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Use of satellite observations for weather prediction

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सार - पिछले छह दशकों के दौरान मौसम संबंधी उपग्रह काफी विकसित हुए हैं और अब मौसम की निगरानी और पूर्वानुमान के लिए इन उपग्रहों का अवलोकन अनिवार्य हो गया है। ये अवलोकन मौसम के विकास की निगरानी के लिए महत्वपूर्ण हैं जैसे: उष्णकटिबंधीय तूफानों और प्रचंड मौसमों की गति और वायुमंडलीय माप प्रदान करते हैं जो सटीक मौसम पूर्वानुमान के लिए संख्यात्मक (NWP) मॉडल में शामिल होते हैं। इस लेख में विभिन्न प्रकार के मौसम संबंधी उपग्रहों, संवेदकों और इन संवेदकों से प्राप्त किए गए वायुमंडलीय प्रेक्षणों का वर्णन किया गया है।इसमें उपग्रह डेटा का उपयोग करते हुए प्रेक्षण प्रणाली सिमुलेशन अध्ययन (OSSE) के परिणामों को संक्षेप में उपग्रह संवेदकों और धरातल पर स्थित पारंपरिक प्रेक्षण नेटवर्क से प्राप्त प्रेक्षणों के सापेक्ष प्रभाव को दर्शाने के लिए विवेचन किया गया है।

ABSTRACT. Meteorological satellites have evolved significantly during past six decades and now the observations from these satellites are indispensable for weather monitoring and prediction. These observations are critical for monitoring the development of weather e.g., the movement of tropical storms and severe weather and provide atmospheric measurements that are ingested into the numerical on (NWP) models for accurate weather prediction. This article describes different types of meteorological satellites, sensors and the atmospheric observations from these sensors. Results of Observation System Simulation Studies (OSSE) using satellite data are briefly described to show the relative impact of observations from satellite sensors and conventional ground based observation network.

Key words – Meteorological satellites, Numerical weather prediction, Data assimilation.

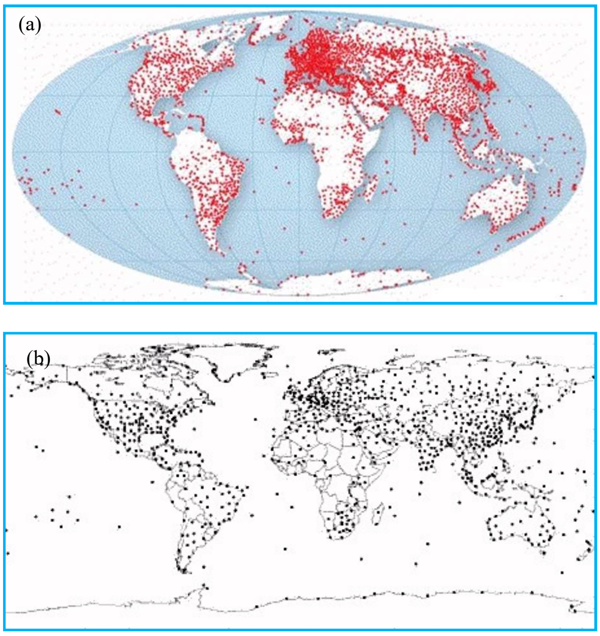
1. Introduction

Understanding and prediction of weather has many applications across various sectors of societal importance that include agriculture and food safety, transport (e.g. aviation, shipping and surface transportation), industries, energy production, disaster management, tourism, sports, etc. Prediction of weather at short range to seasonal time scales is specially crucial for efficient planning of agriculture and energy production. The growing vulnerability of densely populated urban and coastal areas to natural hazards make increased demands for reliable weather forecasts to ensure the safety of life and property (Hollingsworth *et al*., 2002). The importance of weather prediction has long been recognized since the beginning of the human civilization and early attempts to predict the weather were based on human experience, intuition and the understanding of the link between the weather and the natural cycles. By the turn of the twentieth century, scientists theorized that the atmosphere must obey the basic laws of physics (Abbe, 1901; Bjerknes, 1904). Bjerknes stated that 'subsequent atmospheric states develop from the preceding ones according to the physical law' that can be represented as the mathematical equations. This essentially means that the problem of weather forecasting is an initial value problem and accurate observations from the atmosphere could be used in a mathematical model to predict the future state of the atmosphere. Developing from the ideas of Abbe and Bjerknes, Richardson (1922) presented a set of equations describing the physical processes governing the atmospheric processes and argued that it should be possible to proceed from an initial to a final state of the atmosphere by a purely mathematical process. Although the methods proposed by Richardson could not be implemented for practical weather prediction due to shortcomings unknown at his time, his ideas formed the foundation stone for modern day numerical weather prediction (NWP). Later, Charney and colleagues provided theoretical developments to overcome problems faced by Richardson. The simplified equations they proposed lead to a NWP model, a modern electronic computer and the computer generated weather forecast (Charney *et al*., 1950). Now a days, the operational weather forecasting almost entirely relies on the numerical weather prediction (NWP) models that use fundamental laws of dynamics and thermodynamics and complex computational techniques.

A sufficiently accurate knowledge of the current state of the atmosphere and a sufficiently accurate knowledge of the laws of nature governing the development of the weather are essential and critical for the prediction of the weather. Hence, the development of the meteorological observation networks was considered as important as the development of weather prediction models. This emphasis on the atmospheric observations led to a continuous development of ground based observation network of surface as well as upper air weather parameters. Although the ground based observation network provides very critical input to the weather prediction and climate monitoring, it provides very limited observations over inaccessible areas like mountains, deserts and vast oceanic areas [Figs. 1(a&b)]. Meteorological satellites provide the atmospheric observations that are vast in coverage, narrowly spaced, representative and more frequent compared to observations from conventional ground based network. It is therefore not surprising that the meteorological satellites have been at the forefront of earth observation. The first meteorological satellite, the Television InfraRed Observation Satellite (TIROS-1), was launched on 1st April 1960. In 1963 World Meteorological Organization (WMO) established an operational satellite observation network of geostationary and polar-orbiting meteorological satellites within the ambit of Global Observing System (WMO, 2005).

Observations of atmospheric parameters from satellite are indispensable for modern NWP based weather prediction system. Today, at least 95% of all the observations assimilated by global NWP models are provided by satellites. On the other hand, sensitivity analysis based on NWP model simulations provide valuable guidance in defining and designing new meteorological satellite missions and sensors.

Satellites provide valuable earth observations from low-earth orbit as well as geostationary orbits. Fig. 2 shows the constellation of current geostationary and Low Earth Orbiting (LEO) meteorological satellites. Satellites in low earth orbits that vary in altitude in the range 300-850 km provide high resolution measurements of the atmospheric and oceanic parameters e.g., vertical structure of temperature and humidity, atmospheric moisture, cloud liquid water, vertical structure of clouds and rain, sea surface and land surface temperature, atmospheric aerosols and trace gases, air quality parameters, ocean surface winds, ocean salinity, soil moisture, rainfall, etc. Some examples of low earth orbit, including polar orbiting satellites are Megha-Tropiques (ISRO-CNES), SCATSAT (ISRO), NOAA series of satellites by NOAA, Aqua and Terra (NASA), MetOp series of satellites (EUMETSAT) etc. The information about the vertical structure of atmospheric temperature and humidity provided by LEO satellites is extremely crucial for the NWP model forecasts. At higher latitude regions, these observations have larger impact on weather prediction due to more frequent visits by these satellites at upper latitudes and also due to stronger coupling between thermodynamics and dynamics of the atmosphere over these regions. The LEO satellites visit tropical and sub-tropical regions of the earth less frequently (every 10-12 hours) making it difficult for these satellites to continuously monitor the development of the weather. This is complimented by geostationary satellites orbiting at 36000 km above the equator. These satellites provide very frequent observations (~10 minutes from latest generation geostationary satellites like Himawari -8/9) of full earth disk. A single geostationary satellite can view about 40% of the earth surface. The examples of currently operational geostationary satellites are INSAT-3D, INSAT-3DR, GOES-14, GOES-(14,15,16,17), Meteosat (8,9,10,11), Himawari (8 and 9), FY-2G, FY-2H, FY-4A, etc. Present generation geostationary satellites observe the earth-ocean-atmosphere system at several spectral channels and provide many useful parameters like atmospheric winds, sea and land surface temperature, air-quality etc. The most useful quality of these satellites is their ability to provide the continuous observations of weather, making them suitable for tracking clouds, air-mass, tropical cyclones and thunderstorms. The global system of geostationary satellites is truly a backbone of operational weather services worldwide. Due to much larger orbital altitude of geostationary satellites, the signal strength and spatial resolution of the observed radiances is poorer compared to those from LEO satellites. In recent times the idea of



