Precipitation is one of the most important atmospheric variables in the global hydrological cycle and plays a key role in the Earth’s energy balance. It supplies majority of the liquid water required for human life on the Earth. Precipitation is also associated with the various atmospheric phenomena both in small and large scales. Large-scale variations in its occurrence lead to droughts and floods which have vital socio-economic impacts in human perspective. Large-scale precipitation is also known to have a close relationship with global circulation anomalies [Arkin and Xie 1994].

Accurate measurement of precipitation at different temporal and spatial scales is very important for various disciplines like weather and climate modeling, agriculture and hydrological modeling, flood and drought monitoring, water management etc. The quantitative assessment of precipitation is also needed to improve the understanding of the behavior of global energy and circulation patterns as well as the nature of climate variability. The major portion of the global precipitation occurs over the vast oceans and has great importance for the various hydro-meteorological, oceanographic and climatological applications.

This chapter gives a brief description of the recent developments related to satellite based rainfall estimation methods in perspective of the present work. The chapter encompass an appraisal of the work happened in the fields of rainfall estimation using satellite based IR, MW and applications of satellite-derived rainfall measurements.
regarding the assessment and long-term change studies over the Indian summer monsoon region.

2.1 IR frequency based rainfall estimation

Satellite-based rainfall estimation at high spatial and temporal scales has wider applications in meteorology and hydrology as the conventional rain gauges and ground-based radars give sparse measurements. Most of the satellite-based rainfall estimation methods are carried out using MW and IR bands of the EM spectrum. Even though MW based rainfall estimation is comparatively more accurate, it has low temporal resolution because they are generally mounted on low-earth polar or inclined orbit satellites. IR-based sensors mounted on geostationary satellites have high temporal sampling. In this context IR-based rainfall estimation becomes highly important for the satellite meteorological community. Majority of the IR-based rainfall estimation algorithms are based on establishing a relation between cloud top temperature and surface rainfall. Cloud top temperature has only an indirect relationship with surface rainfall and hence the correlation between them is poor. Arkin [1979] developed the cloud indexing method widely known as Geostationary Operational Environmental Satellite (GOES) Precipitation Index (GPI), which is based on percentage of colder cloudy pixels classified on the basis of thresholding to estimate precipitation. Arkin [1979] developed this method during the GARP (Global Atmosphere Research Programme) Atlantic Tropical Experiment (GATE) on the basis of a high correlation between radar-estimated precipitation and fraction of the area colder than 235 K in the IR. Arkin and Meisner [1987] assigns these areas a constant rain rate of 3 mm h\(^{-1}\), which they tested for tropical precipitation over 2.5° × 2.5° areas. This method is further improved by Adler et al. [1994] and Xu et al. [1999] by applying correction factors to the basic methodology derived from the intercomparison of GPI rain rate and other MW rain data. Vicente et al. [1998] has proposed auto-estimator algorithm which uses a power law based regression method between cloud top temperature and rainfall. The
algorithm also uses a moisture factor and a cloud growth factor. \cite{Ba2001} developed GOES multi-spectral rainfall algorithm (GMSRA). This algorithm combined the information from five channels on the GOES: visible (0.65 \( \mu \text{m} \)), near infrared (3.9 \( \mu \text{m} \)), water vapour (6.7 \( \mu \text{m} \)), and window channels (11 \( \mu \text{m} \) and 12 \( \mu \text{m} \)). The final rain rate is obtained by multiplying the mean rain rate with probability of rain and further adjusted by a moisture factor.

\cite{Mishra2010} developed an algorithm for Indian region using Meteosat IR brightness temperature (Tb) and Tropical Rainfall Measuring Mission (TRMM) - precipitation radar (PR) rain rate. \cite{Prakash2009, Prakash2010} developed and validated (daily and monthly scales) a similar algorithm specific to Indian region. They observed that simple IR-based algorithms underestimate rainfall over the orographic regions like northeast and southwest India. Simple IR-based algorithms have limitations as the cloud top temperature to rain relation may not hold good for different topographic terrains. One of the major drawbacks of the IR-based algorithm is the underestimation of orographic precipitation. Orographic precipitation refers to the rain and snow resulting from flow over terrain. The convective system happening near mountains are affected by channelling of airflow near mountains, capping of moist boundary layers by flow dropping from higher terrain \cite{Houze2012}. Large number of physical processes governs the orographic precipitation encompassing fluid dynamics, thermodynamics and micron scale cloud processes \cite{Gerald2005}. Such convoluting complex processes make orographic precipitation estimation a difficult task. \cite{Suprit2008} developed a scheme of using multivariate interpolation method with elevation as a variable to generate rainfall maps over the Indian west coast. Tall convective clouds are not formed in the orographic regions and the global rain rate regression equations do not represent the actual rainfall occurring in these regions. Regional algorithms for orographic regions can be a solution for this problem. Another important aspect of IR-based algorithm is the rain, no-rain distinction where an important feature of convective clouds can be employed such as the cloud growth index, which can further enhance the basic rain rate derived by the regression algorithm.
2.2 MW frequency based rainfall estimation

