SATELLITE BASED WEATHER FORECASTING

S.R. Kalsi
India Meteorological Department
Mausam Bhawan, Lodi Road, New Delhi

Abstract : Satellite data are increasingly being used in conjunction with conventional meteorological observations in the synoptic analysis and conventional weather forecast to extract information of relevance for agriculture in India. Synoptic applications of satellite imagery as in use at India Meteorological Department are highlighted in this report. Particular emphasis is laid on identification of large scale convective precipitation systems such as monsoon depressions and tropical cyclones. A brief review of national and international satellite systems of relevance to weather forecasts particularly for agriculture is provided. A summary of numerical products being derived from satellite data and their use in numerical models is also given. A brief on the New long range forecasting technique is included.

INTRODUCTION

Reliable weather prediction holds the key for socio economic development and is essential for food security of the human society. Since time immemorial, human race has been fascinated by the ever changing and highly dynamic atmosphere around him and has made concerted efforts to understand the controlling processes and achieve better capabilities of weather forecasting. The recent attempts for satellite based observations, made over the past two decades, have provided new insights in these processes. Synoptic coverage provided by satellites is ideally suited to study weather related atmospheric processes on different scales. The recent advances in satellite technology in terms of high resolution, multi-spectral bands covering visible, infrared and microwave regions have made space data an inevitable component in weather monitoring and dynamic modeling. The impact of satellite data is phenomenal in certain areas of meteorological applications such as short-range forecasts, Tropical Cyclone (TC) monitoring, aviation forecasts etc. With improving trend in accuracy of satellite retrievals, improvements could be carried out in models leading to improved forecasts, especially in the tropics.

Satellite Remote Sensing and GIS Applications in Agricultural Meteorology
pp. 331-346

CONTRIBUTIONS OF SPACE OBSERVATIONS

The launch of the first meteorological satellite TIROS-1 in April 1960 heralded the era of Space observations and gave the first glimpses of the dynamic cloud systems surrounding the Earth. Since then the technology has developed by leaps and bounds in observation capabilities in terms of spatial, spectral and temporal resolutions. A global system of Space observations with both geostationary and polar orbiting satellites has evolved.

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

- Synoptic view of large areas, bringing out the inter-relations of processes of different spatial scales.
- Frequent observations from geostationary satellites provide continuous monitoring while polar orbiting satellites give typical twice daily coverage; such data is relevant for study of weather system dynamics.
- The inherent spatial averaging is more representative than the point in-situ observations and readily usable for weather prediction models.
- High level of uniformity of space observations overcomes the problem of inter-calibration needed for ground based instruments.
- Filling of gaps in observations; Space data covers large oceanic areas and inaccessible and remote land areas, thus giving global coverage.
- New types of data and observations; parameters such as sea surface (skin) temperature, sea surface wind stress, sea level, cloud liquid water content, radiation balance, aerosol are some of the unique parameters provided only by satellites.
- Simultaneous observation of several dynamic parameters provided by different sensors in same platform facilitates study of inter-relationships and knowledge of processes (e.g. Sea Surface temperature and deep convection, cloud development and radiative forcing).

METEOROLOGICAL SATELLITES / PAYLOADS

Currently several operational meteorological satellites are providing global and regional observations. Six different types of satellite systems currently in use are : 1) Visible/ Infrared/Water Vapour Imagers, 2) Infrared Sounders, 3) Microwave Imagers, 4) Microwave Sounders, 5) Scatterometers and 6) Radar Altimeters. Though the water vapour imaging capability is available only on the geostationary satellite, the visible and infrared imagers are available on geostationary as well as polar orbiting satellites. The last four are currently available only on polar orbiting systems. We first describe in detail below the INSAT system which is the primary satellite for weather surveillance in this part of the globe. It is a multipurpose geostationary satellite that caters to the requirements of Meteorology and Communication. It carries a met payload called Very High Resolution Radiometer (VHRR) that enables us to have visible, infrared and now even water vapour images. It is designed to provide the following services:

