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Rainfall estimation using spaceborne microwave radar and radiometric measurements

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सार – इस शोध पत्र में मुख्यतः अंतरिक्ष से निष्क्रिय और सक्रिय सूक्ष्म तरंग मापों से हाल ही की कुछ सूदूर संवेदी तकनीकों का विवेचन वर्षा के आकलन हेतु किया गया है। ई.सी.एम.डब्ल्यू.एफ. से प्राप्त आँकडों और मेसोस्केल के निदर्शों का उपयोग करते हुए विकिरणित अंतरण मॉडलिंग का अनुसरण करते हुए उन्नत पद्धतियों पर आधारित संवेदी विश्लेषण को यहाँ प्रस्तुत किया गया है। उपग्रह सूक्ष्म तरंग मापों, मुख्यतः बहुसमाश्रयण और न्यूरल संजालों से प्राप्त वर्षा की प्रतिलोमी पद्धतियों की संवेदी विश्लेषण के आधार पर यहाँ चर्चा की गई है। टी. आर.एम.एम.–टी.एम.आई, डी.एम.एस.पी.–एस.एस.एम./ आई. और भारतीय आई.आर.एस.–पी.4–एम.एस.एम.आर. रेडियोमीट्रिक चैनलों से अनेक चैलनों को मापने के लिए अनुकरण का उपयोग किया गया है और वास्तविक प्रेक्षणों के साथ उनका मूल्यांकन किया गया है। वर्षा के पैटर्नों के कुछ नमूनों की चर्चा की गई है और उनकी तुलना टी. आर.एम.एम. रेडियोमीटर और रेडार से मानक उत्पादों के साथ की गई है। लगातार तीन वर्षों के विश्लेषण में से मानसून ऋतु के विशेष अगस्त के महीने में वर्षा की कमी से एम.एस.एम.आर. से प्राप्त वर्षा की मासिक दरों के नमूनों से भी गुणात्मक और मात्रात्मक रूप का पता चलता है। यद्यपि वर्षा आकलन का स्तर सर्वांगपूर्ण नहीं है तो भी भविष्य के मेघाट्रापिक्स और भूमंडलीय वर्षा मिशन जैसे मिशनों के लिए तैयारी की दृष्टि से इसे यहाँ प्रस्तुत किया गया है।

ABSTRACT. The present paper deals with some of the recent remote sensing techniques for the estimation of rainfall, mainly from passive and active microwave measurements from space. The sensitivity analysis based on forward approach following the radiative transfer modelling using data from ECMWF and mesoscale models is presented. The inverse methods of retrieving rainfall from satellite microwave measurements mainly from the multiple regression and neural networks are presented based on the sensitivity analysis. The simulations are carried out for the multichannel measurements from TRMM-TMI, DMSP-SSM/I and Indian IRS-P4-MSMR radiometric channels and are assessed with the actual observations thereof. A few examples of the rainfall patterns are described and compared with some of the standard products from TRMM radiometer and radar. The examples of monthly rain rates derived from MSMR, are also shown qualitatively and quantitatively, for a typical monsoon month of August for brevity out of three consecutive years of analysis. Though the status of rainfall estimation presented is not exhaustive one, it is presented in view of the preparedness for the future missions like, Megha-Tropiques and Global Precipitation Mission.

Key words – Radiative transfer, Rainfall, Microwave radar, Radiometer, Polarization, Neural network, Remote sensing.

1. Introduction

The spaceborne measurement and monitoring of rainfall is a topic of major interest since it influences the global hydrological cycle and the nature of climate variability. Rainfall is also associated with various atmospheric phenomena both in small and large scale. Assessment of precipitation contributes to improved weather forecasting, in small and large spatial scales. Rainfall is a highly discontinuous process both in space and time. Accurate and reliable measurements of rainfall over extensive areas of oceans still present a formidable challenge to meteorologists. With best efforts, the ground based measurements cover only a small fraction of the globe (< 10%). In addition to large uncertainties in the derived estimates, there are problems related to non-uniformities of coverage, quality and logistics of operations etc. The global observations and monitoring of clouds from space using remote sensing techniques, has the potential of providing global rainfall information on desired time and space scales.

The development of rainfall estimation techniques based on remote sensing measurements from space has registered tremendous progress and realistic achievements over the last three decades. Like any other fields of endeavor, however, there are limitations too and newer and better measurement and estimation techniques are developed on a continuous basis. The ability of space based measurements to provide a 2-D distribution of rainfall over large areas with sufficiently frequent sampling in time, especially over data sparse oceanic regions, facilitates us with a tremendously powerful tool to detect, closely monitor monsoon system and study the genesis and evolution of the furious tropical cyclonic storm.

Most tropical rainfall that has an impact over more than world's two-third population occurs as a result of convective processes. For years, the need for diabetic initialization of precipitation in numerical models had been fulfilled by the infrared measurements by polar and geostationary satellites, since IR/VI measurements are continuously available with larger viewing areas and high space-time resolution. In general, techniques are based on an empirical relation between cloud top albedo, cloud top temperature and rainfall measured at the ground. Combining positive features of different techniques, it may be possible to provide rainfall estimation with accuracies approaching ~30-40 %, when estimates are averaged over sufficiently large time and space scales. However, due to the intrinsically indirect nature of sensing rainfall, the visible/IR algorithms are not portable from one season to another, or from one region of globe to another etc. Over the Indian region, monthly/daily average rainfall information in the form of quantitative precipitation estimate (QPEs) maps with spatial resolution of 2.5° × 2.5° are produced on a regular basis since 1986 using INSAT-VHRR IR images collected eight times daily (Arkin *et al*., 1989, Kelker, 1994). These maps are produced following the Arkin and Miesner (1987) technique.

The microwave measurements from satellites have been recognized for more applications due to their penetration capability of clouds and to some extent rain, and thus provide another source for rainfall estimation over both land and oceans. The applications that benefit from microwave rainfall estimates include weather forecasting, climate analysis and hydrological studies. The successful use of passive microwave-based rain estimates in applications from various fields encourages the continuation of efforts toward the development of more advanced rain retrieval algorithms, despite obvious limitations associated with the low sampling frequency of orbiting platforms carrying PM sensors. The recent availability of detailed precipitation observations jointly obtained by the first space-borne precipitation radar (PR) and a multifrequency passive microwave radiometer, the TRMM Microwave Imager (TMI), on NASA-USA and NASDA-Japan’s Tropical Rainfall Measuring Mission (TRMM) satellite offers an excellent opportunity for understanding several atmospheric processes. It can also supplement the observations from the IR/VIS measurements if properly integrated/unified and brings out the finer details than any one alone. The series of Defense Meteorological Satellite Program (DMSP) – SSM/I as an important microwave sensor offers yet another source for the rainfall estimation with almost similar frequencies from 15 to 85 GHz range. The higher frequency in recent microwave radiometers (37 and 85 GHz) offers to capture the scattering properties of liquid hydrometeors. The 10 GHz frequency in TRMM-TMI is of an additional advantage both for the retrieval of rainfall and surface parameters. This opportunity of lower MW frequencies have also been provided in Indian Remote Sensing (IRS-P4) satellite having sensitivity to both rainfall and sea surface roughness. In their recent study, Aonashi and Liu (2000) also found the importance of 10 GHz in heavy precipitation retrievals using radiative transfer model by Liu (1998). Present paper highlights the recent developments in the rainfall estimation mainly from microwave remote sensing measurements from Indian and International satellites.

2. Microwave measurements of rain

Satellite microwave radiometers have been successfully used to monitor the temporal and spatial variations of sea surface and atmospheric properties on global scale since the launch of the Soviet Cosmos-243 instrument in 1969. Grody (1993) provided a complete review of past, present and planned future satellite microwave instruments, including their operational characteristics and applications. Microwaves, due to their long wavelengths achieve better penetration and interact strongly with the raindrops present in the cloud. These measurements provide a direct physical basis for rain estimation. Also microwaves are largely intensive to the presence of ice in thin cirrus clouds.

For the retrieval of rainfall from passive microwave radiometers, a variety of theoretical approaches have been utilized. These includes the radiative transfer simulation of variety of atmospheres and then followed by development of retrieval algorithms. Despite various attempts in this direction, still there are differences in rainfall estimates - followed from different rainfall algorithms (Smith *et al*. 1998, Wilheit *et al*. 1994). There are differences in treating the attenuation and scattering in the signal, separating rainfall response from surface variability, accounting for rainfall inhomogeniety in the radiometric field of view; and distinguishing between rain events and non precipitating cloud liquid water. The vertical structure of precipitation is extremely important in determining upwelling microwave radiances and it cannot, unfortunately, be easily characterized in terms a single unknown variable. Predefined cloud structures, however, may be utilized to overcome this problem. Cloud resolving models such as the Goddard Cumulus Ensemble model (GCE), which is a cloud microphysical model developed mainly by Tao and Simpson, (1993) or Tripoli, (1992), are used to supply the required cloud structures. For each cloud model time step, radiative transfer computations are performed at high resolution. This Tb field is then convolved with the approximate sensor antenna gain function to produce a large set of possible cloud profiles along with their respective passive microwave Tb's.

The precipitation monitoring capability of microwave sensors have been demonstrated by many investigators. The utilization of microwave brightness temperature was initiated with the launch of Electrically Scanning Microwave Radiometer (ESMR) instruments on Nimbus-5, with a center frequency of 19.35 GHz. Allison *et al.* (1974) used ESMR to map rainfall areas in the hurricane and tropical disturbances. Later, Olson (1989) used Nimbus-7 SMMR for physical retrieval of rainfall rate during the tropical cyclones. Earlier Katsaros *et al.* (1989) and Gairola *et al.* (1988, 1992, 1994) have used SSM/I, Nimbus and Seasat SMMR data for locating the deep depressions, cyclonic storms and atmospheric fronts using satellite derived parameters like perceptible water, liquid water, rainfall rate, sea surface temperature and surface wind speed. There are numerous studies and investigations reported using SMMR measurements (Prabhakara *et al.*, 1989; Spencer *et al.*, 1989). Wilheit *et al.* (1991) used multichannel microwave measurements for the rainfall retrieval using SSM/I. Negri *et al.* (1989) discussed meteorological interpretations with the false color images of 85 GHz (HH, VV) and 37 GHz (VV) for precipitation processes and clarification of land, ocean and sea ice types with SSM/I. Berg and Chase (1992) estimated and analyze interannual variations in the tropical oceanic rainfall using data from SSM/I. Further studies (Rao and MacArthur 1994; Rao and McCoy, 1997; Rodgers and Piers, 1994) have related information from microwave data to tropical cyclone intensity and intensity change with varying degrees of success. Liu and Curry (1998) investigated the relationship between emission and scattering signal in SSM/I data. Currently, various techniques are used for rainfall retrieval like non-linear regression (Bauer and Schlussel, 1993; Ferraro and Marks, 1995, Varma *et al.*, 1999, etc.), Bayesian approach *e.g.* (Kummerow and Giglio, 1995) and neural network approach (Tsintikdis *et al.*, 1997; Gairola *et al.*, 2001; Bauer *et al.*, 2001, etc.). So far, microwave sensor's capabilities are limited due to their observations only in low orbiting satellites and non-portability to the geosynchronous orbits. Thus utilizing the frequency and polarization discrimination of passive microwave measurements from space, it has been successfully demonstrated that satisfactory rainfall retrievals both over land and oceanic areas are feasible. It has been seen that satellite estimates based on passive measurements portray the rainfall as accurately as radar both in terms of relative intensity and spatial distribution.

