USE OF MICROWAVE RADIOMETRY TO ESTIMATE PRECIPITATION : PHYSICAL BASIS AND INTERCOMPARISON OF ALGORITHMS

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ABSTRACT

The application of microwave radiometry for rainfall estimation is discussed. The first part presents a description of processes by which hydrometeors affect microwave radiation.

In order to show the state-of-art of rainfall estimation with space-borne microwave radiometry five algorithms are intercompared in the second part. Two are based on scattering, one on emission and two are mixed algorithms, which include both emission and scattering.

The algorithms are applied to SSM/I observations over the Atlantic Ocean. The retrieved rainfall rates by the different algorithms partly differ a great deal. The differences depend on climatic regions, demonstrating that the algorithms are probably tuned to certain atmospheric conditions. The question arises whether a globally applicable algorithm is possible at all. A severe problem is the validation of the retrieved precipitation because hardly any direct observations are available. Thus an intercomparison of algorithms is today the only way to understand the behaviour of a scheme in different weather and climate situations and assess its results.

KEYWORDS

Microwave radiometry, hydrometeors, rainfall, satellites, precipitation algorithm

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1. Introduction

Of all present-day available space-borne remote sensing methods for rainfall estimation, microwave radiometry is the only direct one. That means the signal observed at satellite level is directly related to the amount of rain water in a raining cloud. This fact does not mean that microwave radiometry is a priori superior to other indirect methods as e.g., in infrared or visible spectral range. But the latter methods are limited in their applicability and there is more potential in the microwave methods, which are, however, not yet fully exploited.

In this paper the physical principles are discussed which provide the basis for the rainfall retrieval from microwave observations. The state of art of the rainfall estimation with microwave radiometry is demonstrated with a comparison of the results of five published rainfall retrieval algorithms applied to SSM/I (Special Sensor Microwave/Imager, see Hollinger et al., 1987). The lack of in-situ data makes an assessment of the absolute accuracy of the retrieval results impossible.

2. Basic principles

Hydrometeors i.e., water drops and ice particles, affect the microwave (MW) signal by several physical processes:

- self-emission by hydrometeors,
- scattering and absorption of the atmospheric and surface emission by hydrometeors,
- scattering and absorption of the emitted radiation of water drops by hydrometeors at higher levels.

Over the ocean with small emissivity the first process increases the clear-sky emission. The other processes work in the opposite direction. The total effect depends on the amount of rain water, its vertical distribution, and the amount of cloud water and ice content at higher levels. These competing processes can produce an ambiguity in the rainfall - brightness temperature relation as it is typically found in single channel algorithm. (Brightness temperature T_B is defined as the thermodynamic temperature that a black body would have if it would emit the same amount of MW energy which is received by a radiometer; therefore T_B is just another measure for the radiative energy.)

Absorption (emission) and scattering depend on cloud and rain parameters and on the frequency which is used for the observation (see Ulaby et al., 1981). The following considerations are important (here we have assumed Rayleigh approximation, which is valid for $2\pi |m| r\, \nu/c \ll 1$ with c = phase speed of light, m = index of refraction, r = droplet radius, ν = frequency):

1. Instrumental parameter (frequency, ν): absorption ~ ν, scattering ~ ν^4:

   Absorption and scattering increase with increasing frequency and for the scattering the increase is much greater. That means, scattering is more important when higher frequencies are used and on the other hand, scattering can be neglected at low frequencies.

2. Cloud and rain parameters

a) number density of particles, n_o: absorption ~ n_o, scattering ~ n_o.

   Both coefficients are directly proportional to the number of droplets or ice particles.

b) radius of particles r: absorption ~ r^3, scattering ~ r^6

   Both coefficients increase strongly with r; the effect of small particles is therefore negligible. For large particles scattering becomes more important than absorption.

c) K parameter ($K = (m^2-1)/(m^2+2)$): absorption ~ Im(-K), scattering ~$|K|^2$

   The index of the refraction, m, and therefore also K depends on frequency and on temperature and phase of the particles. Because the variation of K with ν and T is small, it is neglected.