Since the advent of spaceborne passive MW sensors; rainfall retrieval using these sensors is of major interest. However, due to high spatio-temporal variability, accurate estimation of rainfall is a difficult task. Emission and scattering are frequently adopted to estimate rainfall intensity from MW data, [Janowiak et al., 1995]. Emission based algorithms use emitted radiations from atmospheric liquid particles to estimate the rainfall intensity. Such algorithms employ the sensitivity of the radiation to surface emissivity. This applies well in oceanic regions as sea surface emissivity is mostly low and relatively homogeneous. The rainfall retrieval in land area gets complicated as the signal signature from the liquid hydrometeors is greatly contaminated due to the high and variable emissivity of the land surface. Scattering based algorithms estimate the rainfall intensity by measuring the extinction of the MW radiation caused by the particles of liquid water or ice. Tb depression due to the scattering from the upper portion of the clouds is readily observed and is free of the varying features of land area. The scattering can be converted into rainfall rate using statistical relation between the ice aloft and rain falling below the base of cloud. The scattering signatures can be separated from absorbing surfaces using the scattering Tb characteristics. This signature is frequently obtained by comparing low frequency measurement (19, 22 GHz) with high frequency measurements (85 GHz) [Ferraro et al., 1994, Ferraro and Marks, 1995]. From this signature an empirical relation can be obtained which is termed as Scattering Index (SI). This index can be used as a representative predictor as it can act as a function of rain rate. Various spaceborne platforms are operational which can be employed to estimate rain. In this thesis, SSM/I measured Tb values are considered due to the similarity of SSM/I sensor channels to Megha-Tropiques MADRAS sensor. Various algorithms have been developed to estimate rainfall by making variable use of MW channels and polarizations. An overview of passive MW methods is given by [Wilheit et al., 1994]. Kidd [1998] have examined advantages and disadvantages of statistically derived, empirically calibrated algorithms. Grody [1991] developed global model to estimate rain
using SI for SSM/I microwave radiometer. This algorithm is further refined by Ferraro et al. [1994], Ferraro and Marks [1995], Ferraro et al. [1996] and validated over the open ocean by Greene et al. [1997]. They used 19V, 22V and 85V for deriving SI. An empirical relation is established between the derived SI and rain rate obtained from PR-2A25 product. Polarization Corrected temperature (PCT) defined by Spencer et al. [1989] is also a very useful tool for rain estimation. Todd and Bailey [1995], in their study, has shown the usefulness of the PCT85 algorithm to estimate rainfall in maritime mid-latitude regions using SSM/I measurements. Kumar et al. [2009] in their evaluation of precipitation features over Indian land and oceanic regions has suggested the use of PCT as one of the suitable predictor variable for the development of operational rainfall retrieval algorithm from MADRAS for the Indo-French Megha-Tropiques project.

Yao et al. [2001] has successfully demonstrated the usefulness of SI and PCT for rainfall retrieval on the Tibetan Plateau. Recent research has shown that artificial neural network (ANN) techniques can be successfully used for the precipitation estimation from radiometric measurements. ANN is a non-parametric method which can be used for representing the complex relationship between radiometric measurements and radar rainfall. Hsu et al. [1997] developed a system for Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) infrared satellite measurements and ground-surface information. Sarma et al. [2008] has used an ANN based rainfall retrieval algorithm for estimating rain over Indian land and oceanic regions. They utilized TRMM-TMI channels along with PCT85 as input channels and PR (2A25) rain rate data product as output. Tapiador et al. [2004] developed and evaluated a new operational procedure to produce half-hourly rainfall estimates at 0.1° spatial resolution using neural networks based approach utilizing passive microwave and infrared satellite measurements.
2.3 Applications of satellite based rainfall measurements

The rainfall monitoring using the conventional networks based on ground measurements becomes a difficult task; especially when the data is required in near real-time. Study of long-term changes in rainfall over oceanic regions is another challenging task due to dearth of in situ measurements. Satellite-based rainfall measurements can complement in situ observations for such applications. In this section, developments in rainfall monitoring and studies of long-term changes in rainfall over Indian monsoon region is briefly described.

