Optimization of an Algorithm for the Estimation of Rainfall from the Special Sensor Microwave Imager Data

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Abstract

The optimization of an algorithm is presented, for the estimation of rainfall over the oceans. The empirical algorithm previously developed was based on a thorough statistical analysis of SMMR and SSM/I data, as well as on radar data obtained during the GATE experiment. Since some results seemed overestimated, we performed a critical revision of the derivation of the algorithm, and calculated new coefficients. This modified algorithm gave satisfactory results in the comparison between the SSM/I derived rainfall and the corresponding values obtained by radar's in the framework of the GPCP program.

1. Introduction

Satellite remote sensing of rain is the best means to improve the climatology of rain over oceans, provided that a reliable algorithm is available.

Several investigators (Kilonsky and Ramage, 1975; Arkin, 1979; Adler and Negri, 1988) have analyzed visible and infrared (VIS/IR) satellite observations, to estimate rainfall from space. However, in these spectral regions, rainfall must be inferred indirectly, since clouds are opaque. Clouds and rain are semi-transparent in the microwave region, particularly at frequencies at or below 37 GHz.

The information on rain based on passive microwave (MW) measurements in the frequency range between 6.6 and 37 GHz can be obtained from the radiometric measurements taken by the Scanning Multichannel Microwave Radiometer (SMMR) (Gloersen and Hardis, 1978) and those between 19 and 85 GHz from the Special Sensor Microwave/Imager (SSM/I) (Hollinger et al., 1987). The brightness temperature ($T_b$) measurements at 37 GHz, with a field of view (fov) of about 30 km, show relatively strong emission from rain. At frequencies less than 37 GHz, the fov is much larger and the extinction is weaker. At 85 GHz (fov≈15 km), the extinction is too strong, and does not yield direct information on the rain below the clouds.

The satellite-borne passive microwave radiometers have a field of view that is much larger than the scale of the rain cells, which are only a few kilometres in size. Rain rates associated with different rain cells, present in the fov of the radiometer at a given time, can vary widely. Moreover the radiometer response reaches saturation and the brightness temperature does not increase with further increase in the rain rate.

Prabhakara et al. (1992) developed an empirical method to sense rain rates from SMMR and SSM/I data, which inherently incorporates these effects. However in the mid-latitudes this technique seems to overestimate rain. Moreover the GATE July 1974 observed mean rain rate was 0.49 mm/h, while the mean rain rate for July 1979 obtained from SMMR was 0.55 mm/h (Prabhakara et al., 1992). This suggests that the algorithm used for the satellite data overestimates rain. The overestimation was evident when the data from the Global Precipitation Climatology Project (GPCP) program became available (WMO, 1990; Lee et al., 1991).

For this reason, we modified the procedure followed to obtain the algorithm, which gave new coefficients, with the same approach. In this study, the modified algorithm was tested by comparing the SSM/I derived rainfall with the corresponding values obtained by radar's and rain gauges in the framework of the GPCP program.

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2. Methodology

Prabhakara et al. (1992) examined the data obtained by SMMR and SSM/I during the period from July to August 1987, when both instruments were functioning simultaneously, to investigate the response of the various channels to meteorological conditions that ranged from clear skies to heavy rain. From this analysis they found that the $T_b$'s at 37 GHz exhibit a near linear relationship with the corresponding $T_b$'s at lower frequencies. They also found that over the oceans the polarization difference at frequencies $\nu \leq 37$ GHz is inversely proportional to $T_b$. For example, the polarization difference, $T_{V}^{37} - T_{H}^{37}$, is inversely proportional to $T_{H}^{37}$. Since the sea surface is essentially the polariser, the observed polarization difference at 37 GHz is produced by the ocean in the fov of the radiometer that is not obscured by opaque clouds and rain. Thus the polarization differences and $T_b$'s obtained from the multichannel SMMR and SSM/I observations at frequencies $\nu \leq 37$ GHz relate to one strong information pertaining to the hydrometers. This one independent piece of information, i.e. the effective rain area in the fov, is not sufficient to retrieve the distribution of rain over global oceans.

The GATE data (Chiu, 1988) and rain gauge measurements at several stations in the United States (Jones and Sims, 1978) show that the convective rain rates have frequency distributions that are highly skewed. Figure 1 shows the percentage cumulative frequency of rain rate $R$ plotted against the logarithm of $R$, obtained with the GATE radar data in 1974.

