Atmospheric Liquid Water Content Derived from Parameterization of Nimbus 6 Scanning Microwave Spectrometer Data

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ABSTRACT

An empirical-theoretical method to determine liquid water content and water vapor amount over land surfaces from Nimbus 6 SCAMS channels is described. The method is based on parameterization of the resulting calculations from the microwave radiative transfer program involving clouds and precipitation. Brightness temperatures selected from satellite passes for five days over the United States are used to test the empirical parameterization method. Liquid water contents derived from the SCAMS data for two days show close comparison with NOAA 6 satellite mosaics as well as values inferred from Nimbus 6 HIRS sounders for the same time period reported previously by Feddes and Liou (1978) in this journal. Applications of the present technique to mesoscale mapping of liquid water content are displayed and its limitation is further discussed.

1. Introduction

In a recent paper published in this journal, Feddes and Liou (1978) presented results of the mesoscale ice and water content mapping utilizing the HIRS (High-Resolution Infrared Sounder) data based on the parameterization of the infrared radiative transfer calculations for various cloudy atmospheric models. It was pointed out that because of the large opacity of water clouds in the infrared portion of the spectrum, the mapping of liquid water content of low clouds could not be carried out using the HIRS channels. Thus, for the purpose of deriving the liquid water content of low precipitating and nonprecipitating clouds, the only possible sounder would have to be in the microwave region.

The purpose of this note is to report our investigation on the atmospheric liquid water content determination utilizing the SCAMS (Scanning Microwave Spectrometer) channels and to compare the resulting liquid water water contents with those derived from the infrared sounders.

2. Parameterization of microwave radiative transfer calculations and SCAMS data

The Nimbus 6 satellite is in an 1100 km, sun-synchronous polar orbit, with a local noon (ascending) and

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midnight (descending) equator crossing, and an 81° retrograde inclination. The SCAMS radiometer scans to each side of the subpoint track and provides nearly full earth coverage every 12 h. The SCAMS consists of five channels. The first channel is centered at 22.235 GHz, located on a weak water vapor resonance. Channel 2, centered at 31.4 GHz, is located in a spectral window, where the atmosphere is essentially transparent at microwave frequencies. Channels 3 (52.85 GHz), 4 (53.85 GHz) and 5 (55.45 GHz) are on the edge of the 60 GHz oxygen band where the atmosphere is nearly opaque at these frequencies, with the peak weighting functions centered at approximately 4, 9 and 14 km, respectively. The ground resolution of SCAMS is approximately 145 km at nadir and 330 km at 43° from nadir.

We have developed a microwave radiative transfer program for nonprecipitating and precipitating cloudy atmospheres similar to the one described by Liou (1974). The microwave radiation program takes into consideration effects of scattering and absorption properties of cloud particles and hydrometeors in an inhomogeneous absorbing gaseous atmosphere. The single-scattering parameters for five SCAMS channels required for microwave radiative transfer calculations were obtained through a Mie scattering program for polydisperse spheres. The real and imaginary indices of refraction used were based on values derived by Gunn and East (1954) and were interpolated and extrapolated to the correct frequencies. The clear-column transmittances of SCAMS channels were kindly provided to us by Woolf (personal communication). For nonprecipitating clouds, several drop size distributions were used in numerous numerical experiments. It was found that no significant change in scattering parameters occurred between various models, and the computed brightness temperatures depend primarily on the total liquid water content. As for precipitating clouds, a theoretical drop size distribution based on rainfall rate developed by Marshall and Palmer (1948) was used.