   The main dependency is on phase of the particles. The imaginary part of K (Im(-K)), which determines the absorption coefficient σ_a, is about 10^{-3} smaller for ice particles compared to water drops. The ratio of $|K|^2$ for both phases is about 5, for water larger than for ice. As a consequence absorption by ice particles is far less than the absorption by water drops, even though both hydrometeors may have similar scattering properties.

For larger drop sizes and higher frequencies Rayleigh approximation is no longer valid and Mie theory shows that absorption and scattering can decrease again. From the above discussion, the following conclusions can be drawn for the appli-

cation of microwave radiometry to determine rainfall:

- water clouds ($r < 100$ µm) have only a small effect at low frequencies ($\nu < 20$ GHz),
- ice clouds are "almost invisible" for frequencies up to about 40 GHz,
- for high frequencies (85 GHz and higher) scattering is the dominant effect of ice clouds,
- emission is the dominant effect of water clouds and rain for all frequencies but scattering will increase with increasing droplet size.

A further property of the radiation field, which has to be considered, is polarization. Radiation emitted by the sea surface is linearly polarized, in contrast to the radiation of the atmosphere and of water and ice drops (as long as the latter two randomly oriented). The degree of polarization of the received microwave signal is therefore a measure of the contribution of radiation from the sea surface to the total signal. Thus, it is a measure of cloud transmission (rain intensity) and/or the amount of cloud-free ocean viewed by the antenna within the beam width.

These different effects of rain clouds on the microwave signal lead to three fundamentally different rain retrieval algorithms employing channels found on the SSM/I:

- emission type affected however by scattering (19, 37 GHz),
- scattering type including polarization (85 GHz),
- mixed type (19, 37, 85 GHZ).

3. Development of algorithms

Although the physical processes are understood, it is not possible to solve the radiative transfer equation analytically, or to calculate rain intensity directly. In order to develop sufficient algorithms, physical and statistical approaches are accomplished.

A pure physical approach is not carried out. Instead two different methods are applied. First, parameters which are related to rain intensity are theoretically derived or based on physical reasoning. The polarization corrected temperature introduced by Spencer et al. (1989) or the scattering index defined by Petty (1994)

are such parameters. Their relation to rain intensity has to be empirically derived on a statistical basis. Second, a method is applied which make use of statistical inversion technique. Brightness temperatures of several channels (frequencies) are simulated assuming a prescribed cloud vertical structure (e.g., Kummerow and Giglio, 1994). See also the paper of Weinman et al. in this volume, they used the method with air-borne observations and retrieve the vertical distribution of hydrometeors from radar measurements.

Most often statistical approaches are applied. The most simple one is to take direct observations of brightness temperatures and associated rain intensities and carry out a multiple regression analysis. Based on physical reasoning the regression can be taken non-linear. There are, however, disadvantages with this procedure. First, direct observations of rain intensities at the times of the satellite overpass are very rare (in particular over the oceans). Second, since brightness temperatures depend not only on rain water but on many other atmospheric and surface parameters, such a regression may only be representative for a certain climatic region or time of the year, i.e., for situations which are similar to those included in the original observation data set.

An alternative to these problems is to apply simulated data: brightness temperatures are calculated given the state of the atmosphere and surface and given a great variety of rain intensities (e.g. Wu and Weinman (1984), Bauer (1992)).This approach, though most often followed, may lead to uncorrect results too. Since atmospheric parameters are well correlated with each other (though the relation is not exactly known), rain water for example cannot be changed independently of the vertical distribution of temperature and humidity and may be correlated to cloud water and ice. Thus, multiple regession analysis may be applied to totally unrealistic situations.

The latter problem can be solved by a combination of the radative transfer model with a numerical cloud model (e.g. Mugnai and Smith (1988), Adler et al. (1991)). This gives an excellent insight into the interaction between cloud and rain particles and microwave radiation.