As far as the applications are concerned, the microwave remote sensing of rainfall and humidity profiles is being recognized as tremendous success in providing a comprehensive description of climate systems. Most recently, Hou *et al.* (2000, 2001) demonstrated that assimilating both precipitation and total precipitable water from TRMM can significantly improve the quality of global analysis. Particularly in the tropical areas, the most intensive energy exchanges occur through the radiative exchanges, latent heat exchanges, transport of constituents and energy through dynamic processes. Microwave measurements from satellites have shown to provide rainfall, water vapour and humidity profiles simultaneously for these purposes over the tropical regions (Gairola *et al.* 1985, 1996 Basu *et al.*, 1995). Precipitation from the algorithm by Gairola and Krishnamurti (1992), that uses different satellites co-registered spatially and temporally (about 1° × 1° grid) have been used by Krishnamurti *et al.* (1994) with global spectral model. A very large impact in the initialization and medium range forecast was observed when the microwave data from spaceborne radiometers were assimilated. The most important results found were the improved now-casting skill from the physical initialization and in generating mesoscale rain structures (Krishnamurti *et al.*, 1996) when SSM/I data was included. It has further demonstrated a major improvement in the one day rainfall forecast over the global tropics from physical initialization with improved rainfall by integrated IR and microwave observations by satellites. More recent applications of the rainfall from various microwave sensors of TRMM includes, the diurnal variation of rainfall over the global tropics (Imaoka and Spencer, 2000), characterizing the 1997-98-El Nino signatures in Pacific and Indian Ocean by Gairola *et al.* (2002) to name a few.

3. Microwave characteristics of rainfall – land and oceans

The issue of rainfall estimation over the land and oceans is of high importance due to the large differences in monitoring capabilities even as on today. While the ocean surface has a low microwave emissivity ~0.5 that produces good contrast of atmospheric phenomena against a low brightness temperature background, the land surface emissivities are usually close to unity, making atmospheric features much more difficult to identify against a higher brightness temperature background. In addition, the land surface emissivities are not only variable in space and time but also very complex to model since they are modulated by vegetation, topography, flooding and snow, among other factors. Further limitations also originate in the multiple hydrometeor profiles that can be associated with a set of multifrequency microwave measurements (*i.e.*, lack of unique solution). The indeterminacy over land retrievals is also due to the warm background brightness temperatures that limit the use of lower-frequency observations (*i.e.*, 10, 19 and 22 GHz). Three different approaches to retrieving rainfall from passive satellite microwave measurements are utilized: emission based algorithms, scattering based algorithms and retrievals utilizing a radiative transfer model (which combine emission and scattering). Emission based rainfall retrieval utilizes the fact that rain cloud emit more radiation than does the background ocean and cloud–free atmosphere. In certain rainfall range the brightness temperature will increase with rainfall rate. Scattering-based rainfall retrieval techniques utilize the scattering by ice particles at the rain cloud top, implicitly assuming that a large amount of ice particle at cloud top is associated with the heavier rainfall. The polarization diversity of passive microwave measurements from space (polarization from surface and de-polarization from hydrometeors) has been utilized satisfactorily for rainfall retrievals both over land and oceanic areas.

In total, the applications that benefited from microwave rainfall estimates include weather forecasting, climate analysis and hydrological studies. Many investigators have successfully attempted rainfall retrieval over the oceans. In the beginning an algorithm for oceanic rainfall was developed for 19.35 GHz observations from Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR) by Wilheit *et al.*(1977). Further modification to the algorithm was made by using statistical technique for multichannel data in the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) data (Wilheit and Chang 1980). Wentz and Spencer (1998) presented an all weather unified ocean algorithm for rain retrievals. Some of the recent research related to the retrieval of geophysical parameters over land could be followed from Aires *et al.*, 2001 and Yao *et al.* 2001. The 85 GHz channel in DMSP-SSM/I (F10, F11, F13 and F14) and TRMM-TMI offers better possibilities of rainfall estimation. Despite the obvious limitations associated with the low sampling frequency of orbiting platforms carrying PM sensors and well known “beam filling problem” which is assumed to be largest error source in instantaneous rainfall retrieval (Petty, 1994; Wilheit *et al.*, 1994), the successful use of passive microwave-based rain estimates in applications from various fields, encourages the continuation of efforts towards the development of more advanced rain retrieval algorithms. The recent availability of detailed precipitation observations jointly obtained by the first space-borne precipitation radar (PR) and a multifrequency passive microwave radiometer, TMI on NASA and NASDA’s TRMM satellite (Simpson *et al.*, 1996) offers such an excellent opportunity for studying three dimensional structures of rainfall.

Some algorithms, referred to as physically based, are derived using radiative transfer calculations through cloud-model simulated fields (Smith *et al.*, 1994a, Kummerow and Giglio 1995, Haferman *et al.*, 1997). The GCE model by Tao and Simpson (1993) has been used in estimating rainfall over both land and oceans and the algorithm is popularly known as Goddard Profiling (GPROF) algorithm. The profiling algorithm being used by TMI makes use of Bayesian methodology to relate the multichannel brightness temperatures to the hydrometeors provided in a pre-existing database. The pure physically based algorithms were mainly investigated in over ocean retrievals. Such physically based retrieval over land are few and have not indicated better performance relative to purely statistical algorithms (Druen and Heinemann 1998), which are conceptually simpler and more practical for applications.

4. Satellite systems and data

4.1. *TRMM – TMI and PR*

TRMM was launched on 27 November, 1997, by United States and Japan, to carry out a systematic study of tropical rainfall required for major strides in weather and climate research. The TRMM includes three principal types of instruments. The first and most innovative of the three is the first quantitative precipitation radar (PR) in space, providing height profile of precipitation content from which the profile of latent heat release can be estimated. The second type of instrument is a combination of cross track scanning multichannel dual polarization passive TRMM Microwave Imaging radiometer (TMI). The radiometers give relatively better measurement of rainfall rates over oceans than over land where the inhomogeneous surface emissivity makes interpretation difficult. A complementary Advanced Very High Resolution Radiometer (AVHRR) is also included in the TRMM instrument, which is a VIS and IR sensor for rain estimation called VIRS. Additionally, the TRMM satellite also carries two related instruments *viz*. Cloud and Earth's Radiant Energy System (CERES) and the Lightening Imaging System (LIS). The space segment of TRMM is a satellite in 350 km (now augmented to ~402 km) circular orbit with 35° inclination angle. The combination of satellite borne passive and active sensors deployed on TRMM provides critical information regarding the three dimensional distribution of precipitation and heating in the tropics (Simpson *et al.*, 1996). The complete description of sensor package of TRMM and some of the performance characteristics of the TMI channels are provided by Kummerow *et al.*, 1998.

4.2. *SSM/I*

A major milestone was achieved in the satellite based rain rate estimation when DMSP-F8 in June 1987, carried onboard a Special Sensor Microwave/Imager (SSM/I) (Hollinger *et al*., 1987). Since then all series of DMSP-SSM/I has been carrying seven separate total power radiometers at frequencies of 19.35, 22.235, 37 and 85.5 GHz, respectively. Polarization measurements are taken at 19.35, 37 and 85 GHz and only vertical polarization is observed in 22.235 GHz. The advantage of polarization at lower and higher frequencies is that their difference characterize the emission and scattering signatures from the hydrometeors in atmosphere. The spatial resolution at these frequencies of SSM/I ranges from 69 × 43 km at 19.35 GHz to 15 × 13 km at 85 GHz. The SSM/I had a conical scan with a swath width of about 1400 km on the Earth's surface and the antenna beam intersect the Earth's surface at an angle of 53°. Local sampling occurs approximately twice a day, during early morning and late afternoon. Currently there are three SSM/I sensors operational on F11, F13 and F14 DMSP series of satellites which provide very important data sets for rainfall estimation in different equatorial crossing times. Several algorithms have been developed for SSM/I sensors. One of the algorithms for SSM/I rainfall retrieval was recently used by Varma *et al*. (2002). Precipitation retrievals using SSM/I, however, proved to be less accurate for strong precipitation (Smith *et al*., 1998).

4.3. *IRS-P4-MSMR*

The Oceansat-1 also known as Indian Remote Sensing Satellite (IRS-P4) was launched by India on 26 May, 1999. This satellite carried a Multichannel Scanning Microwave Radiometer (MSMR) and an Ocean Colour Monitor (OCM) onboard. MSMR provides measurements of brightness temperatures at 6.6, 10, 18 and 21 GHz frequencies in both horizontal and vertical polarizations. The operational geophysical parameters available from MSMR measurements are wind speed, cloud liquid water, water vapour and surface temperatures over the global oceans (Gohil *et al*., 2001; Varma *et al*., 2002). MSMR frequencies and channels are similar to those of a radiometer flew on Nimbus satellite. Sensitivity of the MSMR channels to rain rate is studied using radiative transfer simulations by Gairola *et al*. (2002). MSMR covers a swath of about 1350 km and it achieves a complete global coverage in 2 days. MSMR brightness temperature data used in this study is provided by National Remote Sensing Agency (NRSA), Hyderabad, India as daily global data files on three different resolution grids of 50, 75 and 150 km, which are referred as grid 1, grid 2 and grid 3 respectively. The 150 km grid data file contains brightness temperature from all 8 channels, whereas 75 km grid data file contains brightness temperatures (Tbs) from 6 channels (all channels except 6.6 GHz) and 50 km grid data file contains Tbs from 4 channels (all channels except 6.6 and 10.65 GHz). Data values in each grid points are provided with corresponding time tag, geo-location and quality flag etc. Present study uses Grid 2 data that does not contain 6.6 GHz brightness temperature values. Attempts have been made for rainfall estimation from MSMR, taking advantage of the signal dominantly from microwave absorption/emission of clouds and rain systems (Varma *et al*., 2002). Rainfall from MSMR has also been used for the study of inter-annual variations of rainfall over the Indian Oceanic regions (Varma *et al*., 2002).