Figs. 1(a&b). Global distribution of (a) AWS stations (b) Stations for upper air meteorological observations

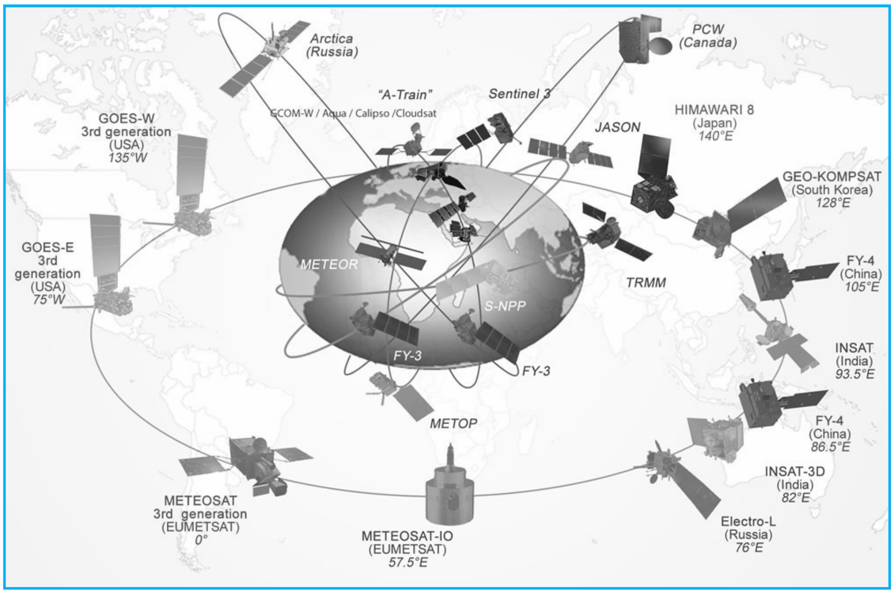


Fig. 2. Constellation of geostationary and low earth orbiting meteorological satellites
(*Source* : WMO/CGMS)

deploying a swarm or a fleet of several small LEO satellites is gaining popularity, in which several LEO satellites will be so strategically placed that at any point of the earth surface, at least one satellite will provide the required observations of the atmosphere.

2. Visible/Infrared sensors

2.1. *Visible/Infrared imagers*

The earliest satellite observations were made by using visible/infrared wavelengths and even today, these observations are regarded equally important for operational meteorological applications. Almost all geostationary satellites occupying different slots along the equatorial belt of the globe use visible/infrared sensors to obtain regular observations of earth-atmosphere system at regular time intervals. For example, India's INSAT-3D and INSAT-3DR 6-channel imagers provide full earth coverage at every 30 minute interval, with a spatial resolution of 1 - km in visible and short-wave-infrared (SWIR) channels.

2.2. *Applications of imager observations for synoptic scale analysis*

Fig. 3 shows the full-disc earth view in six imager channels of INSAT-3D. Each channel reveals different feature of earth atmosphere system. For example, the visible channel indicates the reflected solar radiation. In the context of clouds, the higher reflectivity in visible channel indicates higher cloud liquid water, or high thickness in clouds. SWIR channel also indicates reflection, but the reflectivity is very sensitive to the water phase in the clouds and the icy parts of the cloud are less reflective compared to the water part. This channel is also sensitive to the cloud droplet size. Thus the SWIR channel in combination with visible and other channels is helpful in detection of cloud microphysical properties (Platnick *et al*., 2003), which may be indicative of the rain potential of the cloud systems. Middle Infrared (MIR, 3.9 µm) channel works as a reflective channel during daytime and emission channel during night. While the reflectivity of this channel is sensitive to the microphysical properties of the cloud, the emission in MIR channel is sensitive to small changes in the physical temperature of the objects. Thus this channel is useful in detection of low clouds and often used in Land Surface Temperature (LST, Petitcolin and Vermote, 2002), Sea Surface Temperature (SST) and fog (Chaurasia *et al*., 2011) retrieval algorithms during night time. Split thermal infrared channels TIR-1 (10.3-11.3 µm) and TIR-2 (11.5-12.5 µm) are dual-window channels that are applied together in several retrieval algorithms to eliminate the atmospheric attenuation effects. These channels help in accurate estimation of SST, LST, outgoing longwave radiation (OLR), cloud top height, cloud top height, precipitation (Varma, 2018), etc. The water vapor channel (6.7-7.1 µm) channel is highly useful in detection of atmospheric dynamics in the cloud-free regions (Deb *et al*., 2008) and retrieval of upper tropospheric humidity (Thapliyal *et al*., 2006; Dey *et al*., 2014) and OLR (Singh *et al*., 2007). Unlike other imager channels, radiances at water vapor channel are significantly influenced by the atmospheric

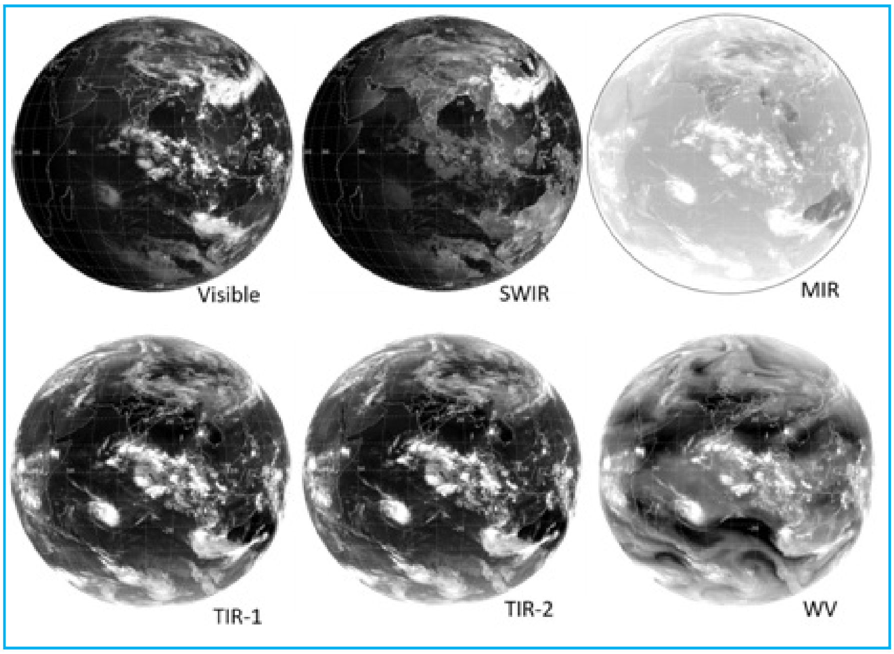
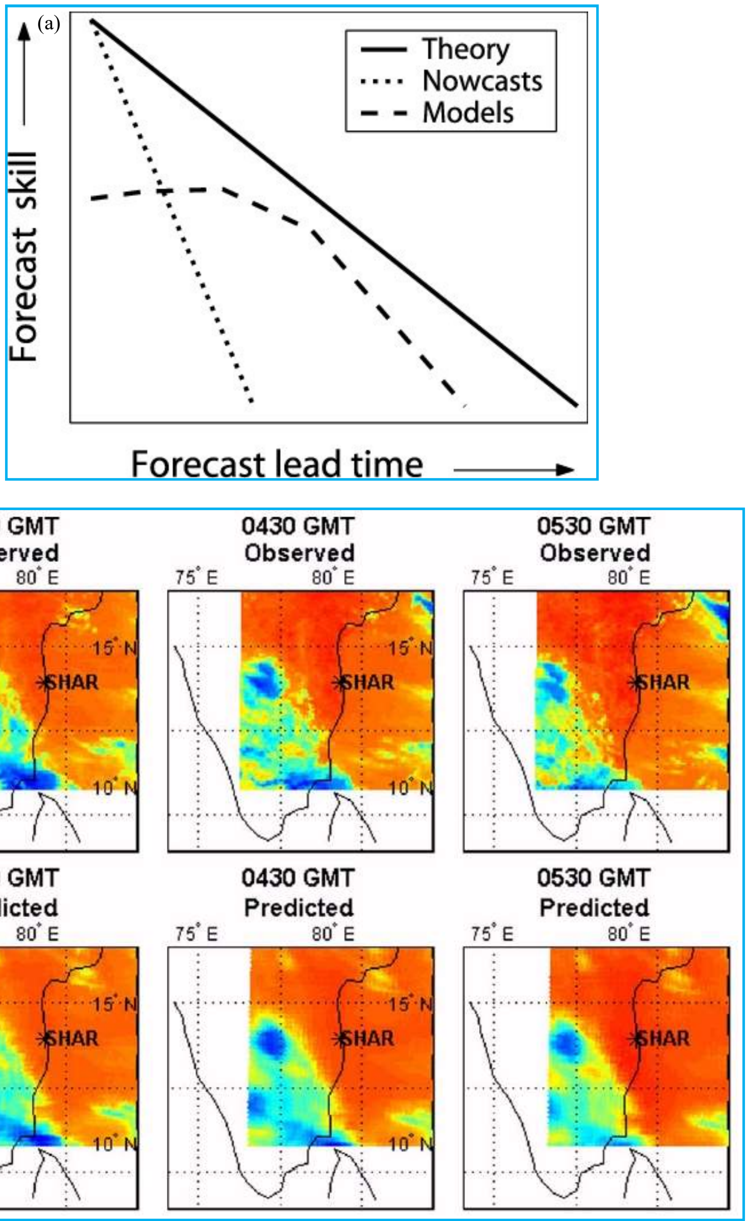