Fig. 1 (examples from the work of Adler et al.) shows the rain intensity brightness temperature relationship for 19, 37 and 85 GHz. It clearly demonstrates the ambiguity in the rainfall estimation when using a single channel algorithm. The 19 and 37 GHz T_B's increase only for low rainfall rates.

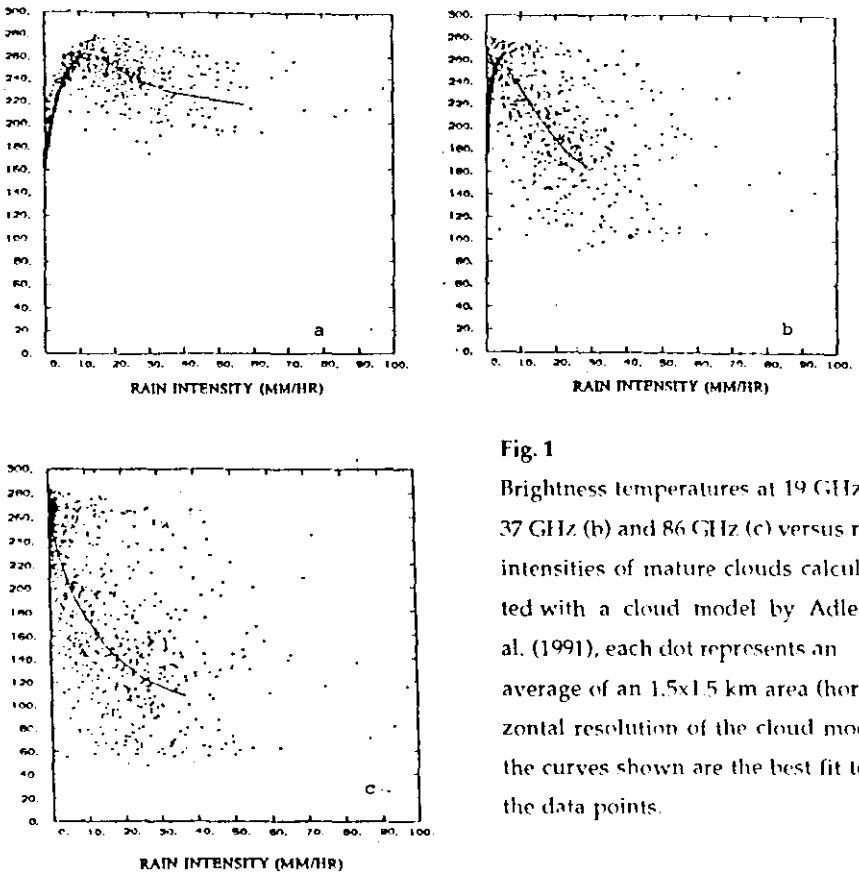

Fig. 1
Brightness temperatures at 19 GHz (a), 37 GHz (b) and 86 GHz (c) versus rain intensities of mature clouds calculated with a cloud model by Adler et al. (1991), each dot represents an average of an 1.5x1.5 km area (horizontal resolution of the cloud model), the curves shown are the best fit to the data points.

Brightness temperature maximum exists at intermediate rain rates. The T_B's ultimately decrease as the rain rates increase because in heavier rain cloud optical thickness is increased, and it contains more large drops which scatter the microwave radiation back to the earth. The reduction of T_B is even more intense at higher frequencies (85 GHz and partly 37 GHz) because of scattering effects caused mainly by ice hydrometeors. The figures also show a large variation of T_B. It demonstrates the effect of the other atmospheric parameters as for example

cloud and ice water, temperature and humidity distribution or surface properties. The effect of variable cloud properties can be reduced if the spatial resolution is decreased or results are averaged over larger areas. Then for example a linear decrease of T_B at 85 GHz with increasing rain intensity is found. Thus, Adler et al (1993) have developed an algorithm based on 85 GHz channel observation only. Though this approach is very helpful for the development of an algorithm, rainfall data are necessary to derive regression coefficients and to validate the method.