5. Microwave rainfall retrieval

5.1. *Forward modelling - radiative transfer models*

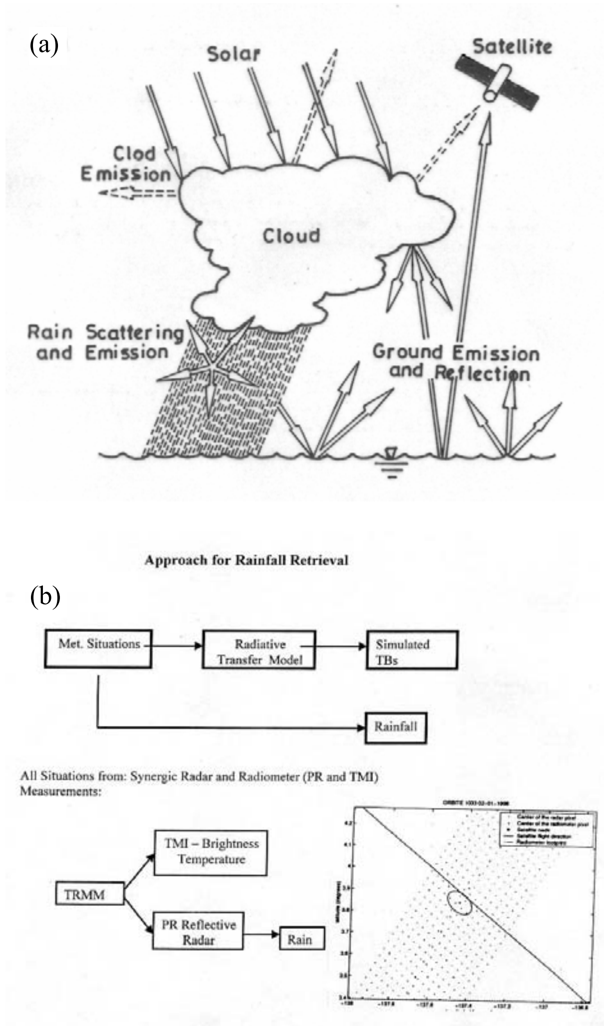
As mentioned earlier, the interpretation of rain and cloud remote sensing data requires, accurate radiative transfer calculations in order to establish the link between the observed radiances and the state of the atmosphere which causes these radiances. Many investigators have reviewed the basic physics of radiative transfer. However here we describe briefly the radiative transfer models to the possible extent of relevance. The simulation of upwelling radiances measurable by TRMM-TMI type of sensors are based on the equations that describe the transfer of microwave radiances through a horizontally infinite and vertically structured plane parallel atmosphere. It forms the basis for calculations of upwelling radiances measurable by radiometric channels. The brief description of radiative transfer is outlined below. The basic equation for the differential radiant intensity can be written as (Chandrasekhar, 1960).

$$-\mu \frac{dI(\tau,\mu)}{d\tau} = -I_{\nu}(\tau,\mu) + J(\tau,\mu) \qquad (1)$$

Where $I(\tau, \mu)$ is the radiant intensity at optical depth τ and $\mu = \cos(\theta)$ where θ is the zenith angle. Thus the basic equation describing the transfer of monochromatic radiation at frequency ν can be written as

$$\cos\theta \frac{dI_{\nu}(z,\theta,\phi)}{dz} = -k_{\nu}(z)[I_{\nu}(z,\theta,\phi) - J_{\nu}(z,\theta,\phi)] \qquad (2)$$

where $I_{\nu}(z,\theta,\phi)$ is the radiance at height z, propagating in the direction of θ, ϕ, k is the extinction

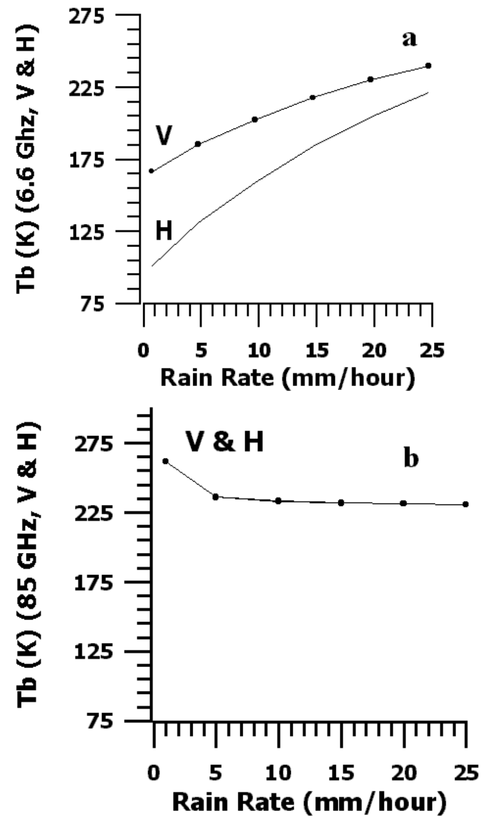


Figs. 1(a&b). A passive remote sensing scenario. Components of the ocean atmosphere that contribute to the radiative transfer

coefficient of the medium, and $J_\nu(z,\theta,\phi)$ is the source function J is defined as

$$J_\nu(z,\theta,\phi) = [1-a(z)]\,B[T(z)] + \frac{a_\nu(z)}{4\pi}\int_0^{2\pi}\int_{-1}^{+1} P_\nu\left(\theta,\phi;\theta',\phi'\right) I_\nu\left(z,\theta',\phi'\right)\mathrm{d}\left(\cos\theta'\right)\mathrm{d}\phi' \tag{3}$$

where $a(z)$ is the albedo for single scattering, $T(z)$ is the ambient temperature of the medium, $B_\nu[T(z)]$ is the Plank's function at frequency ν and temperature $T(z)$, and $P\left(\theta,\phi;\theta',\phi'\right)$ is the phase function for scattering of radiation from direction θ, ϕ into θ ϕ, and P_ν is the single scattering phase function. Though the phase function calculations are required only in the presence of rain, we



Figs. 2(a&b). Simulations for raining cases : Rainfall vs TB's

assume that the presence of hydrometeors in the form of liquid water contributes to scattering. The source function is inherently a function of optical depth at height z. The equation for τ, the extinction optical depth at any point in the medium is

$$\tau(z) = \int_z^{z^*} k_{\mathrm{ext}}\left(z'\right)\mathrm{d}z' \tag{4}$$

where the k_{ext} is the extinction coefficient , z^* is the cloud top altitude and z, the altitude in kilometers (Olson 1989). In plane-parallel Eddigton approximation followed here based on Kummerow (1993), the radiances and phase function are expanded in series of Legendre and associated Legendre functions:

$$I(z,\theta,\phi) = I_o(z) + I_1(z)\cos\theta + \cdots\cdots \tag{5}$$

The ability of passive microwave radiometry to infer geophysical parameters, depends largely on the contrast between these brightness temperatures by multichannel dual polarized observations over raining and non-raining regions. In essence, the above radiative transfer equation states that the change in radiant intensity results from the attenuation in intensity along the path of

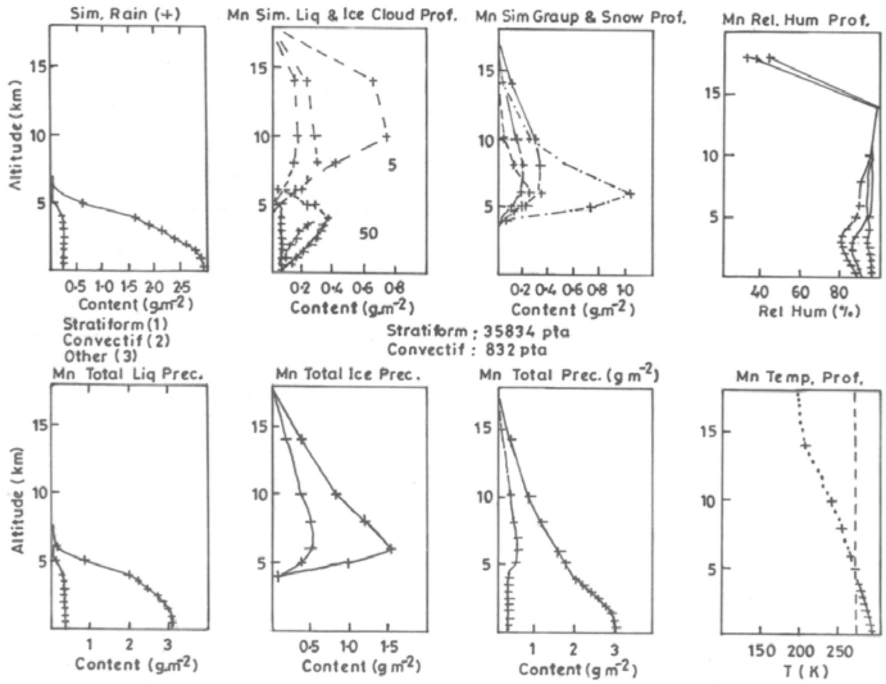


Fig. 3. Vertical profile of temperature, humidity and other hydrometeors from mesoscale model simulations

propagation due to absorption and outward scattering and from the change of intensity due to scattering of the incoming radiation and thermal emission by the atmospheric constituents. The schematic diagrams showing the radiative transfer process in the atmosphere and the general approaches for rainfall retrieval are shown in Figs. 1(a&b) respectively.

5.2. *RT model simulations*

There are series of radiative transfer model developments so far that has taken place specifically for the retrieval of rainfall. Description of the model being used and described with its results, may be found in Weinman and Devis (1978), Kummerow (1993) and Viltard *et al.* (1998), among many others. Basically the Kummerow's model described here is based on the discrete ordinate method but with the Eddington's approximation, where the radiances and phase function are expanded in series of Legendre and associated Legendre functions and first few orders are selected to simplify the phase matrices. The resulting equation which is a second order differential equation has a suitable solution with the constants to be determined from the boundary conditions. In order that the above conditions are satisfied in each atmospheric layer, the atmosphere is generally divided into homogeneous layers. The fluxes at the top and bottom of the layer which are downward and upward fluxes respectively from the upper and lower boundary conditions. At the layer interfaces, the flux continuity is assumed. The radiant intensity can be expressed in more conventional units as the brightness temperature which is the thermodynamic temperature of a black body emitting an equivalent intensity.

Since it is always desirable to have cross calibration of the different models working for the same atmospheric conditions, another model description is followed in this section. In this method the continuum of propagation directions is discretised into a finite number of directions so that the integro-differential equations are converted into system of ordinary differential equations with constant coefficients, the solution of which are calculated by eigenanalysis. The discrete ordinate-eigenanalysis method is applicable when the medium has homogeneous absorption and scattering profiles. We follow here the DOM model developed by Moreau (2000) for the simulations similar as in Kummerow's model simulations mentioned above. The difference in two models is evident that later model does not use such an approximation while Kummerow model use Eddington's approximation. This approximation consists in using a simplified phase matrices to offer faster computation of the scattering coefficients. In both radiative transfer models the radiative properties of the atmosphere are computed using the Mie theory and are integrated over the drop size distributions for each input grid cells.