The frequency distributions of the satellite brightness temperature measurements, presented on a linear scale, show a behaviour similar to the corresponding distributions of the logarithm of rain rate $R$ (Fig. 2). Obviously the distribution shown contains all events, and it is necessary to exclude $T_b$ values that do not correspond to rain, to compare

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Fig. 1. Cumulative frequency distribution of rain rate $R$ for GATE observations at 4 $\times$ 4 km$^2$ and 40 $\times$ 40 km$^2$ resolutions taken from the analysis of Chiu (1988).

Fig. 2. Frequency distribution of measured 37 GHz brightness temperatures obtained from SMMR data on the GATE area for the same time interval.

Fig. 3. Cumulative frequency distribution for the same data presented in Fig. 2.
the statistics of GATE data with those of satellites. For this reason \( T_1 \)'s that are less than a discriminant temperature \( T^* \) are excluded, where \( T^* \) can be chosen as the brightness temperature at the maximum of the frequency distribution (see Fig. 2). When we plot the cumulative frequency distribution of the remaining \( T_1 \)'s, as shown in Fig. 3, the similarity with the cumulative frequency distribution of the GATE radar data (Fig. 1) becomes evident.

This similarity in the percentage cumulative frequency distribution of GATE data of July 1974, and the SMMR \( T_{37} \) data over the GATE area for July 1979, is used in this study to develop a rain retrieval algorithm.

Prabhakara et al. (1992) analysed the microwave data as a function of latitude, to gain a better understanding of \( T^* \). In Fig. 4, the SSM/I measurements during one month are used to generate the frequency distribution of \( T_{37} \) at each latitude, from 60°N to 60°S, along 145°W longitude. From this figure we notice that the minimum in \( T_{37} \) (\( T_{37\min} \)) varies systematically from 60°N to 60°S. This minimum depends on the ocean temperature and on the water-vapour content in the atmosphere as a function of latitude. Prabhakara et al. (1983) determined this dependence with radiative transfer calculations, using a large number of temperature and water-vapour profiles, observed by radiosondes at island stations spread over a wide latitudinal range. From these calculations, they showed that in clear-sky conditions \( T_{37\min} \) can be related to the water-vapour content \( w \) (g/cm²) in the atmosphere by the following linear relationship:

\[
T_{37\min} = 124 + 7.9w. \tag{1}
\]

The \( T_{37\min} \) calculated here, including only water vapour and no clouds, corresponds to the \( T_{37\min} \) shown in Fig. 4.

Maximum frequency in the distributions shown in Fig. 4 occurs at a temperature denoted by \( T^* \), which is about 15 K warmer than the minimum \( T_b \) at any given latitude. The value of \( T^* \) ranges from about 175 K in the highly convective tropical oceans to about 145 K in the high latitudes. The statistical observations shown in Fig. 4 imply that, on the global oceans, \( T_{37} \) has to grow by about 15 K above the minimum in brightness temperature to correspond to rain-producing clouds.

The temperature \( T_{37\min} \) given by satellite microwave observations (Fig. 4), can be used to derive seasonal maps of columnar water-vapour content \( w \) in the atmosphere (Prabhakara et al., 1985). The satellite derived \( w \) can be included as a second piece of information in the rain-retrieval scheme. The discriminant brightness temperature \( T^* \) is the third parameter, and can be obtained over global oceans as a function of season from \( T_{37\min} \), i.e. \( T^* = T_{37\min} + 15 \) (see Fig. 4). These two independent pieces of information, \( T_{37} \) and \( T_{37\min} \), yield the three parameters \( T_{37} \), \( w \), and \( T^* \), which are used for the empirical rain-retrieval scheme.