4. Intercomparison of different algorithms

The many processes of interaction between a rain cloud and the MW radiation field are the basis for different rainfall algorithms. From the above discussion one may come to the conclusion that one single algorithm for all different types of rain clouds may be impossible to derive. In order to learn what different algorithms are able to perform, we have carried out an intercomparison of five rainfall algorithms. All of these were available to us from the literature. All are applicable to SSM/I data and determine rain intensity over the ocean. The five algorithms are cited in Table 1; shown also are the algorithm types, used channels, the methods applied for the algorithm development, and how a threshold rain/no rain is set. The channels, which are given in parentheses, are used for the description of the state of the atmosphere and ocean surface as for Petty and Katsaros or to determine the rain/no rain threshold as for Adler et al. The algorithm of Petty and Katsaros (1990) is based on theoretical consideration how polarisation of the 85 GHz radiation is altered by rain water. They defined a scattering index which is mainly a function of the polarisation difference of the 85 GHz brightness temperatures. The rain intensity is directly related to this index. The coefficients in this relationship are empirically determined including a threshold for the scattering index which has to be exceeded if rain water is present.

Bauer (1992) used a radiative transfer model to simulate brightness temperatures of the SSM/I channels. Input of model are radiosonde profiles and a great variability of rain rates. Multiple regression analysis applied to the rain rates and the simulated T_B yields his algorithm. Since small rain are overestimated, Bauer defines an external threshold of 0.3 mm/h, estimated rain rates lower than these

Algorithm	Mode	SSM/I channels	Method	Threshold
Petty/Katsaros (1990)	scattering polarization	85 H+V(19 H+V, 22 V, 37 H+V)	theoretical, empirical	internal
Bauer (1992)	mixed	19 H+V, 22 V, 85 V	multiple regression of simulated data (schematic clouds)	external
Liu/Curry (1992)	mixed	19 H, 85 H	theoretical, empirical	external determined for each region
Prabhakara et al. (1992)	emission	37 H	statistical analysis of rain fall data, empirical	internal
Adler et al. (1993)	scattering	85 H (19 H+V, 22 V, 37 H)	regression of simulated data (cloud model)	external, decision tree for each pixel

Tab. 1 Algorithms included in the intercomparison study
Mode = basic physical process of the algorithm (mixed = emission and scattering); H, V = horizontal, vertical polarization.

values are set to zero.

Liu and Curry (1992) use also the results of a radiation transfer model. They deduced from these results that the difference of the emission dependent 19 GHz T_B and the 85 GHz T_B which depends mainly on the scattering effect can be related to the rain rates. The coefficients of their algorithm are empirically determined. SSM/I observations of a cloud free ocean are used to derive a rain/no rain threshold on a statistical basis.

Prabhakara et al. (1992) performed a statistical analysis of rain fall data and brightness temperature. The statistical results (e.g. cumulative frequency distributions) are similar. Their algorithm is developed on the basis of these comparison results. Empirically determined coefficients depend on total

precipitable water, which has to be retrieved by SSM/I observations in addition. A minimum 37 GHz T_B is determined depending on the total precipitable water, it serves as a rain fall threshold of the algorithm.
Adler et al. (1993) evaluated results of their numerical cloud model and could show that the 85 GHz T_B is linearly related to rain intensity. If rain fall increases 85 GHz T_B decreases because of the increase of the scattering effect, mainly of ice particles. A decision tree programme based on 19, 22 and 37 GHz T_B is applied to distinguish between rain and no-rain pixels.