- Round the clock surveillance of weather systems including severe weather events around the Indian region.
- Operational parameters for weather forecasting – cloud cover, cloud top temperature, sea surface temperature, snow cover, cloud motion vector, outgoing long wave radiation etc.
- Collection and transmission of meteorological, hydrological and oceanographic data from remote/inaccessible areas through Data Collection Platforms.
- Timely dissemination of warning of impending disasters such as cyclones through Cyclone Warning Dissemination Systems.
- Dissemination of Meteorological information including processed images of weather systems through Meteorological Data dissemination system.

INSAT applications programme started with the launch of INSAT-1 series of satellites in early 1980s. INSAT-2 series that followed was designed based on user feedback. INSAT-2A and 2B launched in 1992 and 1993 carried VHRR payload with improved resolution of 2 km in visible and 8 km in thermal band. The imaging capability included three modes, viz. full frame, normal mode and sector mode of 5 minutes for rapid coverage of severe weather systems.

INSAT-2E launched in 1999 carried an advanced VHRR payload operating in three channels – visible (2 km), thermal and water vapour (8 km). The water vapour channel is capable of giving water vapour distribution and flow patterns in the middle troposphere. Besides this, INSAT-2E also carried a CCD camera with 3 channels – visible, near infrared and short wave infrared with 1 km resolution to map the vegetation cover.

A geostationary meteorological satellite (METSAT) system devoted totally to meteorology was launched in 2002. It has been renamed as Kalpana-1 and is currently the operational satellite system being used by IMD.

INSAT-3A has been launched in April 2003 and carries identical payloads as in INSAT-2E. INSAT- 3D planned for future will also carry atmospheric sounder for temperature and water vapour profiles and split thermal channels for accurate sea surface temperature retrieval. Data from INSAT satellites are being used to retrieve a number of quantitative products. INSAT imagery is being used very exhaustively to provide support for synoptic analysis and weather forecasting. The quantitative products available from INSAT and its applications are described in subsequent sections.

Infrared Sounders

These systems are available on geostationary (GEOS N SERIES) and polar orbiting (NOAA 15-17/HIRS) Satellites. The primary application lies in direct assimilation of IR radiance in NWP models. IR sounders are going to have (2 orders of Magnitude) increase in the infrared channels. This will lead to large improvements in the vertical resolution of derived temperature and moisture profiles in clear areas and above cloud top level and improve the initial temperature and moisture fields.

Microwave Sounders

Similar to the microwave imager data, microwave sounder data from NOAA-15-17/AMSU instrument can provide valuable information below cloud top level. Tropospheric thermal measurements can be obtained in non-raining cloudy region. Microwave sounders data has proved to be very useful in determining upper tropospheric warm anomaly. This in turn is used in diagnosing intensity and intensity change of tropical cyclones (Brueske and Velden, 2000).

Microwave Imagers

VIS and IR provide proxy variables. Exact positioning of the eye is possible in VIS and IR imagery. Microwave (passive) sensors monitor radiation from below the cirrus shield and provide information on atmospheric WV, cloud liquid water, precipitation, intensity and regions of convective activity. In June of 1987 the first satellite from the Defence Meteorological Satellite Programme (DMSP) carrying a microwave radiometer called Special Sensor Microwave/Image (SSM/I) was launched. It overlapped with the European Research Satellite (ERS-I) launched in July 1991 which carried a scatterometer. The swath width of the ERS-I scatterometer was only 500 km resulting, however, in the less than-complete coverage of the tropical regions each day.