From the analysis of the rainfall data and the results of theoretical studies (Adler and Mack, 1984; Lopez et al., 1989), we can relate the effective rain area \( A \) in the fov of the radiometer to the logarithm of rain rate \( R \) averaged over the same fov. To satisfy the condition \( R = 0 \) for \( A = 0 \), we take

\[
\ln(R + 1) = aA^\chi, \tag{2}
\]

where \( a \) and \( \chi \) are constants greater than zero.
For the interpretation given to $T^*$, the area $A$ also approaches zero for $T_{37} \to T^*$. Thus, we take

$$T_{37} - T^* = bA,$$

where $b$ is a constant. From Eq. (2) and (3) we have

$$\ln(R + 1) = \beta(T_{37} - T^*)^x,$$

where $\beta = a/b^x$ is constant for a given oceanic region. The rain rate $R$ is then given by

$$R = e^{\beta(T_{37} - T^*)^x} - 1.$$

Eq. (4) can also be written as

$$\ln L_R = \chi \ln (T_{37} - T^*) + \ln \beta,$$

with $L_R = \ln(R + 1)$. Equation (6) shows that $\ln L_R$ and $\ln(T_{37} - T^*)$ are linearly related. A least squares fitting of the data presented in Table 1 gives $\chi = 1.09$ and $\beta = 0.02$, with a correlation coefficient of 0.998.

The values listed in Table 1 are taken from the 40 km resolution GATE data (see also Fig. 1), and the SMMR 37 GHz data shown in Fig. 3. In this table the percentage cumulative frequency, presented in Figs. 1 and 3, is taken as a common parameter to relate the rain rate $R$ and $T_{37}$.

Rain statistics over global oceans can vary regionally and as a function of season; this variability over the global oceans is modelled in terms of the columnar water-vapour content $w$ in the atmosphere, which is a function of seasonally varying sea surface temperature, and it also depends on the dynamic state of the atmosphere (Prabhakara et al., 1977). The constant $\beta$ can then be assumed to increase with $w$.

An analysis of the July rainfall statistics obtained in the GATE experiment over the tropical North Atlantic shows that

$$\beta(w) = (5 + 3.3w) \times 10^{-3}$$

where $w$ is in g/cm$^2$. Equation (5) then becomes

$$R = e^{\beta(w)(T_{37} - T^*)^x} - 1,$$

which indicates that the convective rain rate increases exponentially with $w$.

For each grid box and time interval, we find $T_{37 \text{ min}}$, and take $T^* = T_{37 \text{ min}} + 15$. Then $w$ can be calculated from Eq. (1), and $\beta$ from Eq. (7). Finally Eq. (8) gives the rain rates for each grid box.

Since the information given by the SSM/I 85 GHz data relates to the hydrometeors above the clouds, and not directly to the rain, we have not utilised this channel in this study.

### Table 1. Percentage cumulative frequency CF and rain rate $R$ taken from Fig. 1, and the corresponding $T_{37}$ taken from Fig. 3. $L_R$ is $\ln(R + 1)$, and $T^* = 175$ K.

<table>
<thead>
<tr>
<th>CF</th>
<th>R mm/h</th>
<th>$L_R$</th>
<th>$T_{37}$</th>
<th>$T_{37} - T^*$</th>
</tr>
</thead>
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<tr>
<td>0.23</td>
<td>1</td>
<td>0.69</td>
<td>201</td>
<td>26</td>
</tr>
<tr>
<td>0.14</td>
<td>2</td>
<td>1.10</td>
<td>214</td>
<td>39</td>
</tr>
<tr>
<td>0.09</td>
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<td>1.39</td>
<td>225</td>
<td>50</td>
</tr>
<tr>
<td>0.07</td>
<td>4</td>
<td>1.61</td>
<td>230</td>
<td>55</td>
</tr>
<tr>
<td>0.05</td>
<td>5</td>
<td>1.79</td>
<td>237</td>
<td>62</td>
</tr>
</tbody>
</table>

### 3. Comparison with GPCP data

The most difficult part in the development of a technique for the estimation of rainfall from satellite data, is its validation with in situ measurements.

Rain is highly variable in space and time, and is characterised by horizontally inhomogeneous distributions in the liquid water content and drop size. The microwave radiometer, with an fov that is large compared to individual rain cells, is responding to some area-averaged properties of these variables. Moreover the radiometer response is not directly proportional to the amount of emitting matter (liquid drops) in the fov because of saturation effects.

The response, $T_\beta$, is apparently dependent on the effective area occupied by the emitting hydrometeors (Prabhakara et al., 1989; Petty and Kastanos, 1990).

For these reasons, satellite remotely sensed rain rates cannot be compared directly to the corresponding in situ measurements, but the comparison has to be performed only on suitable area-time averaged values.