Since we had no in-situ rainfall data available, the intercomparison is indirect. SSM/I data of November 1987 over the Atlantic Ocean were applied to the five algorithms. Rain intensities were calculated and intercompared. A validation was not possible, rather the intercomparison study shows differences between the different algorithms. The calculated rain intensities were spatially averaged for each 0.5° x 0.5° longitude, latitude area and each satellite overpass. These spatial means of every day of the month were then summed up to give the monthly value.
The Fig. 2 a - c show scatter diagrams of the monthly values of the four other algorithms against the scattering algorithm of Petty and Katsaros for three climatic regions (each dot represents a monthly value of a 0.5° x 0.5° longitude, latitude area). It is interesting that the estimated rainfall agrees best in mid latitudes. The largest differences occur in the tropics. The two scattering algorithms (Petty and Adler) show in general the smallest differences, even between these results large biases are found, even in the tropics, where the scattering on ice clouds dominates. The largest differences are found between the scattering and the emission (Prabhakara et al.) algorithms in the tropics. In general the Prabhakara et al. algorithm shows the greatest scatter with respect to the others.
With this study it is not possible to analyse the causes for the different behaviour of the five algorithms because the structure of the raining systems in each region is not known in detail. The partition into three climatic regions asssumes that the rain clouds are different: high convective clouds within the ITCZ (tropics), broken (may be warm) clouds in the subtropics and warm and cold front rain systems (mid-latitudes). This assumption is true in a climatic mean, how

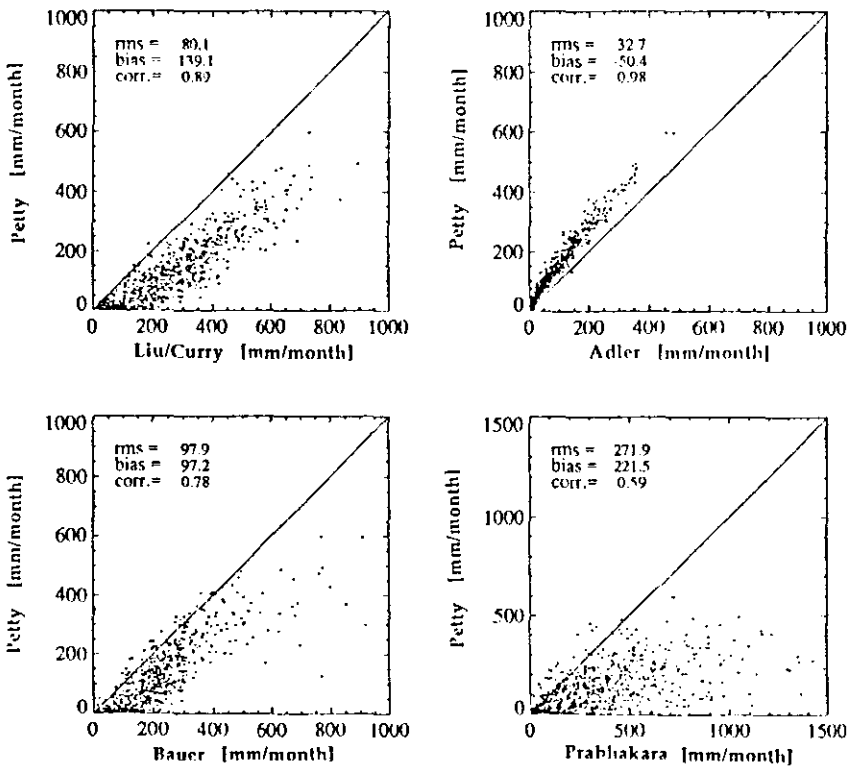

Fig. 2 Intercomparison of the five rainfall algorithms. The scatter plots show the November 1987 means for each 0.5° x 0.5° longitude, latitute area over the North Atlantic Ocean.

a) Tropics (01 - 08° N, 20 - 50° W)