The low horizontal resolution of some current radiometers may limit the usefulness of some parameters but the 15 km resolution of 85 GHz channel of SSM/I provides meso-scale information. This channel provides radar like imagery and is able to discern the circulation centres. Velden *et al.* (1989) describe the advantage of centre-fixing in TCs using 85 GHz imagery compared to conventional VIS and IR images where centres are covered in cirrus overcast. NASA launched a special satellite that aimed at making new measurements of meteorological quantities in the tropics. The Tropical Rainfall Measuring Mission (TRMM) has completed 3 years of successful data taking in 2000. With the change of its altitude from 350 km to 400 km, it will have enough fuel to provide continuous measurements upto 2005 (Velden and Hawkins, 2002). TRMM Microwave Imager (TMI) provides horizontal resolution of 5-7 km for 85 GHz channel which is 2-3 times better than the SSM/I, and the higher resolution TMI 37 GHz channel; can penetrate deeper into tropical cyclone to reveal additional details.

The Indian Remote Sensing Satellite (IRS-P4) launched in 1999 carried Multichannel Scanning Microwave Radiometer (MSMR). It is providing measurements at 6.6, 10, 18 and 21 GHz frequencies in both H&V polarizations. Attempts have been made to provide estimates of integrated water vapour, liquid water content, precipitation intensity, and SSTs over the global oceans (Gohil *et al.*, 2001).

Scatterometers

The primary application of the scatterometers is for Ocean Surface Wind Vectors. A scatterometer sends microwave pulses to the earth's surface and measures the backscattered power from the surface roughness elements. The back scatter power depends not only on the magnitude of the wind stress but also on the wind direction relative to the direction of the radar beam. The relation between backscatter signal and ocean surface winds is not well established under the strong wind and rainy conditions of a cyclone because of lack of validation. After the failure of NASA's NSCAT system, there has been rapid deployment of a new system called Quikscat that provides a wide swath of 1800 km and unprecedented global ocean coverage. Wind fields from quikscat are available on near real-time to most TC forecast offices. The standard wind product has a 25 km spatial resolution. The data has provided the outer wind structure of tropical cyclones. It is also used to determine the radius of 35 knots (De Muth *et al.*, 2001), and for identifying closed circulations of developing systems and in providing lower limits for maximum sustained winds. Sarkar (2003) has reviewed techniques for surface wind measurements over global oceans from space platforms. The most successful wind sensor has been the microwave scatterometer.

Radar Altimeters

Many studies have shown that sub-surface thermal structure plays an important role in tropical cyclone intensification. The sub-surface structure can often be deduced from the satellite altimetry data. Research to better use these data in statistical forecast algorithms and the coupled ocean-atmosphere models has the potential to improve tropical cyclone intensity forecasts. The altimeter observations would be more useful with improved temporal and areal sampling. Multi-beam altimeters potentially can dramatically increase spatial sampling and fill the data voids.

SYNOPTIC APPLICATIONS IN IMD

The major application of satellite data has been the monitoring of Synoptic weather systems ranging from thunderstorms to cyclones and planetary scale phenomena such as monsoon. The dynamic nature of weather systems could be captured through the time series of satellite observations leading to better understanding of the process of genesis, growth and decay. This has led to satellite based technique (Dvorak technique) to assess the intensity of TC accurately and estimate the growth potential. The specific applications include identification of primary weather system such as low pressure, depression, troughs/ridges, jet streams regions of intensive convection, inter-tropical convergence zones etc. and onset and progress of monsoon system.

Following are the major applications of satellites images in operational weather forecasting:

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

ii. Identify and locate primary synoptic systems like troughs/ridges, jet streams, regions of intense convection, inter tropical convergence zones etc.

iii. Monitor onset and progress of monsoon systems.

iv. Detect genesis and growth of TC and monitor their intensification and movement till landfall. This application is included in the next section.

Satellite imagery is being extensively used by synoptic network in conjunction with other available conventional meteorological data for analysis and weather forecasting. Zones of cloudiness are identified from the satellite imagery as regions of upward velocity and hence potential areas for occurrence of rainfall. Visible, infra red and water vapour images have distinctive uses and are complementary to each other.