The functional form of the algorithm previously presented was based on a thorough statistical analysis of SMMR and SSM/I data (Prabhakara et al., 1992), and the coefficients were obtained by forcing the normalised cumulative frequencies of the GATE and SSM/I results to match, for the same area and time interval (unfortunately not the same year). Similarly, a test of the performance of the algorithm could be done only on the cumulative monthly rainfalls, with the best in situ data set available.

The Global Precipitation Climatology Project (GPCP) (WMO, 1990) is planned to provide analyses of area-averaged rainfall, obtained from rain gauges and radar’s. The Algorithm Intercomparison Programme (AIP) of the GPCP provides a test of the performance of the techniques developed for the retrieval of rainfall information from satellite data, with the aim of selecting an algorithm adequate to meet the requirements of the World Climate Research Programme (WCRP).

In situ data over the seas around Japan were averaged on grid boxes comparable to the fov of the 37 GHz channel, and the total rain of the month of
June 1989 was calculated for each grid box. These values were compared with the corresponding values of the cumulative precipitation estimated with Eq. (8) from the SSM/I data, and the comparison is presented in Fig. 5.

The comparison on the same GPCP data around Japan, performed with the algorithm presented in our previous paper (Prabhakara et al., 1992), shows an overestimation of precipitation by as much as 30%, even if the correlation coefficient is about the same, i.e. 0.82. As an example of application of this modified technique, we present a map of the total precipitation for the month of June (Fig. 6).

The dispersion of the data seems to suggest the presence of two thunderstorm systems of different type during the month of June.

4. Discussion and conclusions

The microwave measurements from SMMR and SSM/I contain only one strong piece of information related to the rain emission. Thus, an empirical parameter, $T^*$, which is deduced from the spatial and temporal variations in the $T_{37}$ data, is introduced as a threshold above which rain is present. Moreover, the same measurements can also give the columnar water-vapour content $w$ in clear sky conditions, assumed to be present when $T_{37} = T_{37 \text{min}}$. Using these parameters, Prabhakara et al. (1992) developed an empirical scheme to estimate rain rates from SMMR and SSM/I data.

In this paper, we introduce a revision of this empirical scheme, and propose new coefficients for the algorithm.

We apply this modified algorithm to the SSM/I data over the seas around Japan, and compare with the corresponding Global Precipitation Climatology Project (GPCP) program data. Even with the relatively high standard deviation shown in this comparison, the results obtained are satisfactory, particularly when considering the many problems present in the validation procedure of the estimate of precipitation from satellite data.

The results obtained have demonstrated the feasibility of using satellite data to derive information useful to improve the climatology of rain over oceans, and possibly meet the requirements of the World Climate Research Programme.

It is important to test the algorithm developed with a much richer data set, and in particular it is necessary to check its performance in different seasons and latitudes.

The precipitation sensing technique developed in this study does not address the beam filling issue explicitly. When one follows the radiative transfer theory, applicable to horizontally homogeneous precipitation, to retrieve rain rate in a large field of view, a significant underestimation of rain results. Short and North (1990) and Chiu et al. (1990) show that average rain rate in the fov of the radiometer is generally underestimated because of the highly non-linear horizontal distribution of rain. This underestimation can range from about 40% to 70%.

Our empirical rain retrieval method, which depends on effective rain area deduced from the 37 GHz polarization information, incorporates implicitly this beam filling effect (see also Prabhakara et al., 1992). This is accomplished through the parameters $\beta$ and $\chi$ in Eq. (8). Furthermore these parameters have the flexibility to match our rain retrievals to those given by the algorithms of Short and North (1990) or Chiu et al. (1990).
Acknowledgements

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References


SSM/I イメージデータによる降雨量評価アルゴリズムの最適化

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海上での降雨量評価のアルゴリズムの最適化をおこなった。これまでに開発された経験的アルゴリズムは、SMMR と SSM/I データ及び GATE 実験データの統計解析に基づいている。このアルゴリズムを用いたいくつかの結果は過大評価の傾向を示したので、今回新しい係数を用いてアルゴリズムの改良を行なった。

改良されたアルゴリズムを SSM/I データに適用した結果、GPCP プログラムにおけるレーダーから得られた降雨量と比較して満足すべき値が得られた。