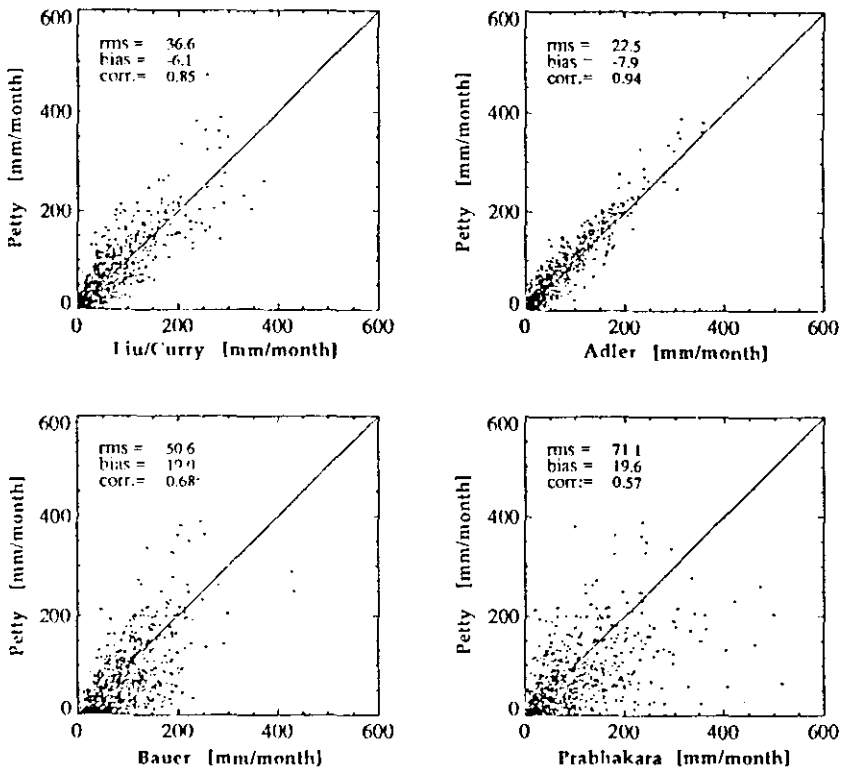

Fig. 2 continued

b) Subtropics (30 - 37° N, 30 - 60° W)

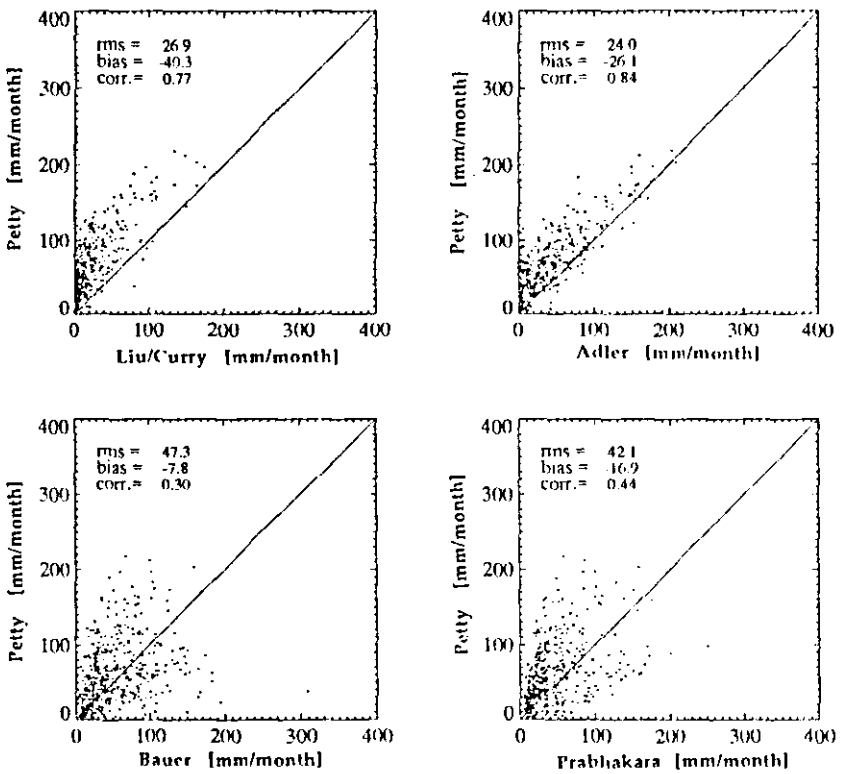

Fig. 2 continued
c) Mid-Latitudes (50 - 57° N, 00 - 30° W)

different the cloud systems are in this actual case of November 1987 is not known. In order to understand and to explain their behaviour we plan to apply these algorithms to the results of our numerical cloud model which gives the vertical distribution of rain water, cloud water and ice.