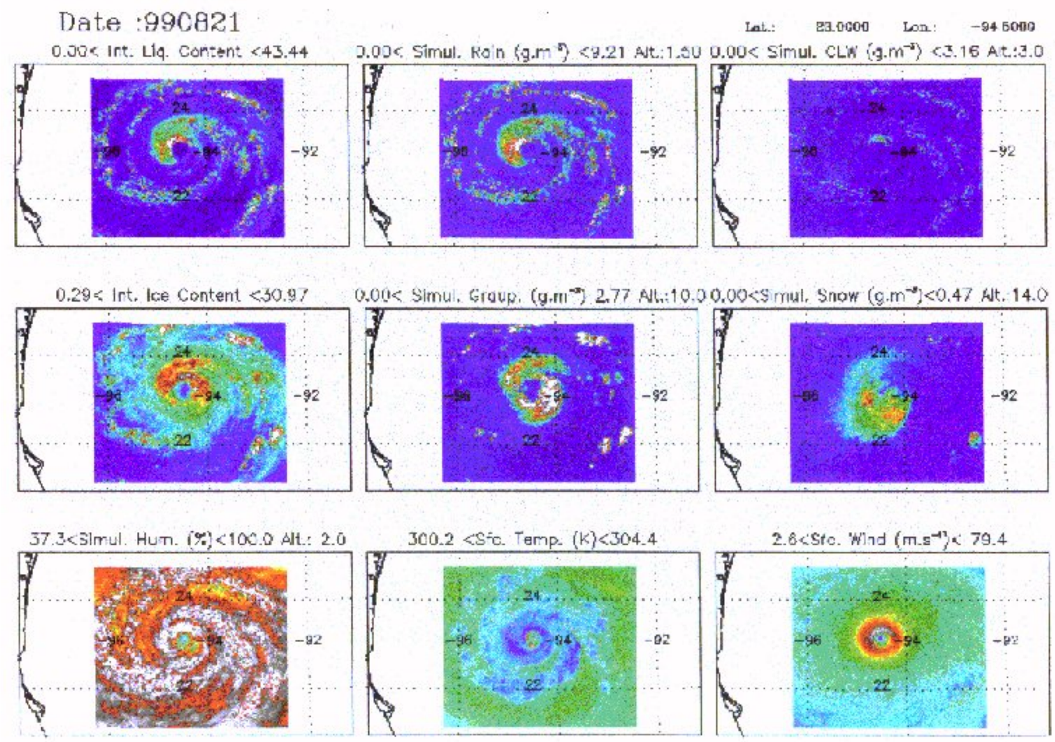


Fig. 4. A horizontal profile of surface parameters and hydrometeors - mesoscale model simulations

6. Some results of simulations

The TMI instrument measures brightness temperatures at 5 different frequencies : 10.65, 19.35, 21.3, 37.0 and 85.5 GHz, each being polarized both vertically and horizontally but for the 21.3 GHz which is only polarized vertically. Thus the simulations are mainly carried out for these frequencies here out of which many are going to be common in MADRAS (Microwave Analysis and Detection of Rain and Atmospheric Structures) sensor of Megha-Tropiques (with exclusion of 10 GHz and inclusion of 157 GHz). Some of the preliminary results from the radiative transfer simulations based on the Eddington approximation are presented recently by Gairola *et al*. (2002) for TMI and IRS-P4-MSMR frequencies.

In the upper layer of clouds, a mixed population of ice crystals and water droplets are present. There may also be some drops of super cooled water. As the ice crystals fall through the cloud under the force of gravity, they combine with other crystals and become larger. On reaching lower warmer regions, it melts to form raindrops, which eventually fall, as rain. Such raining clouds are tall enough to reach sub-freezing altitudes and in these clouds the ice phase is invariably present. Sometimes, of course rain is observed to fall from clouds which do not extend above the freezing level. These are called warm clouds and indicate that it is not always necessary to have ice-phase to produce rain. In such cases rain drops are produced by collision and coalescence of small cloud droplets into big drops. In these clouds, when the rain drops start falling under the force of gravity, they finally acquire a terminal velocity. For typical drop size 25 μm, this works out to be approximately 10cm/s. At this rate of fall, the 25 μm drop would take hours to fall through a 1 km thick cloud. As larger drops fall, they grow by gobbling up the smaller ones on their way. Through such collision and coalescence, larger raindrops of mm size are produced. The raining clouds fall under the categories of cumulus, cumulonimbus and nimbostratus etc. These clouds show larger vertical growth, reaching as high as 15 km on occasion. However, the simulations above were first performed from the data base in the absence of the ice hydrometeors (Gairola, *et al*., 2002) (Fig. 2). For brevity, the results for only the lowest frequency (6.6 GHz of MSM) and highest frequency (85 GHz of TMI) are shown.

In order to represent the coexistence of above large species of hydrometeors in the input profiles, the similar RT model simulations were carried out during a cyclone named Bret (Gairola *et al*., 2002), for which the input data base from mesoscale model was utilized. The vertical

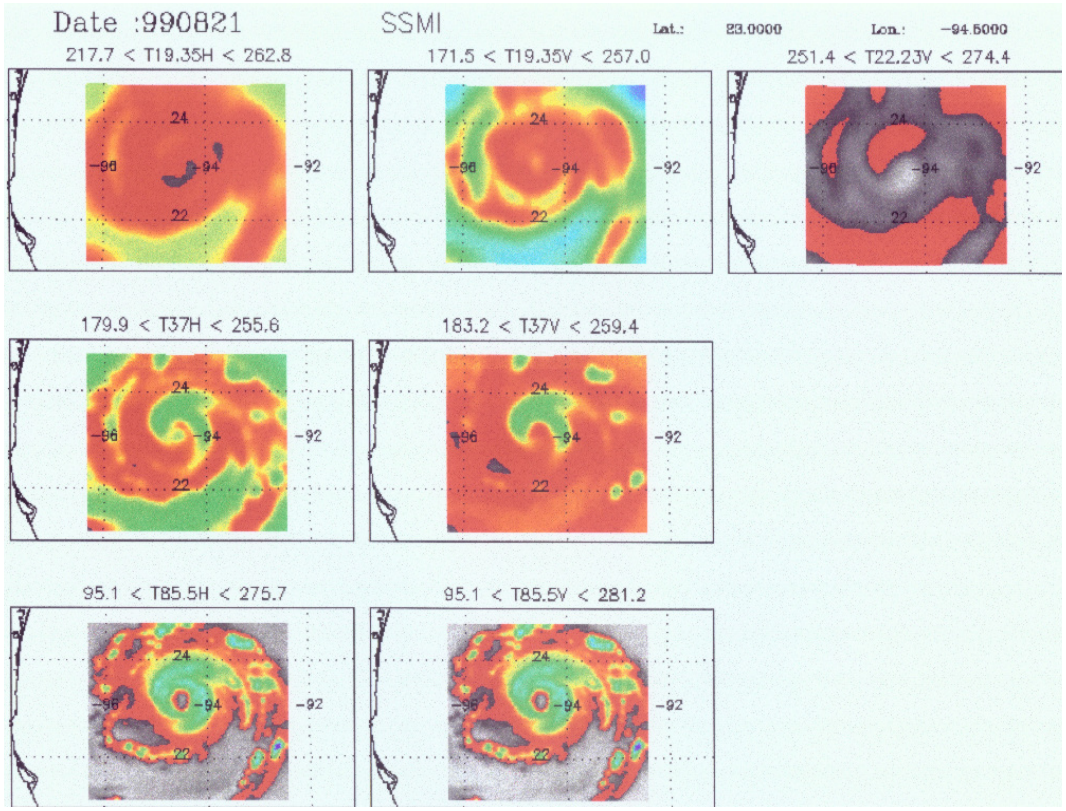


Fig. 5. Radiative transfer simulations for the SSM/I frequency channels

profiles of the water contents and other parameters are shown in Fig 3. The profiles of cloud liquid water, rainfall, graupel and snow in 2-D and along and across track directions for the same cyclone are shown in Fig. 4 which are simulations from mesoscale model. The eye of cyclone is clearly evident from the cross track profile of the PR in all the parameters. Various species of hydrometeors were available from the model and the RT simulations for the SSM/I radiometric channels which are nearly common in TRMM-TMI are shown in Fig. 5 (Gairola, *et al*.,2002). These situations represent the global applicability for various kinds of hydrometeors like, precipitating liquid water (rain drops), non-precipitating liquid water (cloud droplets), precipitating ice.

The dynamic ranges of brightness temperatures show good qualitative agreement with the emission and scattering characteristics of clear and cloudy/rainy atmospheric conditions that would show such dynamic ranges for the respective TRMM-TMI radiometric channels over the oceans. The two branches of the brightness temperatures in 37 and 85 GHz shows the increase in brightness temperature due to the emission and then the decrease due to the scattering and is coherent in both the figures. The hydrometeors have been assumed to be spherical. Even though the sphericity assumption is not strictly proper, especially for ice particles, the average phase function of a randomly oriented ensemble or non-spherical particles tends, in general, to approach that of polydisperson of equal-volume spheres. However the assumptions may introduce a bias and might limit the representativity of the simulated data (Moreaue, 2000). The gaseous absorption part is calculated based on Liebe *et al*., (1993) formulations in both the models. The TRMM observations are also shown for the normal and cyclonic conditions in order to verify the simulations for the similar cases both qualitatively and quantitatively (Figs. 6 and 7) which corresponds to tropical Atlantic (Florida Bay) and Indian Ocean (Bay of Bengal) respectively. The dynamic ranges are in quantitative agreement with the simulations shown in Fig. 5.

ECMWF analyzed fields also provide a wide variety of vertical structures of atmosphere, clouds and rain but are found to have a limited dynamic range of the rainfall (up to 15 mm/hr) while the simulations or the Bret cyclone covers the dynamic range upto 50 mm/hr and together represent the global tropical rainfall situations.

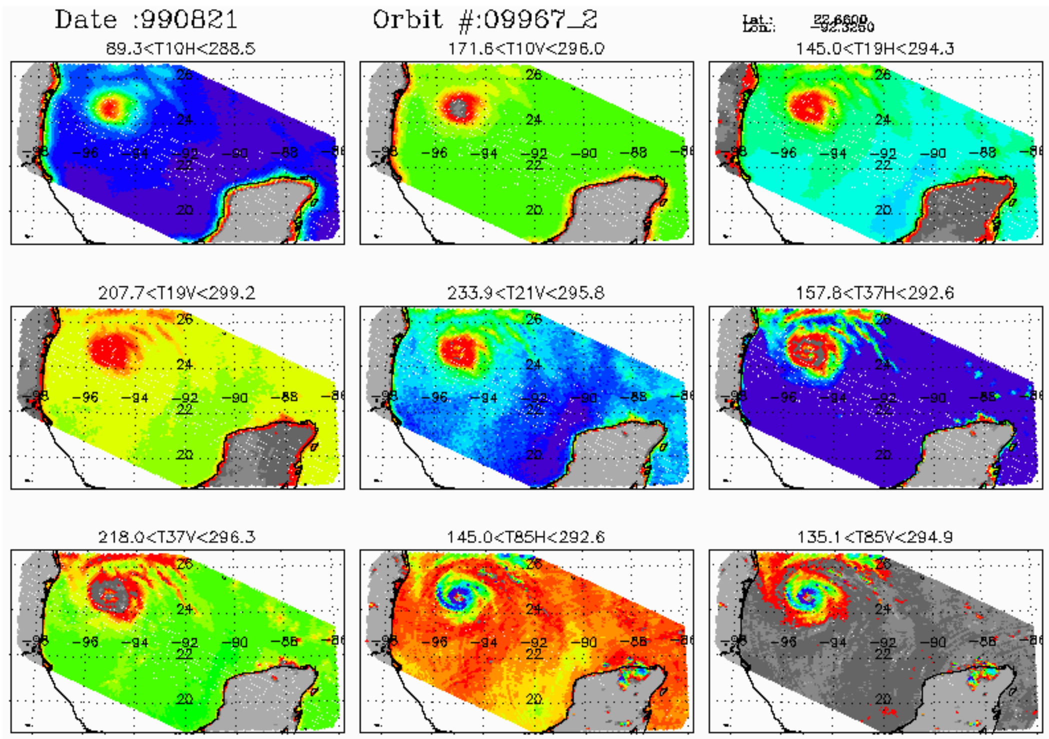


Fig. 6. TMI observations of a cyclone over tropical Atlantic

Based on the above RT simulations, to accomplish retrieval part of study, the real data from co-located TMI and PR of TRMM was simultaneously arranged in collocated manner. From the simulations above with two different radiative transfer models, it is evident that all the horizontally polarized channels from 10 to 85 GHz, are more sensitive to the rainfall. However the real measurements from TMI are resolution dependent. In the present experiment, the beam filling issues are not addressed here and almost all the channels are used for the retrieval ahead based on the sensitivity analysis of simulations.