We shall summarize below very briefly some of the very important applications in the operational synoptic analysis and weather forecasting.

Satellite imagery is very handy for remote and inaccessible areas such as Himalayas where heavy precipitation usually builds up. Though the characteristic cloud patterns of cold and warm fronts are not seen over India, the Western disturbances giving rise to heavy snow fall are well captured in the Satellite imagery (Kalsi and Mishra, 1983). The Cloud band ahead of well marked westerly trough is clearly seen in the Satellite imagery. The characteristic structure of snow is easily identified and its areal extent is monitored for estimating run-off and also for long range prediction of monsoon.

Deep penetrative CB clouds and thunderstorm complexes (Kalsi and Bhatia, 1992) are rather easy to be identified in visible and infrared imagery. Squall lines are clearly seen in the satellite loops. Satellite imagery provides powerful signals for forecasting severe weather (Purdom, 2003).

The rain bearing Southwest monsoon system advances northward usually as an intermittent band of cloudiness called inter-tropical convergence zone (ITCZ). It comprises of numerous rain showers and thunderstorms associated with the convergence in the shear zone. One of the earliest studies (Sikka &

Gadgil, 1980) showed the 30-40 day oscillatory nature of monsoon flow. The INSAT and NOAA sounding data have brought out the unique nature of monsoon onset with large scale changes in wind and moisture profiles in lower troposphere prior to monsoon onset. Using satellite data Joshi *et al.* (1990) have also noted a spectacular rise in the 300 mb temperature over the western central and eastern Tibetan Plateau and over the region of the heat low over Pakistan. They noted this rise commencing almost 2 weeks prior to the onset of monsoon rains over southwestern India. This appears to be an important parameter for monitoring the onset of monsoons and requires to be monitored in connection with forecast of the onset of monsoon operationally. Joseph *et al.* (2003) have identified conditions leading to onset of monsoon over Kerala using SST, OLR and winds obtained from satellite systems.

The monsoon depressions are the principal rain bearing systems of the southwest monsoon period over India. Substantial amounts of rainfall are generated by the westward passage of monsoon depressions forming in the bay. Monsoon depressions usually develop from innocuous looking cloud systems and from diffuse pressure fields over the head Bay of Bengal. Satellite imagery shows heavy overcast cloud mass in the southern sector with low level cumulus clouds determining the Low-Level Circulation Centre (LLCC) to the northeast. The LLCC is often free of deep convection. The widespread and heavy rainfall in the southwest sector is often accompanied with deep convection in that sector. Kalsi *et al.* (1996) have shown from satellite imagery that a few of these depressions acquire structure of marginal cyclones with almost vertical structure upto mid-tropospheric levels. Following Scoffield and Oliver (1977), Mishra *et al.* (1988) also used the enhanced infrared satellite imagery to compute satellite derived rainfall estimates which were found to be realistic. These signatures provide a lot of insight into physical and dynamical processes at work in the case of monsoon depressions and are extremely useful for short range forecasting.

The 16 parameter statistical model used by India Meteorological Department has several parameters that are provided by Satellite data such as the SST, Snow Cover, E1 Nino event etc. Several recent modeling studies show that a significant fraction of the inter-annual variability of monsoon is governed by internal chaotic dynamics (Goswami, 1998). The numerical weather prediction of monsoon received impetus from the satellite observations. The parameters of SST, cloud motion vector, OLR are found to have impact on model results.