Comparisons between calculated and observed brightness temperatures were carried out for selected clear, cloudy and precipitation cases in which the observed temperature and humidity profiles were employed in the calculation. We divide the cloudy cases into two groups, thin and thick clouds, based on the examination of the satellite photograph and the surface cloud report. A 1 km and a 4 km nonprecipitating cloud were assumed for the thin and thick overcast cases, respectively. As for precipitating cases, the rainfall rates were obtained from the surface weather observations. During the period from 21–25 August 1975, 21 clear cases, 23 cloudy nonprecipitating cases and 20 cloudy precipitating cases were investigated. The emissivity values for dry soil are assumed to be 0.95–0.97 and for wet soil, 0.92–0.95 (Gloersen *et al.*, 1972). Utilizing the known atmospheric profiles and cloud compositions, the computed brightness temperatures were compared with the observed values. Agreements between the calculated and observed brightness temperatures were in general satisfactory. For clear cases, the standard deviations of the calculated values from the observed brightness temperatures for channels 1–5 were less than 1.3 K. As for cloudy and precipitating conditions, they were less than 1.8 and 1.5 K, respectively. The larger errors in cloudy cases are expected in view of the uncertainty of the cloud composition encountered in the microwave transfer program.

In order to apply the theoretical microwave radiative transfer program to infer the liquid water content, it is necessary to develop an empirical equation in which the liquid water content is explicitly given. Inspection of the microwave spectrum shows that below 40 GHz, the clear-column transmittance is approximately unity. On the basis of further approximations and analyses on the liquid water and water vapor transmittances, the brightness temperature may be expressed by (Grody, 1976)

$$T_B(\nu)\approx\epsilon_s(\nu)T_s+2[1-\epsilon_s(\nu)]T_s[Q/Q_0(\nu)+W/W_0(\nu)], \tag{1}$$

where Q_0 and W_0 are certain constants, ϵ_s denotes the surface emissivity, T_s is the surface temperature, and Q and W are total liquid water and water vapor amount. It follows that the liquid water and water vapor amount may be expressed in the forms

$$Q=q_0+q_1T_B(\nu_1)+q_2T_B(\nu_2), \tag{2}$$

$$W=w_0+w_1T_B(\nu_1)+w_2T_B(\nu_2), \tag{3}$$

where $T_B(\nu_1)$ and $T_B(\nu_2)$ are brightness temperatures at frequencies 22.235 and 31.4 GHz, respectively; q_i and w_i ($i=0$, 1, 2) are coefficients to be determined through statistical-empirical procedures. Grody (1976) and Staelin *et al.* (1976) have used these equations to infer the water content from Nimbus 5 NEMS channels over the ocean surface.

To carry out theoretical calculations to provide numerical values to establish the statistical basis for the determination of q_i and w_i, the surface emissivity is to be prescribed. For dry soil, emissivity values of 0.95 and 0.96 were used for channels 1 and 2, respectively, while for wet soil, they were 0.93 and 0.94. Satellite observations over the land surfaces, however, do not give information of the wet or dry conditions,

TABLE 1. Surface condition determination.

Channel relationship	Surface condition
$T_B(\nu_3)\leqslant 0.97\ T_B(\nu_2)$	dry
$1.01\ T_B(\nu_2)\geqslant T_B(\nu_3)>0.97\ T_B(\nu_2)$	wet
$T_B(\nu_3)>1.01\ T_B(\nu_2)$	water or water-land combination

TABLE 2. Empirical coefficients for dry and wet lands.

	w_0	w_1	w_2	q_0	q_1	q_2
Dry	−65.17	22.9×10^{-2}	13.6×10^{-3}	18.52×10^{-1}	-59.43×10^{-4}	-39.00×10^{-5}
Wet	64.74	-89.85×10^{-2}	68.05×10^{-2}	33.18	-64.88×10^{-2}	53.36×10^{-2}

which significantly affect the surface emissivities. Thus, it would be desirable to develop a means from which *a priori* determination of the characteristics of the land surfaces may be made. Examination of SCAMS data, computer analysis and statistical verification results in an empirical decision matrix using observed brightness temperatures for SCAMS channels 2 and 3 to determine surface characteristics. Table 1 shows the criterion for the determination of the wet or dry surface condition.