2.3.1 Monsoon monitoring using space-borne rainfall measurements

Reliable information of rainfall over India is very important for a wide range of applications like agriculture, water resource managements, hydrology, etc. Rainfall is highly variable in both space and time. However, uneven distributions of ground-truth data, especially over the unpopulated regions, limit its use at global as well as regional scales. Meteorological satellites give the alternate solution in terms of better homogeneous spatio-temporal resolution. The primary aim of satellite rainfall monitoring is to provide information on rainfall occurrence, amount and distribution over the globe for meteorology, climatology, hydrology and environmental sciences at all scales [Kidd and Levizzani, 2011, Tapiador et al., 2012].

In India, a wide range of weather conditions exists over larger geographical scale with variable topographical features. India’s unique geography and geology, for example the Himalayas in the north and the Thar Desert in the northwest, strongly influence its climate. The Indian sub-continent is characterized by unstable monsoonal and other weather conditions like sporadic droughts, floods, cyclones and other natural disasters. The southwest or summer monsoon, a 4-month period from June to September when massive convective activity dominates India’s weather, is the Earth’s most productive wet season. A product of southeast trade winds originating from a high-pressure mass centered over the southern Indian Ocean (Mascarene High), the monsoon rainfall
contributes about 80% of India’s annual rainfall [Bagla and Prasad, 2006]. Monsoon rainfall influences the economy of the South Asia. In India, agriculture employs 600 million people and contributes about 17% of the national Gross Domestic Product (GDP) [Gadgil and Rajeevan, 2008]. Above normal monsoon activity is generally correlated with successful economy and below normal monsoon activity is associated with widespread agricultural losses and affects the economy. Hence, the accurate estimation of rainfall has great importance in the Indian perspective. Since the advent of earth-observation satellites, Indian monsoon and its variability are extensively monitored using satellite measurements [Kelkar and Rao, 1990; Haque and Lal, 1991; Varma and Bhandari, 1992].

Geostationary satellite observations, currently limited to VIS and IR wavelengths, are significant for rainfall estimation and monitoring as they offer systematic observations of cloud systems. A number of algorithms are developed so far which use VIS or/and IR observations for rainfall retrieval. The Geostationary Operational Environmental Satellite (GOES) Precipitation Index (GPI) developed by Arkin and Meisner [1987] is one of the most widely used approaches based on IR measurements to estimate rainfall at larger spatial and temporal scales. However, this algorithm is not capable to distinguish thin cirrus clouds from deep convective ones. Ba and Gruber [2001] developed the GOES Multispectral Rainfall Algorithm (GMSRA) which uses 5 channels of GOES (0.65, 3.9, 6.7, 11 and 12 µm) to estimate rainfall. The rainfall rate for each raining cloud group is determined by its cloud-top temperature and is adjusted by a moisture factor. Nowadays, the cloud classification schemes using IR and VIS satellite measurements are quite improved [Roca et al., 2002; Berendes et al., 2008; Delgado et al., 2008]. In comparison to using a single thermal IR band, utilizing multispectral data and proper cloud classification scheme has thus the potential to improve rain detection and estimation by identifying warm rainfall and thin cirrus clouds [Behrangi et al., 2010].

At passive MW frequencies, precipitation particles are the main source of attenuation of upwelling radiation. Contrary to IR, MW rain rates are based on measurements that sense precipitation in clouds and do not rely on cloud-top temperature. Thus, MW
techniques in general can be termed as more direct than those based on VIS/IR radiation. The emission of radiation from the atmospheric particles results in an increase of the signal received by the sensor while at the same time; the scattering due to hydrometeors reduces the radiation stream. But the different radiative characteristics of land and sea surfaces underneath make the problem more complex. While the brightness temperatures (Tbs) at 89 GHz may be affected by surface features and the cold water surface beneath and mislead to be convective clouds, the Tbs at 150 GHz are weakly influenced by surface characteristics. Moreover, the MW-based approaches have some problems in the detection of orographic warm rain having deficient ice particles [Huffman et al., 2010]. Several algorithms are available that make variable use of MW channels and polarizations for rainfall estimation. Overview of passive MW rainfall estimation methods over land and oceanic regions are outlined by Wilheit et al. [1994], Petty [1995], Gairola et al. [2003].