RESEARCH AND APPLICATIONS IN THE FIELD OF TROPICAL CYCLONES

With its unmistakable spiral shape and central eye, the tropical cyclone is the most memorable feature on any satellite image. Indeed, if weather satellites detected nothing else besides these monster storms, they would be worth the money invested in them. A number of techniques have been developed to estimate the movement and intensity of tropical cyclones. One of the most widely accepted is the Dvorak (1984) technique which assigns an intensity based on the size and shape of the dense cloud mass adjacent to the centre of the circulation of the storm. TC intensity is estimated using VIS and IR imagery. Fixes are also made using scatterometer, TRMM, multispectral and special sensor microwave imager (SSM/I) data. IR imagery is the workhorse of the TC analysis because of its 24 hours availability. VIS imagery provides the highest resolution and is the best channel available for detection of surface features that may not be seen in the IR or WV imagery. Multispectral imagery which highlights features both at low and high levels is used to determine TC intensity and position. Satellite fixes of position are added to the fixes data base along with fixes from other sources. This is used to develop a Working Best Track and for input of TC bogus into numerical models. A lot of insight has been gained into physical and dynamical progress shaping development of TCs. Satellite imagery has also been very exhaustively used for the analysis of TCs developing in the north Indian Ocean (Kalsi 1999 & 2002). The satellite based observations have opened up new research areas for improved forecasting of intensity and track. Some of the emerging research areas are:

- The 'warm core approach' using MSU sounding data to analyse warm temperature anomalies in upper troposphere and correlate to central pressure fall and maximum winds (DeMuth *et al.,* 2001).
- The objective Dvorak technique (ODT) for intense cyclones (Velden *et al.*, 1998) and Advanced Objective Dvorak technique (AODT) for weak systems.
- Storm surge prediction using satellite derived radius of maximum winds, intensity, direction and speed of cyclones.
- Use of satellite data for synthetic vortex generation in numerical models.
- Assimilation of satellite data as mentioned under section 8 below.

Applications of Water Vapour channel data

Imaging in the water vapour channel greatly enhances insight into atmospheric circulation and humidity in the middle atmosphere. The physical basis of water vapour band is the strong absorption of emitted terrestial radiation by atmospheric water vapour. The water vapour channel peaks at 400 mb and the radiance is used for computation of mid-tropospheric moisture content (Velden *et al.*, 1997; Joshi *et al.*, 2001). Water vapour structure also correlates very well with atmospheric motion and thus can be used to delineate jet cores. Thick CB clouds with anvil appear prominently in both water vapour and thermal data. Water vapour appearing as plumes are indicators of heavy rainfall regions, leading to flash floods. IMD has also started using water vapour images. Some of the applications are:

- Water vapour plumes appearing as a tongue or stream of moisture indicating cyclonic circulation leading to heavy rainfall.
- Forecasting track of cyclones, such as recurvature indicated by the moisture envelop around the cyclone field (Bhatia *et al.*, 1999).
- Filling of gap in upper air observations (low density of radiosonde stations in tropics).

SATELLITE PRODUCTS GENERATED AT IMD

Kelkar (1995) has furnished an exhaustive review of quantitative products available from INSAT data. INSAT Meteorological Data Processing System (IMDPS) computes the following numerical products:

1. Cloud Motion Vectors (CMVs)
2. Quantitative Precipitation Estimates (QPEs)
3. Outgoing Long-wave Radiation (OLR)
4. Vertical Temperature Profiles (VTPRs)
5. Sea Surface Temperatures (SSTs)

CMVs, now also termed as atmospheric motions vectors (AMVs), computed from a triplet of satellite scans are disseminated operationally on Global Telecommunication System (GTS) for international consumption. Since the emphasis in the tropics is on the winds, the CMVs find relevance in the analysis of wind field. They have significant impact on the accuracy of numerical models. Though no systematic validation studies of CMVs computed from INSAT data have been carried out, limited studies made by ECMWF in this regard indicate that the quality of this product has shown some improvement. The problems in the derivation of high quality CMVs in the region of active convective disturbances however, still continuing. There are no CMVs in the areas characterized by deep convection and height assignment is also leading to problems.