Fig. 3. Full-disc earth view in six channels of INSAT-3D Imager

water vapor (mainly the upper tropospheric water vapor) and this feature of WV channel makes it suitable for synoptic scale analysis. WV images may be interpreted to identify the regions of moisture convergence, upper level divergence, atmospheric stability, deep convection in blocking regimes, tropical convective plumes (McGuirk and Ulsh, 1990), regions of enhanced potential vorticity, regions of mid-latitude cyclogenesis, regions of dry air intrusion and subsidence zones etc. (Georgiev *et al*., 2016). WV images also serve as a validation tool for NWP forecasts, in which the NWP forecasts are used to generate simulated WV images with the help of radiative transfer models and these simulated images are then compared with the actual satellite observed WV images for comparison and validation. The scan times of INSAT-3D and INSAT-3DR are staggered in such a way that they together ensure full-earth coverage at every 15-minute interval. Advance imagers on other geostationary satellites like AHI (Advance Himawari Imager) onboard HIMAWARI-8 satellite of Japan, ABI (Advance Baseline Imager) onboard GOES-16 of United States of America and SEVERI onboard Meteosat Second Generation (MSG) of European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) provide full earth-disk coverage in 5-15 minute intervals in several spectral channels in visible and infrared regions of electromagnetic spectrum. Operational meteorological polar satellites like NOAA, Aqua and Terra satellites also make global observations in visible/IR channels providing better spatial and spectral resolution yet poorer temporal resolution than geostationary satellites. A number of meteorological parameters are derived from satellite-based Visible/IR imager observations that include delineation of clouds in the atmosphere, sea surface temperature (SST), land surface temperature (LST), atmospheric water vapor, atmospheric winds determined from tracking of cloud and water vapor features, rainfall amount, fog and visibility, outgoing longwave radiation (OLR), aerosol optical depth (AOD), cloud properties like cloud top temperature and pressure. These observations have significant use in monitoring the location, intensity, movement and the areal extent of tropical cyclones. Vernon Dvorak developed an important and now widely used technique between 1969 and 1984 for determining the cyclonic intensity based on the observations of certain features associated with the cloud fields of tropical cyclones (Velden *et al*., 2006). This technique used originally only the visible (VIS) imagery. Later it incorporated infrared (IR) and other sensors data. It describes tropical cyclone development in terms of day-to-day changes in the cloud pattern of the storm and its environment. The VIS and IR techniques differ mainly in the cloud features that are used in the analysis and the way in which they are measured. The enhanced and digital infrared techniques when applied to storms of very severe strength rely almost entirely on measurements of the 'EYE' temperature and the temperature of the clouds around the eye for the intensity determination. Higher end applications of visible/IR observations include determination of cloud top temperature, cloud height, cloud thickness, classification of clouds into convective/stratiform types and the determination of cloud level winds, known as Cloud



Figs. 4(a&b). (a) Relative skill of nowcasting & NWP models with increasing lead time and (b) Example of nowcasting of convective system based on image prediction method (*Source* : Shukla *et al*., 2013)

Motion Vector (CMV) winds, based on the motion of clouds. The above parameters can be determined at regular time intervals from geostationary satellites and are extremely useful in operational monitoring of tropical cyclones.

2.3. *Applications of imager observations for nowcasting*

Availability of observations of weather systems at short time interval from geostationary satellites (10-15 minutes) is highly beneficial for very short range (few minutes to couple of hours) forecasting or "nowcasting". In general, the techniques of nowcasting are different from those of NWP models and nowcasting mostly relies on tracking the movement and evolution of weather features in rapid sequence of images from Radars or satellites (Kober and Tafferner, 2009). For short term prediction of precipitation (0-3 h), nowcast methods based on Lagrangian advection of radar and satellite images of convective systems offer the most robust and accurate prediction at mesoscale resolution, as the initial conditions are known accurately [Fig. 4(a), Golding, 1998)]. For longer forecast lead times, numerical weather prediction models may have better predictability, as they resolve the larger scales. Observations of INSAT-3D/3DR imagers are used in nowcasting for (a) tracking the convective features in VIS, TIR-1 and TIR-2 images (b) Identification of cloud microphysics (VIS, SWIR, MIR, TIR-1/2) that help detection of growing and decaying regions of convective systems (c) identification of deep convection and cloud growth (TIR-1/2, WV) (d) Identification of regions of high precipitation and their movement (TIR-1/2, WV). Fig. 4(b) shows the example of nowcasting of a convective system based on image prediction method. Nowcasting methods based on INSAT images have been demonstrated to successfully predict the heavy rainfall events in the mountainous regions of India (Shukla *et al*., 2013; Shukla *et al*., 2017). Indian geostationary satellite GISAT to be launch in near future will have multi-spectral infrared imaging capability with high spatial and temporal resolution which is likely to significantly enhance the accuracy of the nowcasting. Recent research emphasizes on the use of NWP for nowcasting with active use of rapid sequence of observations from satellites (Sun *et al*., 2014).

2.4. *Applications of imager observations for precipitation measurements and analysis*

Precipitation measurement is an important application of visible/infrared satellite observations (Arkin, 1979). Visible (VIS) and infrared (IR) techniques for rainfall measurement are grouped together because they share common characteristics. Both provide indirect assessment of rainfall as VIS/IR radiances do not penetrate clouds and hence rain droplets inside the clouds are not directly sensed by them (Barrett and Martin, 1981; Bhandari and Varma, 1995). Because of the indirect relationship between the satellite measured Vis or IR radiances and rainfall, the techniques developed for one region and for a particular temporal and spatial scale do not necessarily work equally well in another region/scale. The factors governing cloud brightness are determined by the physics of optics that requires gaining insight of the scattering theory of electromagnetic radiations. The dimension of the cloud and its orientation with respect to incident beam is important for determining cloud brightness. The other factors that may affect the cloud brightness are phase (water/ice/mixed phase), size and density of cloud droplets, etc. (Barrett and Martin, 1981). Advanced rainfall estimation techniques based on VIS/IR measurements use several other ancillary data such as the prediction of humidity profiles, boundary layer winds and stability indices from numerical model forecasts, orography, to retrieve rainfall with high accuracy and high resolution. Hydro-Estimater (HE) rainfall is such rainfall product routinely produced by NOAA (http://www.orbit.nesdis.noaa.gov/smcd/emb/ff/) that uses observations from GOES satellite and IMD that produces HE rain from INSAT-3D observations at every 30-minute interval. Fig. 5 shows the weekly composite of HE-rainfall during a flood event over Kerala during 13-19 August, 2018.