7. Inverse modelling

Only microwave radiometers can provide a physically reasonable rainfall estimate with sufficient spatial coverage. However, it is equally important to adopt a proper retrieval technique. The most effective techniques that are in operation are briefly explained below with some examples.

7.1. *Multiple Regression approach (MR)*

Radiative transfer calculations can be used to determine a brightness temperature, Tb, given a temperature, water vapour and hydrometeor profile. An inversion procedure, however, is needed to find a rainfall rate, R, given a Tb. Various inversion techniques are used, with microwave brightness temperature data, obtained from remote sensing orbiting platforms, to calculate rain rates. Most commonly used techniques are based on multiple regressions. The generic empirical retrieval problem is essentially a mapping which maps a vector of sensor measurements, X (T) in R^n, to a vector of geophysical parameters Y (G) in R^m. For empirical retrievals, this mapping is constructed using discrete sets of collocated vectors X and Y or matchup data sets $\{X_p, Y_p\}$. Linear regression is an appropriate tool for developing many empirical algorithms. It is simple to apply and has a well- developed theoretical basis. There are several studies using this approach (Bauer, 2001 Ferraro and Marks, 1995 etc.).

7.2. *Neural Network Approach (NN)*

Recent research has shown that Artificial Neural Network (ANN) techniques can be used successfully for the rainfall estimation from radiometric measurements from SSM/I type of sensors (Tsintikdis *et al*., 1997). NN is a non-parametric method for representing the complex relationship between satellite measurements (radar or radiometers) and rainfall rates for instance. The NN's are mathematical models that are capable of learning complex

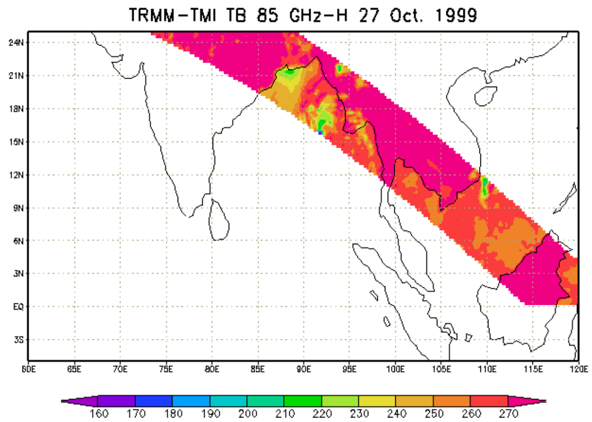


Fig. 7. Example of TMI observations of Orissa super cyclone from 85 GHz TMI channel

relationships, such as in case of multichannel brightness temperatures and rainfall. They consist of highly interconnected, interactive data processing units. Multilayer Perceptron (MLP) neural networks (Rumelhart *et al*., 1986) are computational methods of data analysis that are an extension of traditional statistical methods such as regressions and function approximation. In statistical regressions, the modeler has to a priori specify the functional form of the relationship likely to exist in the data set (nonlinear *vs* linear *vs* multiple regressions). The best functional form for the data is based on an error measure such as the least squares criterion. The NN form an "internal weight" representation of the data as to minimize an error criterion (usually least squares) without too much a priori judgements about on the functional form for the data. A simple conceptual architecture (without connecting all input and hidden nodes due to simplicity of the figure) of the NN is shown in Fig. 8.

7.3. *Bayesian approach*

The most popular algorithm used for TRMM is Goddard Profiling (GPROF) by Kummerow *et al*. (1995). The GPROF is designed to retrieve rain over both ocean and land based on the Bayesian approach. This approach consists in a two step process: (*i*) Building of the database of hydrometeor species profiles and their corresponding Tb's. The initial database is supplied in nonhydrostatic cumulus-scale cloud models using explicit cloud microphysics and (*ii*) The retrieval process itself which uses the vector of the measured Tb's as an input and go through the database to look for the closest Tb vectors based on a pre-defined definition of a distance. The profile associated with this (or these) Tb vector closest to the observations, is the solution of the retrieval. This algorithm was originally developed for the SSM/I and was

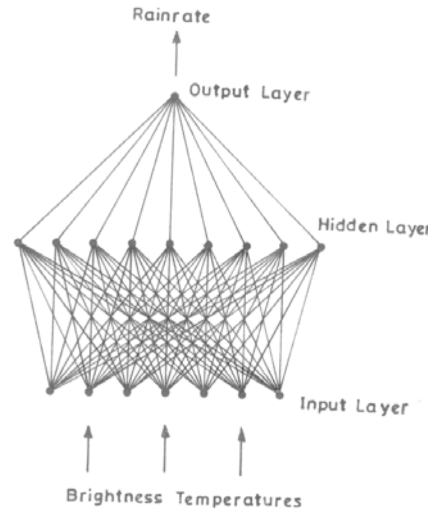


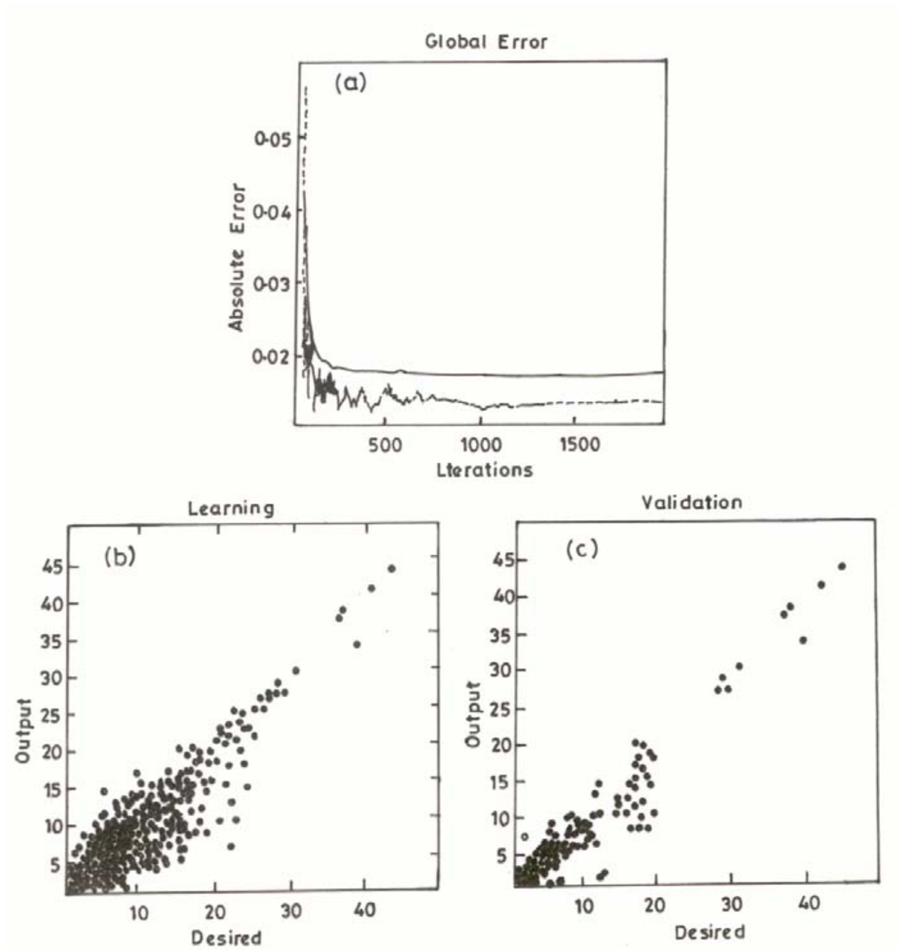
Fig. 8. A simple neural network architecture showing the input and output connections through the hidden units (between rainfall and the radiometric brightness temperatures)

simply reconfigured for the TMI to take somewhat different channels and higher spatial resolutions of the TMI into account.

8. Examples of rainfall retrievals by NN and MR approach

In previous sections (5.1, 5.2) two different radiative transfer models were used for initial sensitivity studies and for conceptually simple consideration of spatial distributions of cloud and rain conditions from ECMWF and mesoscale model database. These models are based on Discrete Ordinate Method (DOM) upto N streams by Moreau (2000) and Eddington's approximation applied to DOM by Kummerow (1993). Both of these models allow for a full range of optical thickness and cloud absorptivities. The main purpose of the simulations is to delineate the frequencies that are most sensitive (as far as brightness temperatures are concerned) to the surface parameters and rainfall characteristics. Following these sensitivity analyses, a combination of passive and active microwave observations from TRMM Microwave Imager (TMI) and Precipitation Radar (PR) of TRMM satellite is used to estimate rainfall using NN technique. The brief about the data used for the ANN are presented below.

A large data base representing all the possible dynamical ranges of rainfall and brightness temperatures is the prerequisite for applying this method. Here the data base is generated from the collocated sets of observations between TMI and PR which share a common swath of about 200 km on the surface. The PR is the first rain radar



Figs. 9(a-c). (a)The distribution of global error from NN training (continuous line) and testing (dotted line) between TMI-TB's and PR-rainfall and (b&c) The scatter plot of the desired and estimated rainfall from NN

in space. Within this area of common swath there are very important observations, *i.e.,* the vertical profile of reflectivity from PR from rain structures and the brightness temperatures from TMI from almost same cloud and rain systems by all nine channels respectively. These sensors makes one of the very suitable pair of coherent observations for estimating rainfall. Two days of TMI and PR data base are used in the present study (1,2 February, 1998).

9. Results of NN retrieval from TRMM

From the simulations in the pervious section it is clear that all channels have considerable effect of rainfall but all measurements from TMI are resolution dependent (around 50 km for 10 GHz and 5 km for 85 GHz). All the channels of TMI are selected for analysis. The collocated TMI and PR points are divided into two parts, first one for training the relationship between the input and output vectors of TMI-TB's and PR rain and finally testing the relationship obtained by NN training using remaining points. Various experiments were carried out with a number of iterations from 1000 to 20000, with back propagation approach that minimizes the cost function (Gairola *et al*., 2001). The variation of global error with number of iterations, which is the evolution of the error during the training phase, shows the credibility of NN to be followed for statistical significance [Fig 9(a)]. The error decreases substantially after a few hundred iterations. The desired versus NN retrieval of rainfall for both training and testing data sets are shown Figs. 9(b&c) respectively. The detailed error statistics could be found for the binned rainfall within interval of 5 mm/hr or less (Gairola *et al*., 2001). There are significant correlation's of 0.91 and 0.90 achieved in both sets for the architecture of the NN that converged to minimum acceptable error in present case with three hidden layers.

