winds from Kalpana imagery on a day when the Indian region was predominantly cloudfree and cloud motion vectors could not have been derived with infrared imagery.

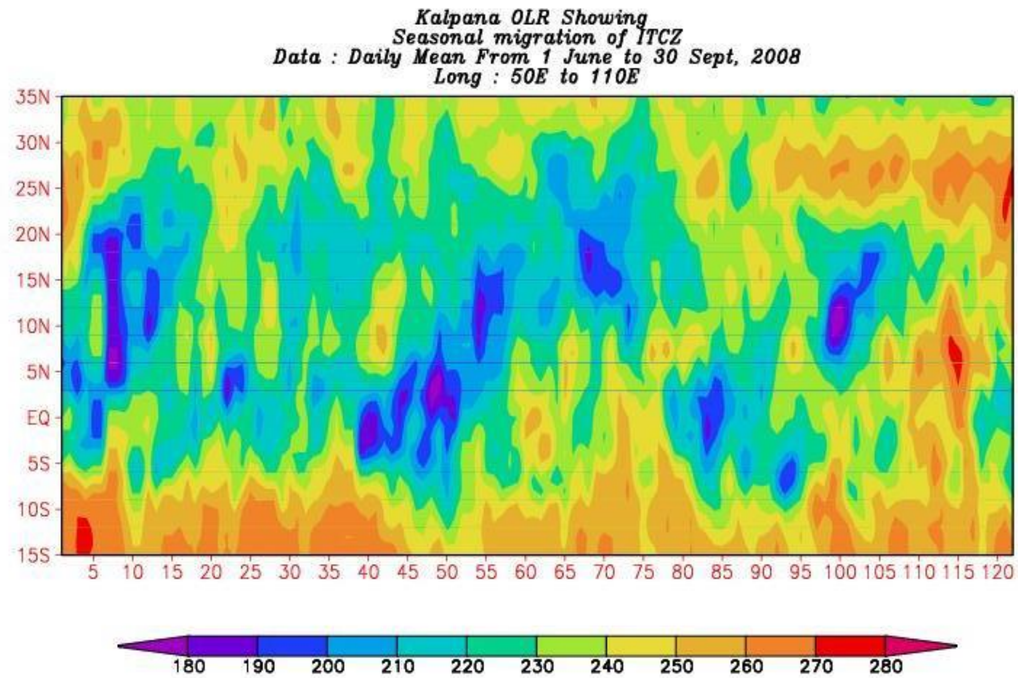

Figure 9. Seasonal migration of the ITCZ as seen from the OLR values derived from Kalpana-1 IR radiances beginning 1 January 2009.