Since IR measurements are continuously available from geostationary and low-earth orbiting satellites with large viewing areas, it seems reasonable to use them as additional information to improve the rainfall estimation from the MW radiometry. Some algorithms to integrate MW and IR observations for rainfall retrieval were described by Gairola and Krishnamurti [1992], Todd et al. [2001], Gairola et al. [2004]. A complete overview of the present status of satellite-based rainfall retrieval methods is recently outlined by Kidd and Levizzani [2011], Tapiador et al. [2012].

Assessment and monitoring of Indian summer monsoon rain using satellite data is of great importance for agricultural applications disaster management and weather forecasting. INSAT Multi-spectral Rainfall Algorithm (IMSRA) is an operational product for the estimation of rain [Prakash et al., 2009, 2010, Mishra et al. 2010] at the India Meteorological Department (IMD) and Indian Space Research Organisation (ISRO) and used for various applications. Unlike GPI that gives rainfall at 1° × 1° latitude/longitude resolution, IMSRA provides rainfall estimates and its distributions at higher spatial resolution (0.25°× 0.25° latitude/longitude). Moreover, IMSRA algorithm uses a proper regional (over Indian region) cloud classification scheme developed by
Roca et al. [2002] and using Kalpana-1 IR and WV channels and calibrated by the Tropical Rainfall Measuring Mission (TRMM) - Precipitation Radar (PR) MW data for the retrieval of rainfall. This technique gives better quantitative and qualitative performance as compared to the GPI method [Mishra et al., 2010; Roy et al., 2012].

2.3.2 Long-term changes in the summer monsoon rainfall over the equatorial trough region

One of the important components of the Indian summer monsoon is the equatorial trough (ET), situated over the warm waters of the equatorial Indian Ocean between 60° E-100° E and 0° E-10° S. The inter-tropical convergence zone (ITCZ) starts its intraseasonal northward propagation from this region during the summer monsoon season [Sikka and Gadgil, 1980]. It is generally observed that the rainfall over the ET and continental monsoon trough show a seesaw pattern on intraseasonal time scales. Joseph [1990] demonstrated that the convective activity over the north Indian Ocean and cyclogenesis over the northwest Pacific Ocean are components of 30-50 day cycle which is responsible for the intraseasonal variability of the Indian summer monsoon rainfall (ISMR). Johri and Prasad [1990] reported the inverse relationship between the intensity of the southern hemispheric ET and the ISMR activity. Moreover, Ramesh Kumar et al. [2005] noticed that about 73% of the breaks in monsoon events are associated with the rainfall more than 30 mm pentad\(^{-1}\) over the ET region. Using the Global Precipitation Climatology Project (GPCP) dataset, they showed that the eastern equatorial trough (EET) becomes more convective during the break monsoon conditions over the middle India (MI) in non-El Nino years whereas the western equatorial trough (WET) is better correlated with the MI rainfall during the El Nino years. These studies reveal a close relationship between the monsoon rainfall over the ET and ISMR. Furthermore, recent studies suggest the long-term changes in the ISMR during current global warming era [Kulkarni, 2012; Rajeevan et al., 2008; Ramesh Kumar et al., 2009; Naidu et al., 2009; Naidu et al., 2011; Kulkarni, 2012]. Kulkarni [2012] demonstrated that the frequency
and intensity of extreme rainfall events during the summer monsoon season have increased over the MI since the middle of the twentieth century. Moreover, Rajeevan et al. [2008] noticed that the summer monsoon rainfall over the MI shows significant interannual and interdecadal variations associated with the variations in the sea surface temperature over the tropical Indian Ocean. The duration and frequency of the break monsoon phases during the peak monsoon months of July and August over India show a significant increasing trend in association with the intensification of near ET and moisture convergence over the eastern Indian Ocean due to large-scale ocean-atmosphere processes [Ramesh Kumar et al., 2009]. Furthermore, the substantial decrease in the ISMR between 1976 and 2004 is more recently reported by Kulkarni [2012]. But, such long-term analysis of rainfall over the large oceanic region is not reported so far, which affects the ISMR significantly, due to paucity of in situ observations. As rainfall over the ET is linked to the ISMR, it becomes important to investigate whether the summer monsoon rainfall over the ET shows any long-term change. With the launch of earth observation satellites, the rainfall estimation techniques have advanced quite rapidly and a number of multisatellite rainfall products with reasonable accuracy are now available to study the rainfall characteristics and its variations over the ocean as well as land. The one of the major advantages of satellite-based rainfall data is its homogenous spatial and temporal availability. But, the satellite-based rainfall data are available only since 1979.