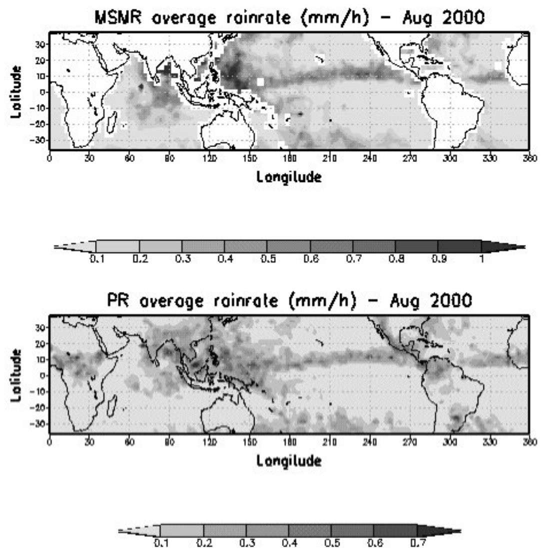


Fig. 10. MSMR derived rain rate (Upper panel) and PR derived rain rate (Lower panel) for August 2000

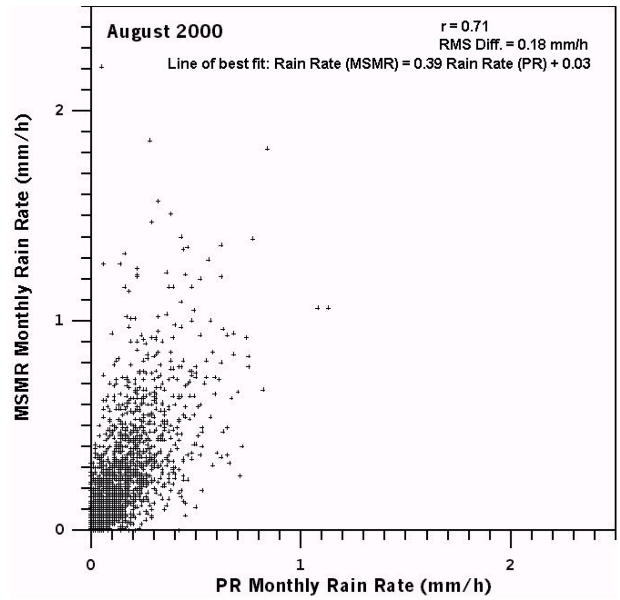


Fig. 11. Scatter plot between MSMR and PR monthly rain rate from Fig. 10

The main concern for NN to work is representativeness of the data in its complete dynamic range of both input and output vector fields while training the network. This is required to achieve significant stability of the weighting coefficients of the NN for the retrieval of rain rates from TMI observations. However, the input data base generation can still be considered a multistage problem, which involves many degrees of freedom in case of rain and clouds. Apart from the surface and background atmospheric contributions to the signal, the cloud and rain parameters themselves impose the large uncertainty. The initial success of simulations for both emission and scattering atmospheres and their corroboration with the observations from TMI and PR allows us for more specific and stringent experiments to be carried out using consistent and statistically representative input fields both over the land and oceanic regions for the treatment of the involved radiative process for the retrieval of rainfall from TRMM and other forthcoming sensors.

For the similar set of data base the multiple regression has also been performed with a variety of the predictor variables that minimizes the rms error. The rms error was found to vary from 2.18 to 1.5 mm/hr and the correlation coefficient from 0.85 to 0.78. Based on these experiments, it is obvious that the NN performs much better than the multiple regressions. Yet, one of the most promising techniques is based on the Bayesian Approach even though it works on the assumption that all the measurements from the radiometric channels are mutually orthogonal and they have no correlation among each other. This assumption is only partly true and in most of the cases the response of the channels to the atmospheric water content and the surface variability are almost of similar nature. It is only during the rain cases that the behavior of the channels might be different. Recent studies by Bauer *et al*. (2001) has shown the superiority of this method on NN and multiple regressions.

10. Rainfall retrievals from MSMR

Varma *et al*. (2002) explored rain estimation capability of MSMR. MSMR brightness temperature data of 6 channels corresponding to three frequencies of 10, 18 and 21 GHz were collocated with the TRMM Microwave Imager (TMI) derived rain rates to find a new empirical algorithm for rain rate by multiple regression. Further, this algorithm was used for generating global average rain rate map for month of August (2001) (shown in Fig. 10). MSMR derived monthly averaged rain rates are compared with similar estimates from TRMM Precipitation Radar (PR) and was found that MSMR derived rain rates match well, quantitatively and qualitatively, with that from PR on monthly scale (Fig. 11).

11. Combined approach using microwave and IR

Over the last few years, a number of groups have embarked on development of so-called hybrid techniques wherein the advantages of geosynchronous VHRR *viz*. Vast coverage and near sufficient space-time sampling, and polar passive microwave radiometers (Adler *et al*. 1994; Jobard and Desbois, 1994; Gairola and

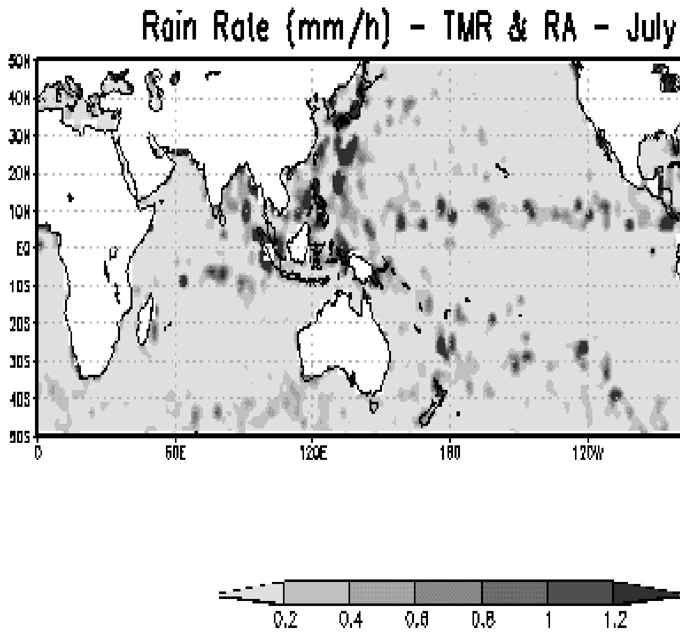
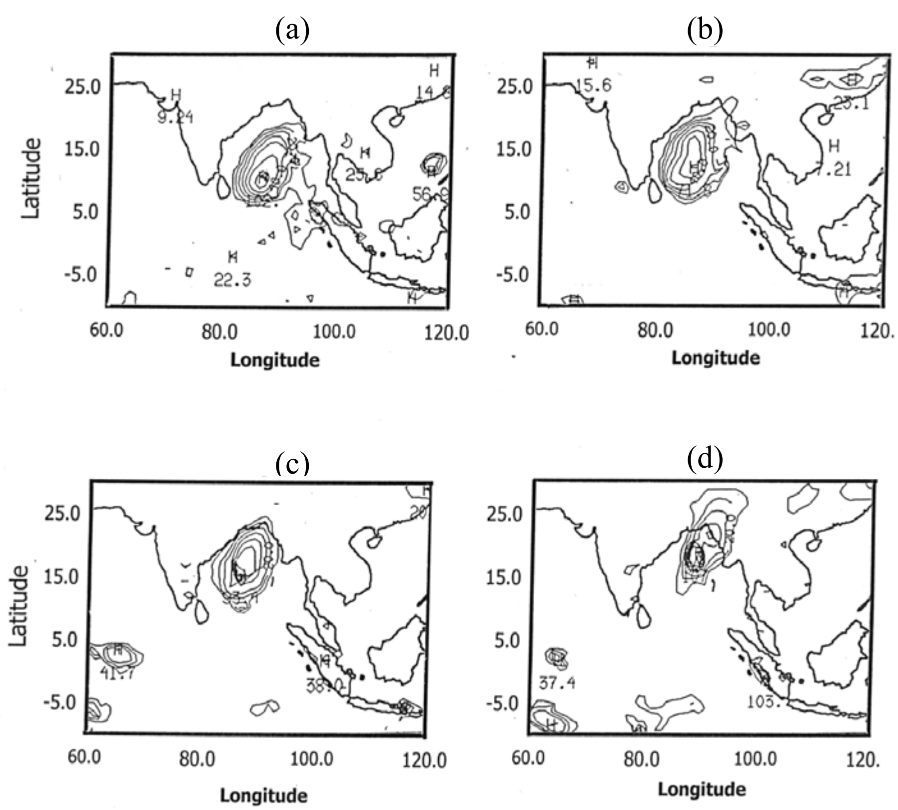


Fig. 12. Combined rainfall from TOPEX radar and radiometer for July 2000



Figs. 13 (a-d). Rainfall patterns using IR and MW data: 26-29 April, 1991

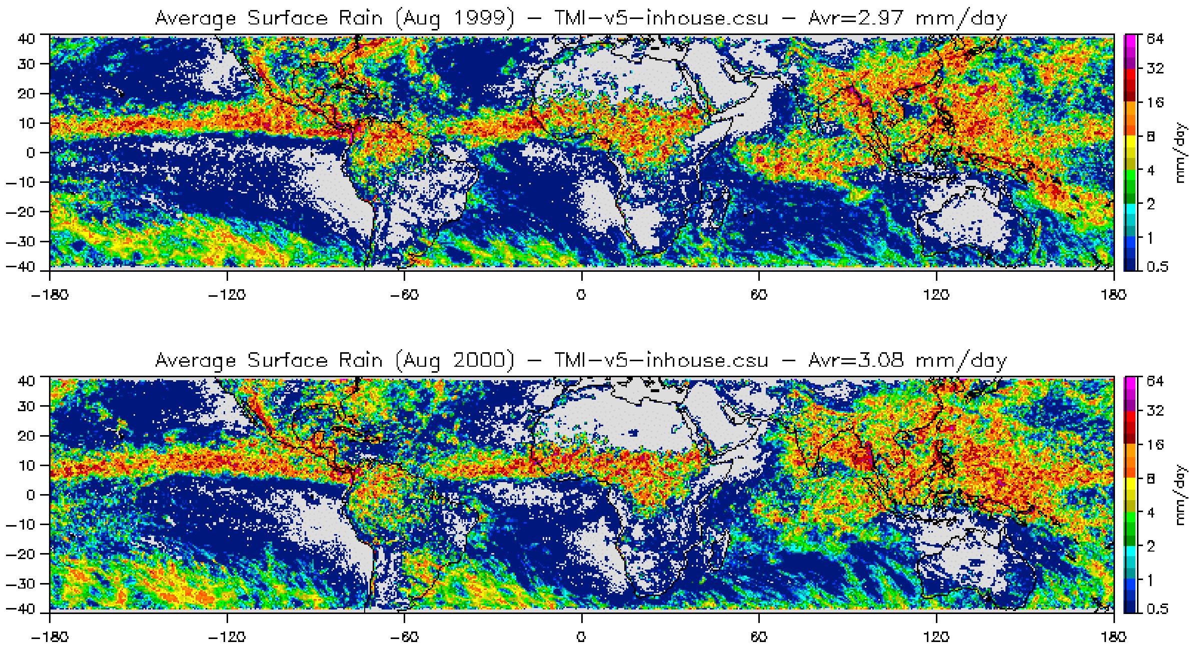


Fig. 14. Example of TRMM-TMI rainfall over the global tropics during August, 1999 and 2000 from NASA-GPROF algorithm

Krishnamurti, 1992 Todd *et al*., 2001; Xu *et al*., 1999; Chen and Li, 2002). As it is clear that in IR/VIS, the clouds tends to be opaque and hence the rainfall is inferred indirectly. Being an indirect method, these measurements deviate from the true interpretations due to different cloud types. More physically based MW retrievals, are synergistically combined with IR observations to generate global maps of tropical rainfall on climate scales using IR observations. The VHRR-IR based estimates are calibrated against the microwave estimates over the common areas of overlap. The required adjustments are then applied to IR estimates to fill the spatial and temporal gaps in the coverage of microwave measurements. The climatological scale rainfall maps produced in this manner represent the known features more closely. Recently Varma *et al*. (1999) and Gairola and Varma (2002) have presented a combined methods for active and passive microwave measurements of rain over global tropics using Topex/Poseido (T/P) microwave radiometer (TMR) and dual frequency radar altimeter. A typical example of global rainfall patterns from such algorithms is presented in Fig. 12 for brevity only. Varma *et al*. (2001) also explored the diurnal variability of rainfall from T/P. Bhandar and Varma (1995) used the concept of differential attenuation of the radar signal due to rain based on the analysis of the data of dual frequency T/P altimeter.