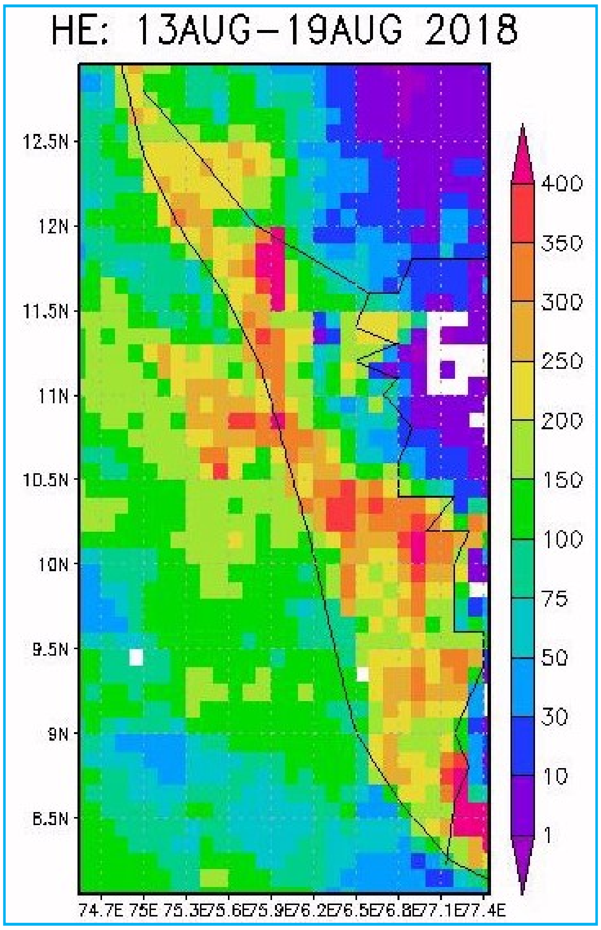


Fig. 5. Weekly composite of HE-rainfall product from INSAT-3D imager

Satellite based precipitation products play a very important role in the development of numerical weather (NWP) prediction. Often the skill of NWP models is validated using the satellite observed rainfall and the analyses of the validation are used for improving the representation of physical parameterization of convection, clouds, boundary layer, turbulence etc. in the NWP models. Until recently, it was a common practice in operational data assimilation centres to avoid the satellite observations over the cloud or rain affected regions because most of the satellite observed radiance measurement get affected by clouds (in VIS/IR observations) & rainfall (VIS/IR/Microwave observations).

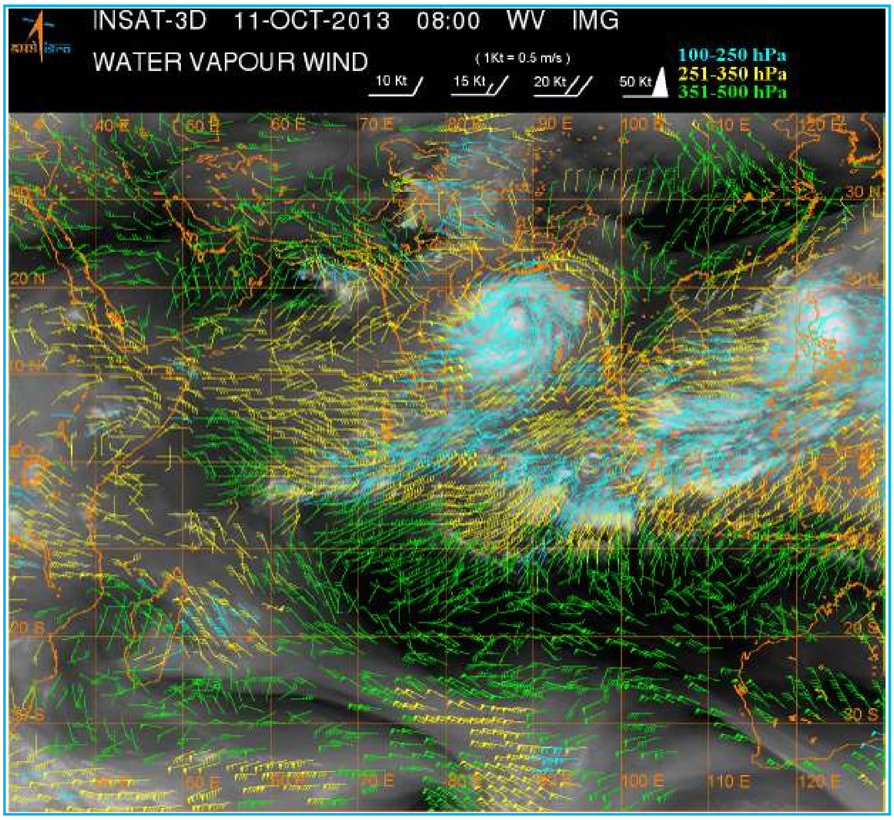


Fig. 6. Atmospheric winds derived from INSAT-3D water vapor channel

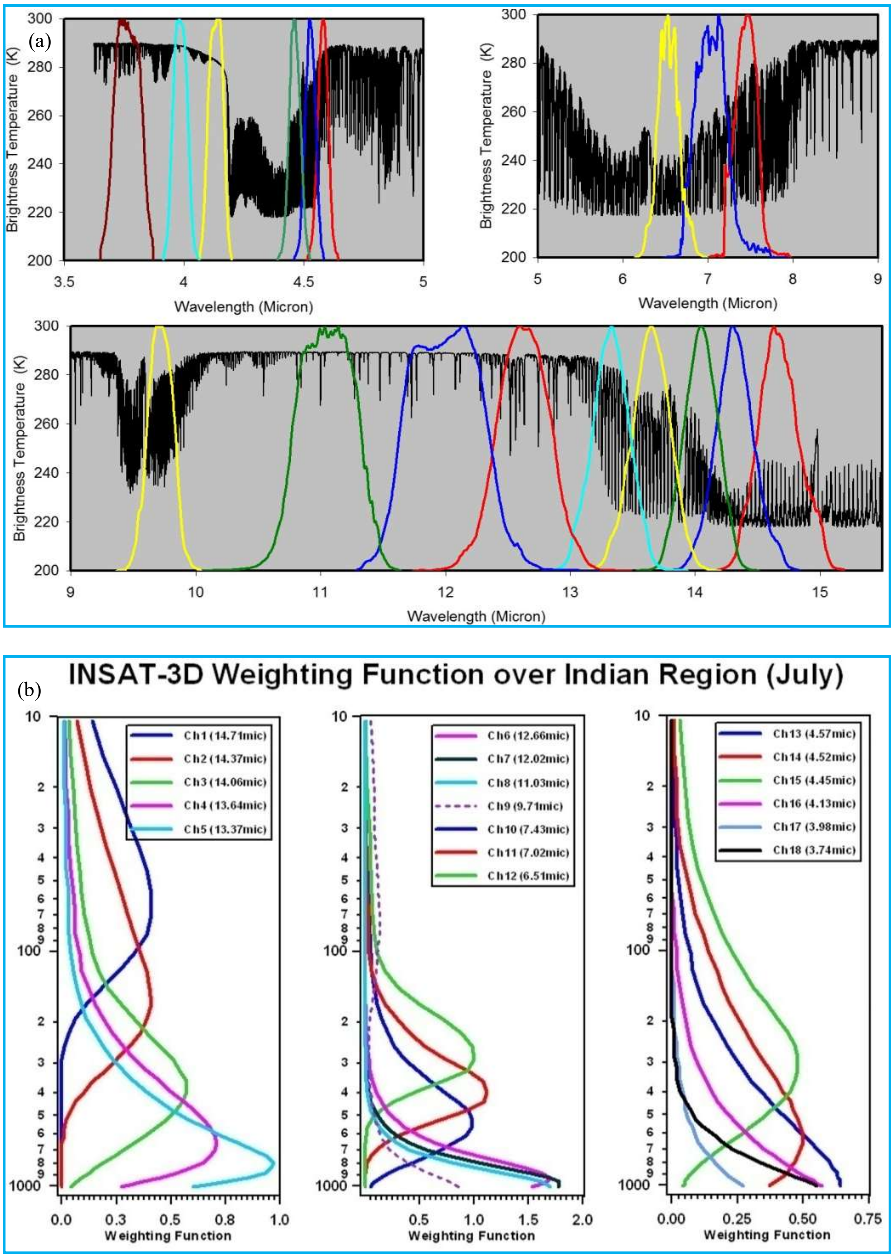
However, now, with the development of advance data assimilation techniques like 4D-VAR technique, the satellite derived rainfall is being considered as a very useful parameter for assimilation in NWP models that has the potential to significantly improve the short-range prediction of temperature, humidity and winds (Kumar *et al*., 2014; Kumar and Varma, 2016; Kumar and Kishtawal, 2017)

2.5. *Applications of imager observations for atmospheric dynamics*

Atmospheric winds derived using the tracking of cloud and water vapor features in Visible and Infrared images are highly useful inputs for assimilation in the NWP models. At present two advanced Indian geostationary meteorological satellites INSAT-3D (launched on 26 July, 2013) and INSAT-3DR (launched on 6 September, 2016) with similar sensor characteristics are orbiting over Indian Ocean region and are placed at 82° E and 74° E respectively. Together these two satellites provide images at every 15-minutes interval. Although atmospheric motion vectors (AMVs) are derived operationally using data of different channels from individual satellite at 30-minutes interval, a new staggering AMVs derived using INSAT-3D/3DR images simultaneously are also available operationally at 15-minute interval. Fig. 6 shows an example of atmospheric winds derived using INSAT-3D water vapor images.