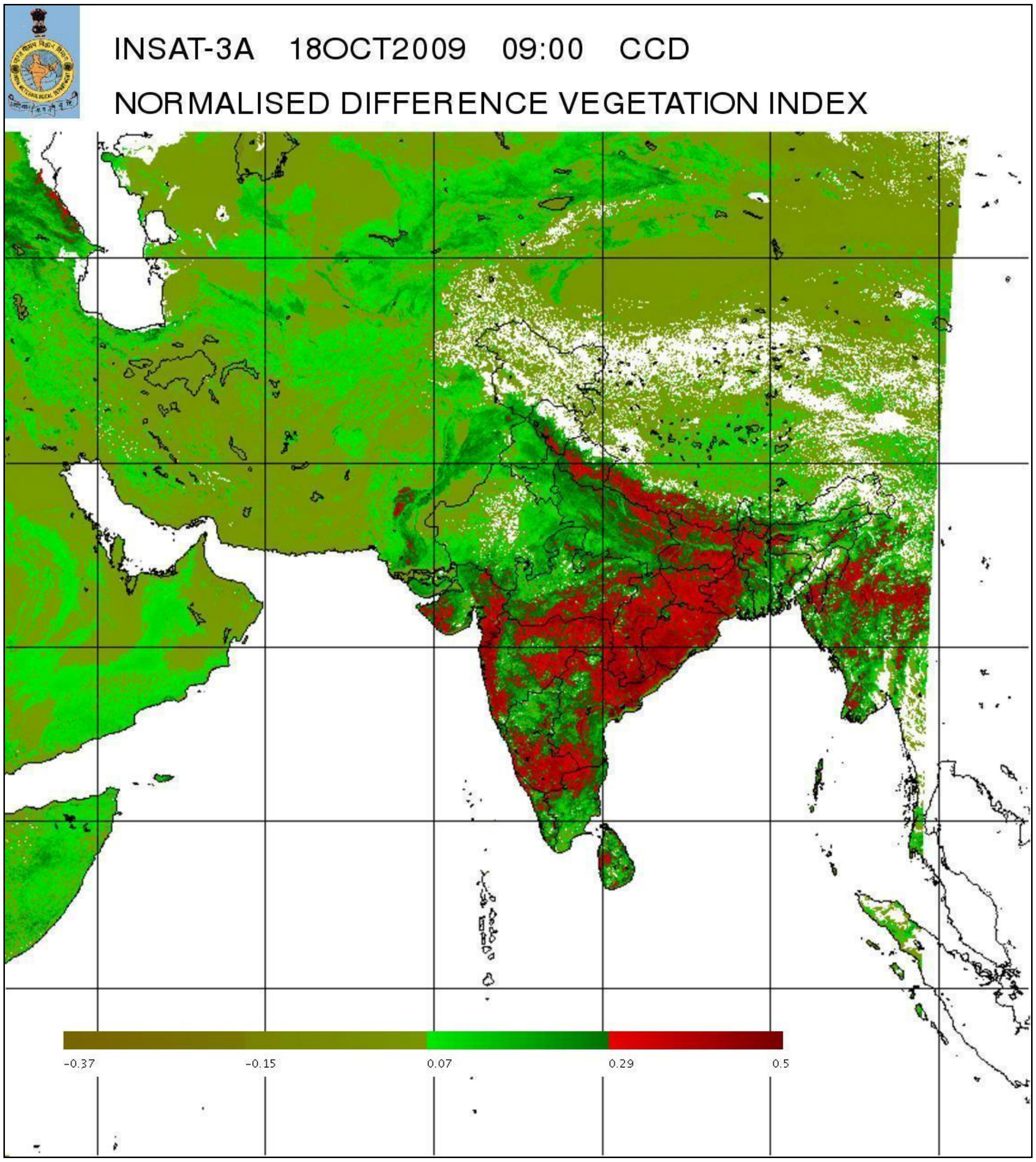

Figure 10. An example of NDVI derived from Kalpana-1 CCD data.

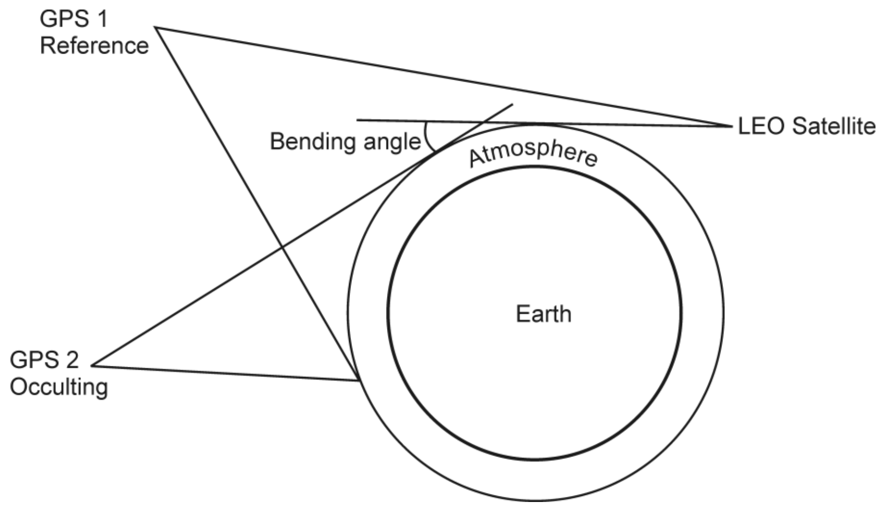

Figure 11. Schematic of the GPS radio occultation technique (Source: Kelkar 2006)

TABLE 1

Meteorological Payloads of INSAT, METSAT and Kalpana Satellites (Source: Kelkar 2006)

Name of Satellite	**Launch Date**	**Meteoro-logical Payload**	**Channel**	**Spectral Range (µ)**	**Reso-lution (km)**
INSAT-1A	10 April 1982	VHRR Very High Resolution Radiometer	VIS IR	0.55-0.75 10.5-12.5	2.75 11
INSAT-1B	30 August 1983	VHRR			
INSAT-1C	21 July 1988	VHRR			
INSAT-1D	12 June 1990	VHRR			
INSAT-2A	10 July 1992	VHRR	VIS IR	0.55-0.75 10.5-12.5	2 8
INSAT-2B	23 July 1993	VHRR			
INSAT-2C	7 December 1995	None			
INSAT-2D	4 June 1997	None			
INSAT-2E	3 April 1999	VHRR CCD Charge Coupled Device Camera	VIS IR WV VIS NIR SWIR	0.55-0.75 10.5-12.5 5.7-7.1 0.62-0.68 0.77-0.86 1.55-1.69	2 8 8 1 1 1
INSAT-3B	22 March 2000	None			
INSAT-3C	24 January 2002	None			
Metsat/ Kalpana-1	12 September 2002	VHRR	VIS IR WV	0.55-0.75 10.5-12.5 5.7-7.1	2 8 8

TABLE 1 Continued

Name of Satellite	**Launch Date**	**Meteoro-logical Payload**	**Channel**	**Spectral Range (µ)**	**Reso-lution (km)**
INSAT-3A	10 April 2003	VHRR	VIS IR WV	0.55-0.75 10.5-12.5 5.7-7.1	2 8 8
		CCD	VIS NIR SWIR	0.62-0.68 0.77-0.86 1.55-1.69	1 1 1
INSAT-3E	28 September 2003	None			
INSAT-4A	22 December 2005	None			
INSAT-3D	To be launched in 2010	VHRR	VIS SWIR MWIR WV TIR TIR	0.52-0.72 1.55-1.70 3.80-4.00 6.50-7.10 10.2-11.2 11.5-12.5	1 1 4 8 4 4
		Sounder	SWIR MWIR LWIR VIS	3.67-4.59 6 channels 6.38-11.33 5 channels 11.66-14.85 7 channels 0.67-0.72 1 channel	10 10 10 10

TABLE 2

Characteristics of INSAT-3D Sounder Channels
(Source: Kelkar 2006)

Channel Number	Central Wavelength (μ)	Main Absorbing Gas
1	14.71	CO_2
2	14.37	CO_2
3	14.06	CO_2
4	13.96	CO_2
5	13.37	CO_2
6	12.66	H_2O
7	12.02	H_2O
8	11.03	Window
9	9.71	O_3
10	7.43	H_2O
11	7.02	H_2O
12	6.51	H_2O
13	4.57	N_2O
14	4.52	N_2O
15	4.45	CO_2
16	4.13	CO_2
17	3.98	Window
18	3.74	Window
19	0.695	Visible