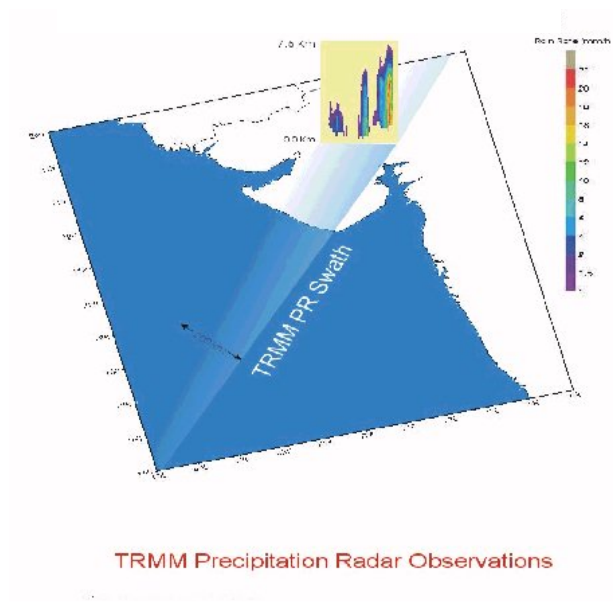


Fig. 15. Vertical structure of rain during 13 July 2000

Recently, one case study of a severe cyclone over Bay of Bengal during 24-29 April, 1991 has been made by Gairola and Varma (2002) based on an approach from Gairola and Krishnamurti (1992) of integrated IR and microwave measurements using various satellite sensors. The combined IR and microwave rain algorithm brings out the finer details of the cyclone structure and precipitation fields (Fig. 13) and shown to be promising for operational applications. Finally, for brevity, the rainfall distribution over both land and oceans by TRMM, is shown in Fig. 14 as an example of state of art GPROF algorithm of NASA for the month of August of 1999 and 2000. The climatic patterns of rainfall are clearly seen with maxima over ITCZ of the Pacific and Atlantic Oceans in the eastern Indian Ocean and over land areas in Brazil, Africa and Indonesia. More detail information of tropical rainfall from TRMM combined with other satellite and rain gauge information could be found in Adler *et al*. (2000). Finally, only as an example of the vertical profile of the rain signatures from the most innovative sensor, precipitation radar of TRMM is shown in Fig. 15, during the flash flood that occurred in Ahmedabad during July, 2000 (details in Agarwal *et al*., 2000). Thus in future more accurate rainfall estimation would depend on the synergistic active and passive microwave measurements from satellites.

12. Conclusions

The present paper is a limited overview of the methodologies for rainfall retrievals from microwave sensors and applications. With the state of art algorithms it has been well demonstrated over the years that passive microwave (PM) instruments on earth orbiting platforms have been providing valuable information for precipitation estimation and have been successfully used in various applications. However, the very intermittent nature of rainfall process, still poses the necessity for the continuation of efforts toward the development of more advanced rain retrieval algorithms. More so the obvious limitations associated with the low sampling frequency of orbiting platforms carrying microwave sensors cant not be ruled out as yet. The need for the synergetic active and passive microwave measurements from satellites and the more precise algorithms thereof are required. The recent availability of detailed precipitation observations by the first space-borne precipitation radar (PR) and a multifrequncy passive microwave radiometer, the TRMM microwave imager (TMI), have led to continue with the new missions, *e.g*., Megha-Tropiques (M-T) satellite planned to be launched under Indo-French Joint Programme in this decade as a part of Global Precipitation Mission (GPM). M-T is a satellite mission designed to study convective systems, focusing on the analysis of water cycle with water vapour distribution and transport, convective systems life cycle and energy exchanges in the tropical belt. The science goal of M-T is to increase the understanding of the energetic and hydrologic processes in the tropics and the way they influence the global circulation of the atmosphere and oceans and climate variability. The currently ongoing ADEAOS-II mission in conjunction with TRMM or M-T are to support climate predictions studies, validation of climate and whether models, over tropical areas, the mission will also provide relevant data for global earth climate understanding.

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References

Adler, R. F., Huffman, G. J. and Keehn, P.R., 1994, "Global tropical rain estimates from microwave adjusted geosynchronous IR data", *Remote Sensing Rev*., **11**, 125-152.

Adler, R. F., Huffman, G. J., Bolvin, D. T., Curtis, S. and Nelkin, E. J., 2000, "Tropical rainfall distributions determined using TRMM combined with other satellite and rain gauge information", *Jour. Applied Met*., **39**, 2007-2023.

Agarwal, N., Kishtawal, C. M., Varma, A. K. and Gairola, R. M., 2000, "Satellite microwave observations of flash flood events of Ahmedabad and Hyderabad during monsoon season of 2000", internal report No. RESA/MOG/SN/01/2000, p19.

Aires, F., Prigent, C., Rossow, W. B., Rothstein, M., 2001, "A new neural network approach including first guess for the retrieval of atmospheric water vapour, liquid water path, surface temperature, and emissivities over land from satellite microwave observations", *J. Geophys. Res*., **106**, 14887-14907.

Allison, L. J., Rodgers, E. B., Wilheit, T. T. and Fett, R. W., 1974, "Tropical cyclone rainfall as measured by the Nimbus-5 ESMR", *Bull. Am. Meteorol. Soc*., **55**, 1074-1089.

Aonashi, K. and Liu, G., 2000, "Passive microwave precipitation retrievals using TMI during the Baiu period of 1998. Part I: Algorithm description and validation", **39**, 2024-2037.

Arkin, P. A. , Krishna Rao, A.V.R. and Kelkar R.R., 1989, "Large scale precipitation and outgoing longwave radiation from INSAT-1B during the 1986 southwest monsoon season, *Journal of Climate*, **2**, 619-628.

Arkin, P. A. and Meisner, B. N., 1987, "The relationship between large scale convective rainfall and cold cloud over the Western Hemisphere during 1982-1984", *Mon. Wet. Rev*., **115**, 51-74.

Basu, S. K., Gairola, R. M., Kishtwal, C. M. and Pandey, P. C., 1995, "Empirical orthogonal function analysis of humidity profiles over the Indian Ocean and an assessment of their retrievability using satellite microwave radiometry", *Jour. Geophys. Res*., **100**, D11, 23009-23017.

Bauer, P. and Schlussel, P., 1993, "Rainfall, total water, ice water and water vapor over sea from polarized microwave simulations and special sensor microwave/imager data", *J. Geophys. Res*., **98**, p20737.

Bauer, P., Amayenc, P., Kummerow, C. D. and Smith, E. A., 2001, "Over ocean rainfall retrieval from multisensor data of the TRMM. Part II: Algorithm implementation", *J. Atmos. Ocean Tech*., **18**, 1838-1855.

Berg, W. and Chase, R., 1992, "Determination of mean rainfall from the special sensor microwave/imager (SSM/I) using a mixed log normal distribution", *J. Atm. Oceanic Tech*., **9**, 129-141.

Bhandar, S. M. and Varma, A. K., 1995, "Potential of simultaneous dual-frequency radar altimeter measurements from TOPEX/Poseidon for rainfall estimation over oceans", *Remote Sensing of Environment*, **58**, 13-20.

Chandrasekhar, S., 1960, "Radiative Transfer", *Dover Publications*, Inc., New York.

Chen, W. J. and Li, C. C., 2002, "Rain retrievals using TRMM and Geostationary Met. Satellite-5 data obtained during the SCSMEX", *IJRS*, **23**, 2425-2448.

Druen, B. and Heinemann, G., 1998, "Rain rate estimation from synergetic use of SSM/I, AVHRR and meso-scale numerical model data", *Meteor. Atmos. Phys*., **66**, 65-85.

Ferriday, J. G. and Avery, S. K., 1994, "Passive microwave remote sensing of rainfall with SSM/I: Algorithm development and implementation", *J. Appl. Meteor*., **33**, 1587-1596.

Ferraro, R. R. and Marks, G. F., 1995, "The development of SSM/I rain-rate retrieval algorithms using ground-based radar measurements", *J. Atmos. Oceanic Technol*., **12**, p755.

Gairola, R. M., Gohil, B. S. and Pandey, P. C., 1985, "Retrieval of precipitable water from Bhaskara-II microwave measurements and its comparison with NOAA-7 and Radiosonde data", *Remote Sensing of Environment*, **18**, 125-135.

Gairola, R. M. and Krishnamurti, T. N., 1992, "Rain rates based on SSM/I, OLR and Rain gauge data sets", *Meteor. and Atmospheric Physics*., **50**, 165-174.

Gairola, R. M., Basu, S. K., Varma, A. K. and Pandey, P. C., 1996, "Improved rainfall and moisture estimation from satellite remote sensing for characterization of hydrological cycle in the tropics", Indo-US symposium/Workshop on Remote Sensing and its applications, 6-9 October, IIT-Bombay, 1ndia.

Gairola, R. M., Mallet, C., Viltard, N. and Moreau, E., 2001, "Rainfall from TRMM-TMI, 2nd ISRO-CNES Science Workshop on MEGHA-TROPIQUES", Paris, France, 1-5 July.

Gairola, R. M., Varma, A. K., Gohil, B. S. and Agarwal, V. K., 2002, "Sensitivity of radiative transfer to the oceanic surface roughness and rainfall for TRMM radiometric channels over Indian Oceanic regions", Under Publication Process.

Gairola, R. M., Gohil, B. S. and Pandey, P. C., 1988, "Study of deep depression and cyclonic storms by Seasat-SMMR data over Indian Oceanic regions", IGU Hyderabad.

Gairola, R. M., Basu, S. K., Gohil, B. S., Varma, A. K. and Pandey, P. C., 1994, "Tropical Rainfall Measuring Mission by USA and Japan- In Indian perspective", (ICORGE-1994), Edited by I.V. Murlikrishna, Tata McGrew-Hill Pub. Comp. Ltd, New Delhi, 757-761.

Gairola, R. M., Gautam, N. and Pandey, P. C., 1992, "Study of latent heat fluxes and associated oceanic and atmospheric parameters over the Arabian Sea and Bay of Bengal using Seaset-SSMR data", *Indian Jour. of Radio and Space Physics*, **21**, June, 143-148.

Gairola, R. M. and Varma, A. K., 2002, "Combined passive-active microwave retrievals of quantitative rainfall from Topex-Altimeter and Topex-Microwave radiometer", In Press, *Remote Sensing Reviews*.

Gairola, R. M., Pokhrel, S., Varma, A. K. and Agarwal, V. K., 2002 "Study of rainfall over global tropics inferred from TRMM: Applications to 1997-98 El Nino", Accepted for Presentation in International Symp. of ISPRS 2002 Hyderabad, , 3-6 December.

Gohil, B. S., Mathur, A. K. and Varma, A. K., 2001, "Geophysical parameter retrieval over global oceans from IRS-P4/MSMR", Proc. of Pacific Ocean Remote Sensing Conference - 2000, 5-8 December, 2000, NIO, Goa, India, 207-211.