2.6. *Land and sea surface temperature from Imager observations*

Another useful parameter determined by visible/IR measurements is the sea surface temperature (SST) which may indicate the regions where intense convection may develop, or, a moving convective system may intensify or decay. Determination of SST normally requires more than one channels in infrared region (e.g., a split window channel: 10.5-11.5 and 11.5 to 12.5 um) for making the corrections for atmospheric absorbers of radiation, like water vapor. Observations of global SST are made by NOAA satellites operationally. However, the accuracy and availability of visible/IR based SST is seriously affected by the presence of clouds and hence it is difficult to obtain these measurements in the close vicinity of weather systems dominated by clouds, such as the tropical cyclones. SST can be determined in presence of clouds using microwave techniques. SST observations are very critical for defining the lower boundary in the mesoscale



Figs. 7(a&b). (a) Spectral response function of INSAT-3D/3DR in the backdrop of atmospheric transmittance spectra and (b) weighting functions of INSAT-3D/3DR sounder instrument

NWP models for short range prediction and as an important initial condition for the coupled ocean atmosphere models for sub-seasonal and seasonal range prediction. Land surface temperature (LST) is also estimated from imager observations using the similar methodology as used for SST retrieval. However, the correct estimation of LST requires prior information about the land surface emissivity that, unlike sea surface, varies significantly within short spatial and temporal scales.

2.7. *Infrared sounders in geostationary satellites*

"Sounders" are the instruments used for measuring vertical profiles of some atmospheric parameter, like temperature or humidity and when such instruments are placed on some satellite, they can provide three dimensional distribution of these parameters. Sounders work on the principle of absorption/emission of electromagnetic radiation by various gases in the atmosphere. Depending upon the variation of physical temperature and density of absorbing gases along the vertical direction, the emitted radiance show a Gaussian type variation with height. The height at which the peak of this Gaussian curve (known as weighting function) occurs, is different for different wavelengths of infrared, because, the absorption efficiency of a gas is a function of wavelength. Thus, it is possible to determine the physical temperature at some height by mathematically inverting the above physical process and temperature at different heights can be known by taking observations at different wavelengths. Retrieval of humidity profiles is also similar in principle, but employs a slightly different procedure. High Resolution Infrared Sounder (HIRS) onboard NOAA satellites is such an operational sounder which uses 13 spectral channels (associated with CO_2 absorption bands, 7 channels placed around 15 um and 6 around 4.3 um) for temperature sounding and 3 channels (associated with water vapor absorption at 8.2, 7.3 and 6.7 um) for determining water vapor concentration in three broad vertical layers. India's geostationary satellites INSAT-3D and INSAT-3DR both are equipped with the infrared sounders with 19 channels, which are used to provide a number of useful meteorological parameters like the profiles of temperature, humidity and ozone, atmospheric stability indices, atmospheric water vapor, etc. at 1-hour interval. Fig. 7(a) shows the spectral response function of INSAT-3D/INSAT-3DR sounder instruments in the backdrop of atmospheric transmittance and Fig. 7(b) shows the weighting functions of the corresponding sounder channels. Unfortunately the quality of infrared sounding is seriously affected by the presence of clouds and the retrievals are not possible if the satellite field of view is totally covered by the clouds. Such situations are quite common in the domain of tropical cyclones.

3. Microwave sensors

Satellite microwave sensors play very important role in the observations of meteorological parameters. The wavelength of microwave signal ranges from 1 cm to 1 meter, which is much larger compared to visible or infrared signal. Due to its large wavelength, the microwave radiation is not affected due to scattering by clouds, haze, dust and light rainfall, which makes the microwave sensors to operate in almost all-weather conditions. The microwave sensors encompass both active and passive sensors. The passive sensors do not use their own source of illumination and collect the radiation emitted, reflected, or transmitted by various objects. The microwave energy emitted by terrestrial objects is much smaller compared to the energy reflected or emitted in visible/infrared region, hence the passive microwave sensors must collect the radiation from a larger area to detect a meaningful signal. Due to this reason, the passive microwave observations are generally characterized by lower spatial resolution. Emitted microwave radiation that reaches the satellite sensor, is a function of surface temperature and emissivity (which is affected by the microwave frequency, surface water content, surface roughness, surface salinity etc.). Due to this characteristic, the passive microwave observations are useful for retrieval of a number of meteorological & oceanographic parameters such as sea surface temperature, atmospheric water vapor, cloud liquid water, rainfall, soil moisture, ocean salinity, ocean surface winds, snow cover, sea ice, oil slicks, etc. When microwave radiation emitted by the earth-ocean surface transmits through the atmosphere, radiation at certain frequencies gets absorbed/re-emitted mainly by atmospheric oxygen and water vapor. This property is used to design special class of passive microwave sensors, called "sounders" for measurement of vertical profiles of atmospheric temperature & humidity under cloudy conditions.

The active sensors like the microwave radars emit the pulses of microwave energy and measure the backscattered radiation. The strength of the backscattered signal and time delay and shape of the return pulse contains crucial information about the target that include the roughness, distance, dielectric properties, etc. Using the radiative transfer based simulation techniques and other complex inversion methods, these signals are then decoded to retrieve a number of parameters that include ocean surface wind vectors, terrain topography, sea level anomalies, ocean wave height, ocean salinity, soil moisture, snow and sea ice extent and thickness, etc.

4. Wind observations from satellites

Observations of atmospheric winds are very crucial for the prediction of weather. Movement of weather systems like clouds, mesoscale convective systems, thunderstorms, tropical cyclones, fronts, squall lines, pollutant-transport etc. can not be predicted without accurate information about the atmospheric winds. Wind observations are required to calculate convergence and vorticity that lead to the prediction of different types of weather systems. Conventionally, the observations of atmospheric winds are obtained by tracking the weather balloons that travel upto the height of 30 km. However, there are only about 1000 upper air observatories worldwide that provide the upper level wind observations. Not only these observations are far too smaller compared to what is needed for the accurate weather prediction, but they also do not cover the regions like deserts, mountains and vast oceanic areas. The frequency of the balloon observations is also limited to once or twice per day.

Atmospheric wind is one of the most important weather parameters provided by the satellite observations.

There are several techniques for determination of atmospheric winds from satellite measurements, but the most commonly they are retrieved by tracking some 'features' in a sequence of images from geostationary satellites (Holmlund, 1993). These features may be cloud segments, or gradients of water vapor, trace gases and aerosols. The range and accuracy of the retrieved winds depends on the image resolution, time gap between two consecutive images, geolocation accuracy and radiometric accuracy of the satellite observations. These retrieved winds are commonly termed as the "Atmospheric Motion Vector" (AMV) winds. AMVs can be determined at different vertical levels of the atmosphere depending upon the vertical location of the tracked feature (Kishtawal *et al.*, 2009; Deb *et al.*, 2016). Recently algorithm for deriving AMVs using high-resolution (1 km) visible images of INSAT-3DR were developed. One major application of INSAT-3D AMVs is demonstrated by assimilating these data in a meso-scale model for the track forecast of the cyclonic storms and other mesoscale systems. The studies indicate that the assimilation of INSAT-3D/3DR AMVs result in improvement of cyclone track prediction and monsoon rainfall prediction by mesoscale models. Also, the AMVs derived from 15-minute staggered INSAT-3D-INSAT-3DR AMVs result in higher positive impact compared to AMVs derived from 30-minute interval images. AMVs from geostationary satellites are very crucial meteorological products for NWP and operational centres worldwide receive a large number (typically 3-5 lakhs) of AMVs derived from international geostationary meteorological satellites at a given assimilation cycle. Although AMVs are mostly determined using the images from geostationary satellites that provide observations every 10-30 minute interval at 1-5 km resolution, observations from a number of polar orbiting satellites may also be used to retrieve AMVs if consecutive polar satellites can provide images with sufficiently short time intervals and high spatial resolution. Images from polar satellites are used for operational retrieval of AMVs near polar region where these satellites visit more frequently. The constellation of geostationary satellites like INSAT-3D, INSAT-3DR, GOES series of satellites, Meteosat, Himawari, KOMSAT, FY-8, etc. provide valuable global observations of AMVs that is a critical input to the global and regional numerical weather prediction models. Additionally, observations from polar satellites MetOP-1 and MetOP-2 together also provide accurate measurements of AMVs.