A large number of schemes have been developed over the years to infer the precipitation estimates from satellite pictures. Since in the tropics, there is preponderance of convective clouds, cloud history methods are of relevance for determination of QPEs. The arkin algorithm (Rao *et al.*, 1989) is being applied to derive operationally large-scale precipitation estimates on daily, weekly and monthly basis. Rainfall is used both as an input in the numerical model scheme for physical initialization and also for verifications of model predicted precipitation. The NWP schemes are unable to account adequately for the diabetic heating.

SSTs are derived from IR Channel (10.5-12.5μm) data from INSAT. A major anomaly in the accurate derivation of SST field is due to attenuation by the moisture in the overlying column, which is compounded by the fact that it is a single broad band channel data. Retrieval of SST during the monsoon season is badly affected due to heavy clouding. Though the seasonal gradients in the SST field are brought out, the accuracy is doubtful.

The Outgoing Longwave Radiation (OLR) is calculated using physical/ statistical algorithm on the IR window channel data received three hourly at IMDPS. Regular OLR derivation have been in progress since 1986. OLR has come out to be a proxy parameter for many of the research applications. OLR data derived from INSAT IR band is being operationally fed to NCMRWF, New Delhi where it is used in their schemes for physical initialization.

Khanna and Kelkar (1993) have described the system for derivation of temperature soundings of the atmosphere over the Indian region using satellite data. They employed physical retrieval method and generated regression estimates using SSU and MSU channels as initial guess. The high resolution sounding data from IMDPS is being assimilated in numerical models at IMD and NCMRWF.

IMPACT OF SATELLITE DATA ON NUMERICAL WEATHER PREDICTION MODELLING

A global spectral model (T-80/L/16) and a global data assimilation system based on short range forecast (six hours) of this model involving Spectral Statistical Interpolation (SSI) scheme of analysis has been operational at the NCMRWF since June 1994. The satellite data sets received on GTS along with many other data sets received directly from the satellite data sources are being routinely used on operational basis. Mitra *et al.* (2003) reported encouraging results made towards assimilation of different types of satellite data on the analysis and forecast system of NCMRWF. Inclusion of high density satellite winds improved the performance of the model in refining many of the flow features during the southwest monsoon season over India.

IMD is also running a limited area analysis and forecast system in which a variety of conventional as well as non-conventional data received on GTS system of WMO is being ingested. Prasad (1997) described the synthetic vortex generation scheme for numerical forecasting of TCs. The scheme basically generates radial distribution of surface pressure within the vortex from a empirical formula proposed by Holland (1980). Basic inputs for generating the surface pressure are the parameters like central pressure of the storm, its environmental pressure, radius of maximum wind, current position, movement and intensity of the storm, which are inferred from the satellite imagery. Surface winds are obtained from the gradient wind relationship. Upper winds are computed from surface winds by using composite vertical wind shear factors proposed by Anderson and Hollingsworth (1988). Recently a Quasi-Lagrangian Model (QLM) has also been installed. Inputs from the satellite data are quite important for initializing the vortex position.

Three areas wherein satellite data have significantly contributed to numerical weather prediction are: defining the initial conditions of the model, setting of the boundary conditions, and defining the forcing functions. The satellite derived parameters on SST, sea surface winds, temperature/humidity profiles etc. have been assimilated into the models and found to have significant impact on the forecast outputs. Boundary conditions play a crucial role in extended/seasonal/long-term predictions and several inputs such as SST-snow cover, vegetation cover, soil moisture, etc. are provided by satellite data. The impact studies carried out using the Extended Range Monsoon Prediction model (Pal *et al.*, 1999) using SST and soil moisture has given new insights into their crucial role. One of the important forcing functions namely radiation budget operationally available from satellites is an important input to models. The most current research is focussing on assimilation of satellite inputs to models for improved performance.