Grody, N. C., 1993, "In Atmospheric Remote Sensing by Microwave Radiometry", M.A. Janseen, Ed, New York, Wiley, 1993, Ch. 6.

Haferman, L., E. N., Anagnostou, D., Tsintikidis, W. F., Krazewski and T. F., Smith, T. F., 1997, "Physically based satellite retrieval of rainfall using a 3D passive microwave radiative transfer model", *J. Atmos. Ocean Technol*., **13**, 832-850.

Hollinger, J., Lo, R., Poe, G., Savage, R. and Pierce, J., 1987, "Special Sensor Microwave/Imager User's Guide", Naval Research Laboratory, Washington D.C.

Hou, A. Y., Zhang, S. Q., Da Silva, A. M., Olson, W. S., 2000, "Improved assimilated global datasets using TMI rainfall and columnar moisture observations, *Journal of Climate*, **13**, 4180-4195

Hou, A., Y., Zhang, S. Q., Da Silva, A. M., Olson, W. S., Kummerow, C. D. and Simpson, J., 2001, "Improving global analysis and short-range forecast using rainfall and moisture observations derived from TRMM and SSM/I passive microwave instruments", *Bull. Amer. Meteor. Soc.,* **82**, 659-679.

Imaoka, K. and Spencer, R. W., 2000, "Diurnal variation of precipitation over the tropical oceans observed from TRMM/TMI and SSM/I", **13**, 4149-4158.

Jobard, I. and Desbois, M., 1994, "Satellite estimation of the tropical precipitation using METEOSAT and SSM/I data", *Atm. Res*., **34**, 285-298.

Katsaros, K. B., Bhatti, I., Mc, Mudri, L. A. and Petty, G., 1989, "Identification of atmospheric fronts over the oceans with microwave measurements of water vapour and rain", *Wea. and Forcasting*, **4**, 449-460.

Kelker, R.R., 1994, "Satellite meteorology in India – an overview", *Ind. J. Radio Sci*., **23**, 325-345.

Krishnamurti, T. N. , Rohali, G. and Bedi, H. S., 1994, "On the improvement of precipitation forecast skill from physical initialization", *Tellus*, **64**A, 598-614.

Krishnamurti, T. N., Bhowmik, S. K. R., Rohali, G., Oosterhof, D. K. and Surgi, N., 1996, "Mesoscale structure implied by physical initialization", *Mon. Weather Rev*.,

Kummerow, C., Barnes, W., Kozu, T. and Simpson, J., 1998, "The Tropical Rainfall Measuring Mission (TRMM) sensor package", *J. Atmos. Ocean. Technol*., **15**, 809-817.

Kummerow, C. W. and Giglio, L., 1995, "A method for combining passive microwave and infrared rainfall observations", *J. Atmos. Ocean. Technol*., **12**, 33-45.

Kummerow, C., 1993, "On the accuracy of Eddington approximation for radiative transfer in the microwave frequencies", *Jour. Geophy. Res*., **98**, D2, 2757-2765.

Liebe, H. J., Hufford, G. A. and Cotton, M. G., 1993, "Propagation Modelling of moist air and suspended water/ice particles below 1000 GHz", Proc. of AGARD Fifty - Second Specialist's Meeting of the Panel on Electromagnetic Wave Propagation, p3-1-3-10.

Liu, G., 1998, "A fast and accurate model for microwave radiance calculation", *J. Meteor. Soc. Japan*, **76**, 335-343.

Liu, G. and Curry, J. A., 1998, "An investigation of the relationship between emission and scattering signals in SSM/I data", *Jour. Atmos. Sci*., 1628-1643.

Moreau, E., 2000, "Restitution de parameters atmospheriques par radiometric hyperfrequence spatiale. Utilisation de methodes neuronales", Ph. D. Thesis, CETP/CNRS.

Negri , A. J., Adler, R. F. and Kummerow, C. D., 1989, "False color display of SSM/I data", *Bull. Amer. Meteor. Soc.*, **70(2)**, 146-151.

Olson, W. S., 1989, "Physical retriaval of rainfall rates over the oceans by multispectral microwave radiometry", Applied to tropical cyclones., *J. Geophys. Res*., **74**, 2269-2289.

Petty, G. W., 1994, "Physical retrieval of over-ocean rain rate from multichannel microwave imgagery", I, Theoretical characteristics of normalized polarization and scattering indices, Meteorol. Atmos. Phys., **54**, 79-99.

Prabhakara, C., Dalu, G. and Vollmer, B. E., 1989, "Tropical oceanic rainfall: estimation from SMMR and SSM/I", Preprint Volume – Fourth Conference on Satellite Meteorology and Oceanography, 16-19 May, San Diego, *Am. Met. Soc*., 79-82.

Rao, G. V. and MacArthur, P. D., 1994, "The SSM/I estimated rainfall amounts of tropical cyclones and their potential in predicting the cyclone intensity change", *Mon. Wea. Rev*., **122**, 1568-1574.

Rao, G. V. and McCoy, J. H., 1997, "SSM/I measured microwave brightness temperature (TB's) anomalies of TB's and their relationship to the typhoon intensification". *Nat Hazards*, **15**, 1-19.

Rodgers, E. B. and Piers, H. F., 1994, "A satellite observational study of precipitation characteristics in the Western North Pacific tropical cyclones", *J. Applied Meteor*., **34**, 2587-2599.

Rumelhart, D. E., Hinton, G. E. and Williams, R. J., 1986, "Learning internal representations by error propagation", in Parallel Dist. Proc., ed. By, Rumelhart and McClelland, MIT Press, Cambr., Mass. 318-362

Simpson, J., Kummerow, C., Tao, W. K. and Adler, R. F., 1996, "On the Tropical Rainfall Measuring Mission", *Met. Atmos. Phys*., **60**, 19-36.

Smith, E. and Lamn, J., Adler, R., Alishouse, J., Aonashi, K., Barrett, E., Bauer, P., Berg, W., Chang, A., Ferraro, R., Ferraday, J., Gooodman, S., Grody, N., Kidd, C., Kummerow, C., Liu, G., Marzano, F., Mgnai, A., Olson, W., Petty G., Shibata, A., Spencer, R., Wentz, F. and Wilheit, T., 1998, "Results of WetNet PIP-2 ", *J. Atmos. Sci*., **55**, 1483-1536.

Smith, E. A., Xian, X., Mugnai, A. and Tripoli, G. J., 1994a, "Design of an inversion based precipitation profile retrieval algorithm using an explicit cloud model for initial guess microphysics", *Meteorol. Atmos. Phys*., **54**, 53-78.

Spencer, R.W., Geodman, H. M. and Hood, R. E., 1989, "Precipitation retrieval over land and ocean with SSM/I: Identification and characteristics of the scattering signal", *J. Atmos. Oceanic Techn*., **6**, 254-273.

Tao, W. K. and Simpson, J., 1993, "Goddard Cumulus Ensemble Model. Part I: Model Description", *Terr. Atmos. Oceanic Sci*., **4**, 35-72.

Todd, M. C., Kidd, C., Kniveton, D. and Bellerby, L. J., 2001, "A combined satellite infrared and passive microwave technique for estimation of small-scale rainfall", *J. Atmos. Ocean. Tech*., **18**, 742-755.

Tsintikdis, D., Haferman, L., Anagnostou, E. N., Krazewski, W. F. and Smith, T. F., 1997, "A neural network approach to estimating rainfall from spaceborne microwave data", *IEEE Trans. Geosci. Remote Sens*., **35**, 5, 1079-1093.

Tripoli, G. J., 1992, "An explicit 3-D non-hydrostatic numerical simulation of a tropical cyclone", *Meteor. Atmos. Phys*., **49**, 229-254.

Varma, A. K., Gairola, R. M., Kishtwal, C. M., Pandey, P. C. and Singh, S. K., 1999, "Rainrate estimation from nadir looking Topex/Poseidon microwave radiometer (TMR) for correction of radar altimetric measurements", *IEEE Trans. Geosci. And Remote Sens*., **37**, 5, 2556-2568.

Varma, A. K., Gairola, R. M., Pandey, P. C. and Singh, K. P., 2001, Use of TOPEX-Altimeter for the Study of Diurnal and Spatial Distribution of South-West Monsoon Rainfall over the Bay of Bengal and the Arabian Sea, Remote Sensing of Environment (USA), **77**, 1, 112-121.

Varma, A., Pokhrel, K. S., Gairola, R. M. and Agarwal, V. K., 2002, "An empirical algorithm to estimate cloud liquid water from MSMR and its utilization in rain identification", Submitted , Under revision, *IEEE Transactions on Geosciences and Remote Sensing*.

Varma, A. K., Gairola, R. M., Mathur, A. K., Gohil, B. S. and Agarwal, V. K., 2002, "Intercomparison of IRS-P4-MSMR derived geophysical products with DMSP-SSM/I and TRMM-TMI finished products", Proceedings of Indian Academy of Sciences – Earth and Planetary Sciences , **111**, 247-256.

Varma, A. K., Gairola, R. M., Mathur, A. K., Pokrel, S., Gohil, B. S. and Agarwal, V. K., 2002, "Rain rate measurements over global oceans from IRS-P4 MSMR", Proceedings of Indian Academy of Sciences – Earth and Planetary Sciences, **111**, 257-266.

Viltard, N., Obligis, E., Marecal, V. and Klapisz, C., 1998, "Retrieval of precipitation from microwave airborne sensors during TOGA COARE", *J. Appl. Meteor*., **37**, 701-717.

Weinman, J. A. and Devis, R., 1978, "Thermal microwave radiances from horizontally finite clouds of hydrometeors", *J. Geophysics. Res*., **83**, 3099-3107.

Wentz, F. J. and Spencer, R. W., 1998, "SSM/I rain retrievals within a unified all weather ocean algorithm", *Jour. Atmos. Sci*. 1613-1627.

Wilheit, T., Adler, R., Barrett, E., Bauer, P., Berg, W., Chang, A., Ferraday, J., Grody, N., Goodman, S., Kidd, C., Kniveton, D., Kummerow, C., Mgnai, A., Olson, W., Petty G., Shibata, A., and Smith, E., 1994, "Algorithms for the retrieval of rainfall from passive microwave measurements", *Remote Sensing Rev.*, **11**, 163-194.

Wilheit, A. T. C. Chang, M., Rao, S.V., Rodgers, E. B. and Theon, J. S., 1977, "A satellite technique for quantitatively mapping rainfall rates over the oceans", *J. Appl. Meteor*., **16**, 551-560.

Wilheit, T. T. and Chang, A. T. C., 1980, "An algorithm for retrieval of ocean surface and atmospheric parameters from the observations of SMMR", *Radio Science*, **15**, 525-544.

Wilheit, T. T., Chang, A.T.C. and Chiu, L. S., 1991, "Retrieval of monthly rainfall indices from microwave radiometric measurements using probability distribution functions", *J. Atmos. and Oceanic. Tech*.,. **8**, 118-136

Xu, L., Gao, X., Sorooshian, S. and Arkin, P.A., 1999, "A microwave infrared threshold technique to improve the GOES precipitation Index", *J. Appl. Meteor*., **38**, 569-579.

Yao, Z., Li, W., Zhu, Y., Zhao, P. and Chen, Y., 2001, "Remote sensing of precipitation on the Tibetan plateau using the TRMM microwave Imager", *J. Appl. Met*., **40**, 1381-1392.