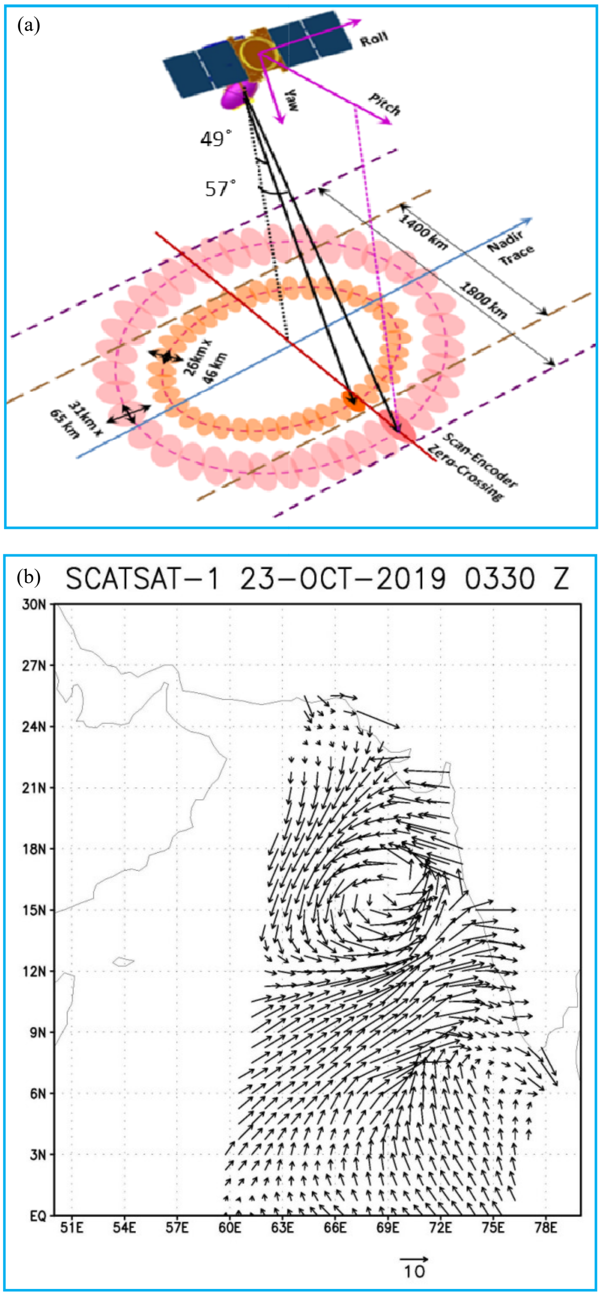
Microwave scatterometers have played a key role in providing global measurements of Ocean Surface Vector Wind (OSVW) that is treated as one of the major parameters in the list of essential climate variables (ECVs). OSVW plays a pivotal role in offshore as well as coastal processing such as upwelling, heat and momentum transfer at the air-sea interface, evolution of oceanic mixed layer, ocean wave and current formation and wave-current interaction, bio-geo-chemical transport in the ocean, coupling of ocean and atmosphere resulting in tropical and extra-tropical disturbances etc. These observations are vital for the study and prediction of ocean state, ocean dynamics, climate change and most importantly for the monitoring and prediction of tropical cyclones [Jaiswal and Kishtawal, 2011; Jaiswal *et al.*, 2019]. Assimilation of ocean surface wind observation in numerical models have positive impact on the prediction of atmosphere and ocean (Singh *et al.*, 2011; Kumar *et al.*, 2012).

Scatterometer is the most commonly used satellite instrument for the measurement of ocean surface winds. Scatterometer is basically a microwave radar that emits microwave energy towards ocean surface and measures the reflected, or backscattered energy. The amount of backscattered energy varies with the ocean surface roughness caused by winds. Scatterometers are designed in such a way that backscattered energy at a particular area is measured from various angles, which helps in determining the direction of the wind at the ocean surface. Scatterometer instruments are precisely calibrated for making accurate measurements of backscattering and hence the ocean surface winds. Several generations of scatterometers have been flown by various space agencies like NASA (USA), ESA (Europe), ISRO (India), JAXA (Japan), CNSA (China) etc. The first operational scatterometer was Seasat Scatterometer (SASS) that was launched in 1978 by NASA. This was followed by ERS-1 and ERS-2 AMI (Advance Microwave Instrument) scatterometers launched in 1991 and 1995 respectively by ESA. In 1999, NASA launched its first scanning scatterometer called "Seawind" onboard the QuickSCAT satellite. In the tandem scatterometer missions, the contribution from Indian Space Research Organization (ISRO) started with the successful launch of Oceansat-2 Scatterometer (OSCAT) in September 2009. The OSCAT continued to provide valuable information of OSVW until February 2014 when a major power failure ceased the mission. Scatsat-1 with a dedicated scatterometer payload, as a follow-on mission to Oceansat-2, was launched on 26 September, 2016 to provide continuity services of OSVW measurement capability. Being a follow-on mission it inherits the design of OSCAT, hence operates in Ku-band with 13.53 GHz central frequency and having a pencil beam design comprising of two beams with incidence angles of 49° and 57° on ground with HH and VV polarization respectively. Fig. 8(a) shows the scan geometry of SCATSAT-1. With a swath width of 1800 km this instrument covered 90% of the earth's surface in a single day. A likely cyclogenesis situation is well captured by SCATSAT ocean surface winds [Fig. 8(b)].

Recently, advance techniques and satellite sensors for the retrieval of atmospheric and ocean surface winds have emerged. Atmospheric Dynamic Mission Aeolus (ADM-Aeolus), launched by ESA in 2018 uses a Laser Doppler Instrument ALADIN to detect the atmospheric motion using precise measurements of the Rayliegh and Mie backscattering signals in the atmosphere. The ADM-Aeolus can provide the vertical profiles of atmospheric winds from surface to 30 km height with high vertical resolution (~100 m) and accuracy (~2 m/s). Another unique concept, the Cyclone Global Navigation Satellite System (CYGNSS) is a system of eight low earth orbiting satellites at 500 km altitude was launched in December 2016. CYGNSS system of satellites measures ocean surface wind fields using a bi-static scatterometry technique based on GPS signals. Each satellite receives both direct GPS signal and the signals reflected from the earth's surface. The direct signal pinpoint the microsatellite position and timing reference, while the reflected or the scattered signal provides the roughness of the sea surface that is related to the ocean surface wind conditions. A network of eight satellites ensures that the measurements of ocean surface are available more frequently, typically every 7-hours. The CYGNSS reflectometry signals are comprised of microwave L-band which has a very large wavelength (~19 cm), which means that they are not affected by clouds or heavy precipitation, enabling them to provide the measurements of very high speed winds within the core of the cyclones. (Clarizia and Ruf, 2016; Morris and Ruf, 2017; Crespo *et al.*, 2019) These wind observations are unique and valuable for understanding the coupling between ocean surface winds, convective dynamics, radiation and thermodynamic processes within the cyclone core and can help understand the processes that lead to the rapid intensification/decay of the cyclones.