For further intercomparisons the mean rainfall maps of the Atlantic Ocean were constructed for November 1987 (Thomas, 1993). All algorithms reproduce of course the general rainfall distribution i.e., maximum within the ITCZ and heavy rain in the storm track regions of the midlatitudes and very little rain within the subtropics. (An algorithm, which cannot reproduce these general structures, is completely useless.) The differences of the absolute amounts are of interest. The purpose of these maps is, to demonstrate how large the differences of a monthly mean rainfall map can be, if one selects just one (published) algorithm. Within the ITCZ the Prabhakara et al. algorithm gives maximum values of about 1000 mm / month whereas Adler et al. determined less than 500mm / month at maximum. Similar differences are observed over the Gulf Stream region. In the Subtropics, in particular over the South Atlantic Ocean, the two scattering algorithms (Adler et al., Petty/Katsaros) give large areas without any rainfall, in contrast Bauer and Prabhakara et al. found nearly no rain-free areas. That is mainly the effect of the different thresholds. The results in the storm track regions agree fairly well at least in the Northern Hemisphere. Very large differences, however, are found in the Southern Hemisphere.

As mentioned above, we cannot assess which algorithm gives the best results, because we had no in-situ measurements. However, the 1st Algorithm Intercomparison of the GPCP (Lee et al., 1991) provided rainfall data (surface measurement and radar) over and around Japan for two time periods of 1989: June and July 15 - August 15 to compare with the estimated values. Four of the above algorithms were applied to this comparison: Adler et al., Petty/Katsaros, Liu/Curry, Prabhakara et al. Though we do not know whether any changes have been carried out to the published version of the algorithms, we assume that these are the same versions we applied.

Very large differences are obtained, for single values of each 1.25° x 1.25° latitude/longitude region deviations of more than 100% are not seldom. Even this intercomparison project does not allow to assess which algorithm works best,

differences from June (frontal precipitation) to July/August (tropical convective rainfall) are large.

5. Conclusion

Our intercomparison shows, the results of the five algorithms do not support each other. The differences are very large. The 1st GPCP Algorithm Intercomparison Project did not yield more clarity. In order to calculate monthly mean rainfall or compare SSM/I retrieved rainfall with the amount measured at the ground, the sampling problem has to be considered. With one DMSP satellite a certain area is viewed only two times a day, in low latitudes even only every fourth day. As a solution to this problem one may consider either to have more satellites with microwave radiometer on board or to use additional data from other satellites with higher viewing frequencies but different channel observations (e.g. geostationay satellites). More research is needed in this direction. One conclusion from the 1st GPCP Project is that for a test phase a period of one month is too short to validate an algorithm sufficiently. During a month the rain process may be not very different so that an algorithm can be suitable to this special process, but totally fail in other situations.

The great variety of the rain processes e.g., with and without ice phases, with high amount of cloud water above the rain or not, leads to the conclusion that one algorithm emission or scattering type cannot estimate the rain intensities in all possible situations. The solution is not a mixed algorithm per se, but a decision tree algorithm, with two main decisions to carry out:

1. Is there rain within this pixel?
2. What type of rain and therefore what type of algorithm has to be applied?

The combination of numerical cloud models with radiative transfer models is a very helpful tool for the development of such algorithms. Additional information about the atmosphere and the vertical structure of the rain cloud is probably necessary.

Also the statistical inversion technique should be investigated in more detail. In order to understand and improve existing algorithms, further intensive intercomparison campaigns are needed.

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