FUTURE MISSIONS

Several satellite missions have been planned to support the operational data needs and ongoing research efforts. The future Metsat missions will carry improved VHRR and vertical sounders for temperature/humidity profiles. The Megha -Tropiques Mission scheduled for 2004 launch will be a joint project by ISRO and CNES, France with the objective of studying the water cycle and energy exchanges in the tropics. With an equatorial inclined orbit, the satellite will have high repetitively over tropical regions.

The future appears bright for our space-based observing system. Advanced, multispectral (visible, IR, and passive microwave) imagers, sounders (infrared and microwave) and scatterometers are planned for launch in the near future. Hyperspectral measurements from newly developed interferometers are expected to be flown experimentally by 2006. The information content will vastly exceed that of the current measuring devices. Instead of a few dozen viewing channels, these instruments will have more than a thousand channels over a wide spectral range. The satellite data downloads are expected to exceed several terabytes per day. Fortunately, communications and computing capacity are increasing at a rate that hopefully can accommodate this data explosion. Emerging new technologies (including the use of rapidly developing visualization tools) will be employed. It is important that the evolving space-based observational system keeps one step ahead of the demands being placed by the user community and advances in numerical weather prediction. While it will become an enormous task and challenge to assimilate this wealth of data into meaningful parameters, the outlook is bright for unlocking the still-unresolved mysteries towards improving our understanding and prediction of atmospheric circulation systems such as tropical cyclones.

CONCLUSIONS

Integrated use of satellite data and conventional meteorological observations is found to be very useful for synoptic analysis and conventional forecast to extract information relevant for agriculture in India. Synoptic applications of satellite images for operational weather-forecasting in India are discussed in this article. A summery of use of numerical products derived from meteorological satellite data in numerical climatic models is also presented.

ACKNOWLEDGEMENTS

The author is extremely grateful to Dr. R.R. Kelkar, Director General of Meteorology, India Meteorological Department, New Delhi to enable him to deliver lecture in the Training Workshop on Remote Sensing Data Interpretation for applications in Agricultural Meteorology Jointly organized by WMO, CSSTEAP, IIRS and IMD from July 7-11, 2003 at Dehradun. The author is also thankful to the organisers for inviting him to the workshop.

REFERENCES

Anderson, F. and Hollingsworth, A. 1988. Typhoon bogus observations in the ECMWF data assimilation systems.

Bhatia, R.C., Brij Bhushan and Rajeswara Rao, V. 1999. Application of water vapour imagery received from INSAT-2E. Current Science, 76: 1448-1450.

Brueske, K.F. and C.S. Velden, 2000. Tropical cyclone intensity estimation using the NOAA-KLM series AMSU : Preliminary results and future prospects. Preprints, 24th Conf. Hurr. Trop. Meteor., Fort Lauderdale, FL, Amer. Meteor. Soc., p. 258-259.

DeMuth, J.D., M. DeMaria, J. Knaff and T.H. VonderHaar, 2001. An objective method for estimating tropical cyclone intensity and structure from NOAA-15 AMSU data. Preprints 24th Conf. Hurr. Trop. Meteor., Fort Lauderdale FL, AMS, p. 484-485.

Dvorak, V.F. 1984. Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS. 11, 44 pp.

Goswami, B.N. 1998. International variations of Indian Summer Monsoon in a GCM : External conditions versus internal feedbacks. Jou. of Climate., 11: 501-502.

Gohil, B.S., Mathur, A.K. and Verma, A.K. 2001. Proceed. of Pacific Ocean Remote Sensing Conf., 2000, 5-8 December, 2000, NIO, Goa, India, 207-211.

Holland, G.J. 1980. An analytical model of the wind and pressure profiles in hurricanes. Mon. Wea. Rev., 108: 1212-1218.

Joseph, P.V., K.P. Sooraj and C.K. Rajan 2003. Conditions leading to Monsoon onset over Kerala and the associated Hadley cell. Mausam, 54(1): 155-164.

Joshi, P.C., Simon, B. and Desai, P.S. 1990. Atmospheric thermal changes over the Indian region prior to the onset as observed by satellite sounding data. Int. J. Clim., 10: 44-56.