5. Observations of vertical profiles of temperature and humidity from satellites

Observations of temperature and humidity profiles are critical inputs for the operational weather prediction. These parameters determine the atmospheric thermodynamic state that defines how the convective and radiative energy within the atmospheric system is exchanged and converted to kinetic energy. In other words, the knowledge of the thermodynamic state of the atmosphere is crucial for the prediction of all the weather developments. In extratropical regions where Coriolis force is strong and the atmosphere is in approximate geostrophic balance, the information about the thermodynamic structure of the atmosphere may lead to derivation of its dynamic structure. Observations from satellite based sounder instruments are indispensable for numerical weather prediction and assimilation of these



Figs. 8(a&b). (a) SCATSAT-1 scan geometry (b) Observations of SCATSAT-1 winds in a cyclogenesis situation in the Arabian Sea (23-October, 2019, 0330 UTC)

observations in the NWP models results in very high positive impact on prediction. High Resolution Infrared Sounder (HIRS) onboard NOAA satellites is such an operational sounder which uses 13 spectral channels (associated with CO_2 absorption bands, 7 channels placed around 15 um and 6 around 4.3 um) for temperature sounding and 3 channels (associated with water vapor

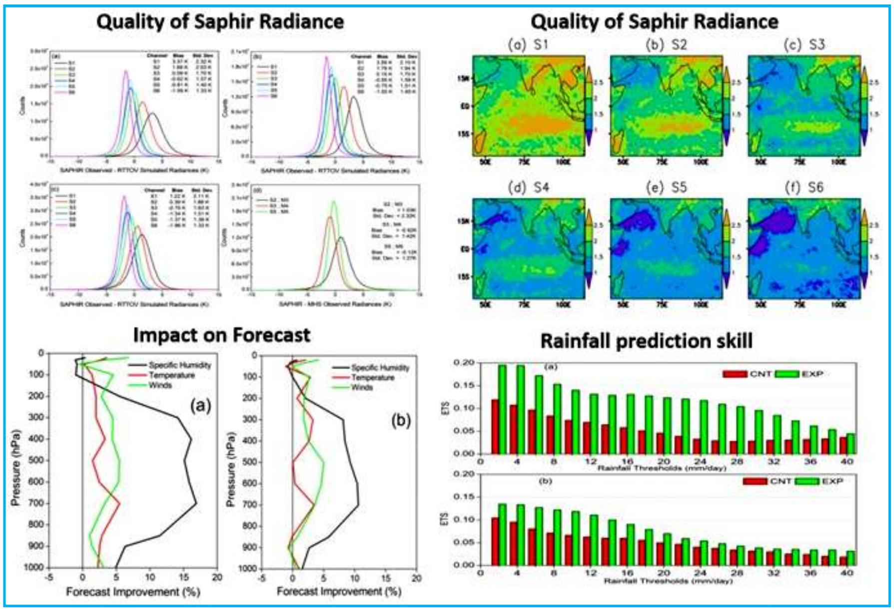


Fig. 9. Upper panel shows the quality of SAPHIR observations. The lower left panels show the impact of SAPHIR observations on the prediction of humidity (black), temperature (red) and wind (green). Lower right panel shows the impact of SAPHIR radiances on rainfall for (a) 24-H and (b) 48-H prediction. Figure is based on Singh *et al*., 2013

absorption at 8.2, 7.3 and 6.7 microns) for determining water vapor concentration in three broad vertical layers. India's geostationary satellites INSAT-3D and INSAT-3DR both are equipped with the infrared sounders with 19 channels, which are used to provide a number of useful meteorological parameters like the profiles of temperature, humidity and ozone, atmospheric stability indices, atmospheric water vapor, etc. at 1-hour interval. Hyperspectral Infrared sounders like IASI onboard MetOp series of satellites provide observations of atmospheric thermodynamic structure using more than 8000 spectral channels. One of the important applications of hyperspectral sounders (sounders with several spectral channels, usually thousands. The examples of hyperspectral sounders include AIRS, IASI, CrIS, etc.) is the calibration of old satellite observations for creation of consistent climate quality records of satellite observations some of them extending back more than 30 years. These climate quality data are used for detection of climate change, including man-made changes. Unfortunately the quality of infrared sounding is seriously affected by the presence of clouds and the retrievals are not possible if the satellite field of view is totally covered by the clouds. Such situations are quite common in the domain of tropical cyclones.

Microwave sounders have the ability to sound through cloud and hence offer nearly all-weather capability. However, their spatial resolution (both vertical and horizontal) is generally lower than that of the IR instruments. The atmospheric sounders in the microwave region operate in oxygen and water vapour resonance bands. The temperature profile retrieval is achieved by utilizing the radiometric measurements in 60 GHz complex or at 118 GHz single resonance line of oxygen absorption while humidity profile is derived from measurements at frequencies 183.3 GHz water vapour resonance region. The example of temperature sounders is Microwave Sounding Unit (MSU) and Advance Microwave Sounding Unit (AMSU-A) onboard NOAA satellites, while AMSU-B is used for humidity sounding. The latest generation of sounders, combining IR (AIRS, IASI, CrIS) and microwave (MHS, MIS, ATMS) capabilities feature improved accuracy of humidity and temperature measurements (of order 10% accuracy for humidity and below 1 K for temperature); better spatial resolution (to 1 km); and improved capabilities in the upper atmosphere. One of the prominent microwave humidity sounder is SAPHIR (Sounder for Probing Vertical Profiles of Humidity) on board Megha-Tropiques (Indo-French joint satellite), launched by the Indian Space Research Organisation on 12 October, 2011. Analysis/ forecast cycling experiments with and without SAPHIR radiances performed over the Indian region during the summer months shows considerable improvements (with moisture analysis error reduction up to 30%) in the tropospheric analyses & forecast of moisture, temperature, rainfall and winds (Singh *et al*., 2013). Fig. 9 shows the quality of SAPHIR observations and their impact on mesoscale weather prediction. Megha-Tropiques satellite operates from low inclination (20°) orbit which ensures that SAPHIR observes tropical regions more frequently compared to the satellites orbiting in polar sun-synchronous orbits. This feature results in larger impact of SAPHIR on weather prediction over the Indian region, compared to three MHS instruments put together (Singh *et al*., 2014).

Today, atmospheric sounders are used to infer a wide range of key atmospheric parameters on an operational basis (mostly on polar orbiting satellites) and their data are used by NWP models to such an extent that the satellite measurements are a vital and integral part of the global observing systems for operational meteorology. They also provide measurements of sea surface temperature, albedo, aerosols, trace gases, precipitation, snow, ice, major fires and more, with frequent global coverage. Whilst these measurements do not usually have the highest spatial resolution or accuracy, they are important sources of information and can be combined with the accurate, but more limited coverage, provided by specialist instruments.

During the past decades, a new class of atmospheric sounding technique has emerged that uses the signals of from Global Navigation Satellite System (GNSS, such as GPS or India’s regional navigation network of satellites, NAVIC) to profile the earth’s atmosphere with high vertical resolution. In this technique, the signals from GNSS satellites travel through the atmospheric layers and are received by several low earth orbiting satellites. The delay in the signal and its bending by the atmosphere is then decoded to reveal useful information about the temperature and humidity structure of the atmosphere. Since these signals are made of low frequency (large wave length) microwaves, they are least affected by the presence of clouds and even rain, thus making them suitable for obtaining the information about atmospheric thermodynamic structure under any weather condition. This technique of sounding is termed as the “Radio-Occultation (RO). These observations provide very accurate measurements of temperature (0.1 K), humidity (~10%) and ionospheric state at very high vertical resolution (~100 m). Some of the recent studies have concluded that the RO based atmospheric profiles provide very high positive impact *per observation* compared to other satellite based observations. At present, the number of RO observations are far smaller compared to other satellite observations and many operational agencies are making efforts to deploy significantly larger number of such systems in future due to high impact of these observations on weather prediction.

6. Observations of trace gases and air quality from satellites

In the recent years, there has been an emphasis on the prediction of air quality due to increase in the air pollutants in the atmosphere like SO_2, NO_2, CO_2, NO, CO, NO_x, O_3, $PM_{2.5}$ and PM_{10}. The existing numerical models are equipped with sophisticated techniques to predict accurate air quality. Similar to the weather prediction models, the accuracy of air quality models also depends of the correct initial conditions. Besides the ground measurements, the satellite-based sensors provides the data regarding wide range of air pollutant species including aerosols (Martin, 2008). Today several advanced satellites like MODerate resolution Imaging Spectroradiometer (MODIS), Visible Infrared Imaging Radiometer Suite (VIIRS), Multi-angle imaging SpectroRadiometer (MISR), Ozone Monitoring Instrument (OMI), Atmospheric infrared Sounder (AIRS), Measurements of pollution in troposphere (MOPITT), Greenhouse gases orbiting satellite (GOSAT), Orbiting carbon observatory (OCO), Tropospheric emission spectrometer (TES), Cross track Infrared Sounder (CriS) are in orbit to measure trace gases and aerosols properties relevant to air quality. A generation of UV/vis/near-IR instruments like Global Ozone Monitoring Experiment (GOME), TROPOspheric Monitoring Instrument (TROPOMI), OMI and Scanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) have spectral channels in a large wavelength (240-790 nm). The data from the different multispectral and hyperspectral channels of above-mentioned satellites is useful for understanding global, regional and local air quality over daily, seasonal, inter-annual and decadal periods (Judd *et al*., 2018).

7. Impact of satellite observations on weather prediction

The importance of satellite observation in operational weather prediction can not be overstated. Decades of satellite observations have enabled scientists to address fundamental questions about weather and climate. Satellite observations yield continually updated knowledge of the state of the atmosphere, helping meteorologists to devise models that project the weather into the future with much improved accuracy compared to pre-satellite forecasts. Consequently, 7-day forecasts have more than doubled in accuracy over the past three decades, particularly in the southern hemisphere (Bauer *et al*., 2015). These improvements are saving countless human lives and have an enormous economic value. Some of the most broadly used products from satellites are weather observations that enable forecasts. Since satellite images have become readily available, no hurricane or typhoon has gone undetected, providing affected coastal areas with advance warning and crucial time to prepare. Various kinds of new satellite sensors have been designed during the past few decades that provide new kinds of observations,

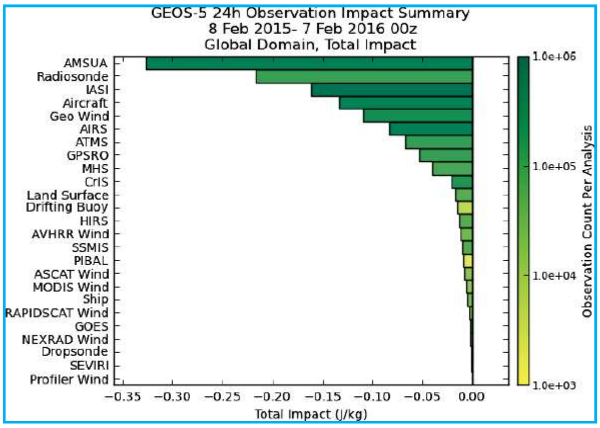
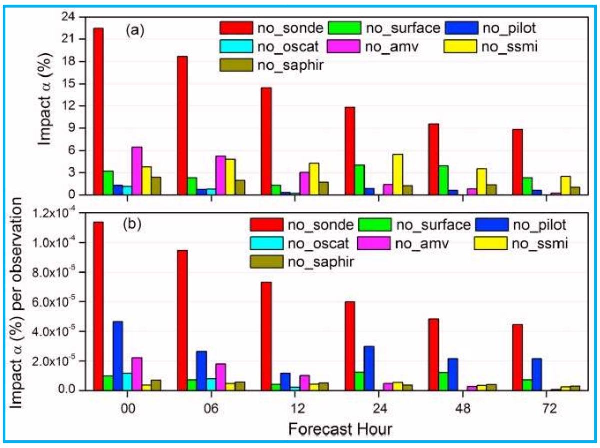


Fig. 10. Impact of different observations on error reduction of weather prediction on global scale by NWP models (negative values show higher impact). The figure is based on reports from Global Modeling and Assimilation Office, NASA-GSFC



Figs. 11(a&b). Impact of different observations on the weather prediction over monsoon region for July, 2012 (*Source* : Singh *et al*., 2014)

which are potentially beneficial for the quality and accuracy of weather prediction. Most of the operational weather prediction in current times is based on the NWP models, which use a huge volume of satellite observations by means of data assimilation. How the data from different satellite sensors impact the skill of the weather prediction, is an important question that helps to define new satellite sensors and form strategy to obtain useful observations for improved weather prediction.

There are two approaches to evaluate the impact of specific types of observation in NWP data assimilation system. In the first approach (data-denial approach), the impact of specific types of observation on analysis and forecast quality of the NWP system is assessed by performing two parallel assimilation experiments. In the first experiment, all the available observation types are assimilated and in the second experiment the specific observation type whose impact to be investigated is removed from assimilation system. The impact of the specific observation type is then estimated by comparing the accuracy of the forecasts generated from these two assimilation experiments. This approach is commonly called as the "data denial" experiment. The second approach uses the adjoint sensitivity approach in which the NWP model, its data assimilation system and their adjoints are used to quantitatively estimate the impact of each individual observation (that goes into data assimilation system) on the skill of weather forecast by the model. According to a recent report by Global Modeling and Assimilation Office (GMAO), the observations from AMSU-A (Microwave temperature sounder) provide the largest impact (on global scale) compared to any other satellite or ground-based observations. This large impact may be attributed to the global coverage of these observations (AMSU-A being placed on several satellites like NOAA-18, MetOP-A, MetOP-B, Aqua, etc. providing global and repeated observations of temperature profiles in all-weather conditions) and due to the capability of microwave observations being less sensitive to cloud and light precipitation compared to infrared sounders. Further, the observation errors of these observations is dominated by well characterized instrument noise (Weston *et al*., 2019). Radiosonde observations of temperature, humidity, geopotential height and wind profiles had second largest impact followed by hyperspectral infrared sounder IASI (Fig. 10). Radiosonde observations still show considerable impact on weather prediction because these observations resolve the vertical structure of the atmosphere better than satellite based infrared and microwave sounders. Atmospheric Motion Vector winds from Geostationary satellites and refractivity profiles from GPS-RO instruments also have significant impacts on the weather prediction. In fact the GPS-RO observations have a very large per-observation impact due to the ability of these sensors to provide the observations of the vertical structure of the atmosphere with high vertical resolution. Singh *et al*. (2014) conducted a data-denial experiment to assess the impact of various observations from satellites and ground based observation network on the forecast of the Weather Research and Forecast (WRF) model over the Asian monsoon region. This study concluded that over the Asian monsoon region, the wind observations (from satellite and non-satellite sources included) have larger impact than the mass (temperature, humidity and surface pressure) observations on the short range forecast (upto 48-hours). This study also concluded that the radiosonde observations of temperature, humidity and winds had the largest impact on the prediction [Fig. 11(a&b)]. This is due to the fact that the *in situ* observations from ground based network, although limited in terms of the coverage and frequency, provide the information of the atmospheric dynamic and thermodynamic structure with higher vertical resolution and accuracy than satellite observations. Moreover, new generation satellite observations like those from wind profiling sensors are expected to overcome this limitation of satellite observations. Singh *et al*. (2014) further concluded that after radiosonde observations, the AMV observations from geostationary satellites and humidity and ocean surface winds observations from satellite microwave radiometers like SSM/I and observations of humidity profiles from microwave sounder SAPHIR had a significant impact on the forecasts. Among satellite data, the observations of AMV had a large per-observation impact for 0-24 hour forecasts, while per-observation impact of SAPHIR observations was higher for 24-72 hour forecast.

8. Summary

Satellite observations are undoubtedly the most important source of observations for numerical weather prediction in present time. Satellites provide valuable observations of temperature and humidity profiles, surface temperature, winds etc. using different sensors and orbital configurations. Satellite observations play very important role in operational synoptic scale analysis and prediction, as well as in nowcasting of important weather events. Data assimilation experiments clearly indicate the value and advantage of satellite observations for weather prediction. On global scale, the assimilation of satellite observations like those from microwave sounders, infrared hyperspectral sounders, atmospheric motion vector winds, ocean surface scatterometer winds and thermodynamic profiles from GPS-RO show very high impact on numerical weather prediction. One of the main reasons that satellite observations have large impact on weather forecast at global scale is their ability to observe vast oceanic regions and parts of southern hemisphere where conventional observations are sparse. However, at regional scale, particularly for the Indian monsoon region, the impact of conventional radiosonde observations is still higher than satellite observations because in a cloudy environment, these observations resolve the vertical dynamic and thermodynamic structure of the atmosphere better than satellite observations. However, the observations of atmospheric temperature and humidity profiles from satellite microwave sounders, vertically integrated water vapor from microwave radiometers, ocean surface winds from microwave scatterometers and atmospheric winds from geostationary satellites have significant impact on the prediction of monsoon by NWP models. With the advancements in sensor technology, the satellite observations are getting better in terms of volume of data, spatial and spectral resolution, coverage, temporal frequency, etc. Moreover, new and innovative observations are getting available from satellites. New generation sensors like atmospheric wind profilers and GPS-RO have the capability to significantly enhance the predictability of weather. This article has described the main types of satellite observations used in numerical weather prediction, but it is not an exhaustive account. The growing importance of air quality forecasting and links to climate studies, means that information on aerosol and chemical species is also of increasing interest.

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