Kalsi, S.R. and Mishra, D.K. 1983. On some meteorological aspects of snowfall over Himalayas and observed by satellite. Proc. of the First National Symp. on Seasonal Snow Cover, 28-30 April, 1983, New Delhi, p125-132.

Kalsi, S.R. and Bhatia, R.C., July-December 1992. Satellite observations of thunderstorm complexes in weakly forced environments. Vayu Mandal, 22: 65-76.

Kalsi, S.R., Rao, A.V.R.K., Misra, D.K., Jain R.K. and Rao, V.R. 1996. Structural variability of tropical disturbances in the Bay of Bengal. In Advances in Tropical Meteorology, Ed. by R.K. Datta. Concept Publishing Company, New Delhi. 449-458.

Kalsi, S.R. 1999. Multiple eyewall structure in an Arabian Sea Cyclone. Current Science 77 (8): 1175-1180.

Kalsi, S.R. 2002. Use of satellite imagery in tropical cyclone intensity analysis and forecasting. Meteorological Monograph, Cyclone Warning Division No. 1/2002, India Meteorological Department, New Delhi-110003, India.

Khanna, P.N. and Kelkar, R.R. 1993. Temperature sounding of the atmosphere over the Indian region using satellite data. Mausam, 42(2): 167-174.

Kelkar, R.R. 1995. Satellite products from IMD. WMO TMRP Series Rep. No. 52, 91-94.

Mishra, D.K., Kalsi, S.R. and Jain, R.K. 1988. The estimation of heavy rainfall using INSAT-1B. Mausam, 39(4): 19-40.

Mitra, A.K., Das Gupta, M., Prasad, V.S., Kar, S.C. and Rajan, D. 2003. Weather and Climate Modeling. New Age International Publishers, p. 23-36.

Pal, P.K., Prakash, W.J., Thapliyal, P.K. and Kishtwal, C.M. 1999. Technique of rainfall assimilation for dynamic extended range monsoon prediction. Meteo. Atmos. Phys. 71: 157-168.

Prasad, K. 1997. Prediction of tropical cyclones by numerical models-A review. Mausam, 48 (2): 225-238.

Purdom, J.F.W. 2003. Local severe storms monitoring and prediction using satellite systems. Mausam, 54(1): 141-154.

Rao, A.V.R.K., Kelkar, R.R. and Arkin, P.A. 1989. Estimation of precipitation and outgoing longwave radiation from INSAT-1B radiance data. Mausam, 40: 123-130.

Sarkar, A. 2003. Space based techniques for remote sensing of oceanic winds: A review. Mausam, 54(1):111-120.

Scoffield, R.A. and Oliver, V.J. 1977. A scheme for estimating convective rainfall from satellite imagery. NOAA Tech Memo NESS 86, Washington D.C., 47.

Sikka, D.R. and Gadgil, S. 1980. On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon. Mon. Wea. Rev., 108: 1840-1853.

Velden, C.S., C.M. Hayden, S.J. Nieman, W.P. Manzel, S. Wanzong and S.J. Goerss, 1997. Upper tropospheric winds derived from geostationary satellite water vapour observations. Bulletin of Amer. Met.Soc., 78: 173-195.

Velden, C.S., T. Olander and R. Zehr, 1998. Evaluation of an objective scheme to estimate tropical cyclone intensity from digital geostationary satellite infrared imagery. Weather Forecasting, 13: 172-186.

Velden, C.S., Olson, W.S. and Roth, B.A. 1989. Tropical cyclone centre-fixing using SSM/1 data. Preprints of 4th conf. on Sat. Met. Ocean., AMS, Boston, MA 02108, J36-39.

Velden, C.S. and Hawkins, J.D. 2002. WMO TMRP Rep No. 67, Rapporteur Report on Topic 0.3.