A total of 64 atmospheric conditions were used to compute brightness temperatures using the microwave radiative transfer program described previously. Liquid water contents or rainfall rates were added artificially to a selection of atmospheres in varying amounts to get the effects of liquid water content on the brightness temperatures $T_B(\nu_1)$ and $T_B(\nu_2)$. A three-dimensional linear regression technique was used to determine the coefficients q_i and w_i denoted in Eqs. (2) and (3) over dry and wet land surfaces based on empirical-theoretical analyses. They are given in Table 2. Using the empirical coefficients in Table 2, Eqs. (2) and (3) enable the determination of water vapor over dry and wet lands to within standard errors of 0.87 and 0.97 g cm^{-2}, respectively, while liquid water content over dry and wet lands can be obtained with standard errors of 0.18 and 0.22 kg m^{-2}, respectively. Note that these empirical coefficients are derived purely based on the computer-generated data points.

3. Liquid water content determination from SCAMS data

SCAMS data for two days (22 and 25 August 1975) covering the area from 40 to 55°N and from 90 to 110°W with significant weather were chosen and analyzed to derive water vapor and liquid water content amount employing the empirical-theoretical equations described above. There were two areas of overcast conditions under the Nimbus 6 Satellite on 22 August 1975. The surface map at 1200 GMT shows a low-pressure center over eastern Maine with an associated frontal system extending across southern Canada, southern Lake Michigan and across Iowa and Nebraska. Shower activity was present all along this frontal system. A low pressure area in Alberta had a cold front extending into Montana and Idaho, with a warm front through eastern Montana. Showers were present along this frontal system also. The subtrack of the SCAMS pass was along a line from 18.7°N, 91.6°W to 52°N, 104°W. Examination of the NOAA 4 visible and IR pictures, published and discussed previously by Feddes and Liou (1978), indicates a good cloud system north of 43°N on the satellite subtrack. On 25 August 1975, a strong surface low was located southwest of Hudson Bay with a cold front extending through Lake Superior, south through Kansas and westward through Colorado. A stationary front extended across the Great Lakes and New York. Shower activity was present along the U.S.-Canadian border from Maine to Montana with heavy shower activity along the frontal system in Illinois, Iowa and Missouri. The SCAMS pass had a subtrack extending from 19°N, 85.6°W to 52°N and 98.7°W. This pass provided good coverage of the strong activity in the midwest as well as the clouds north of Lake Superior.

The analysis of the SCAMS data for the two days is displayed in Figs. 1–5. In Figs. 1 and 3, the water vapor and liquid water values are plotted for the satellite subtrack for 22 and 25 August respectively. The figures also contain radiosonde (RAOB) data where it was available within 300 km of the subtrack, and a plot of the liquid water derived by Feddes and Liou (1978) from HIRS data for the same subtrack and time frame. In general, wet surface conditions were found between 42 and 45°N and between 48 and 54°N, while on 25 August the wet surface conditions were found between 40 and 42°N and between 49 and 54°N. Fig. 2 shows the brightness temperatures for channels 1, 2 and 3 along the satellite subtrack for 22 August. The surface conditions were first determined using the criteria denoted in Table 1. Liquid water and water

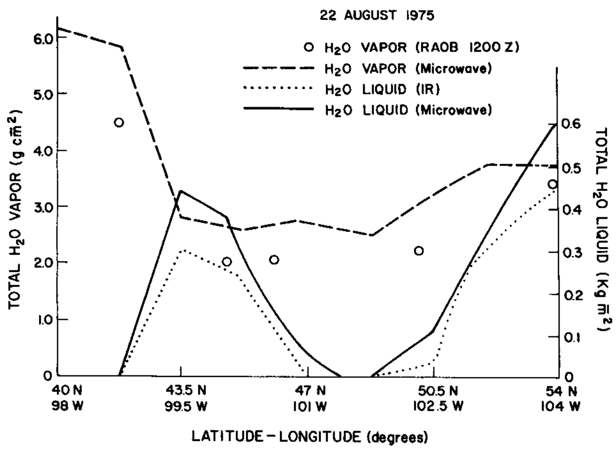

FIG. 1. Computed atmospheric water vapor and liquid water content from SCAMS data along the Nimbus 6 satellite subtrack with comparisons to RAOB observations and results obtained by Feddes and Liou (1978) from HIRS data for 22 August 1975.

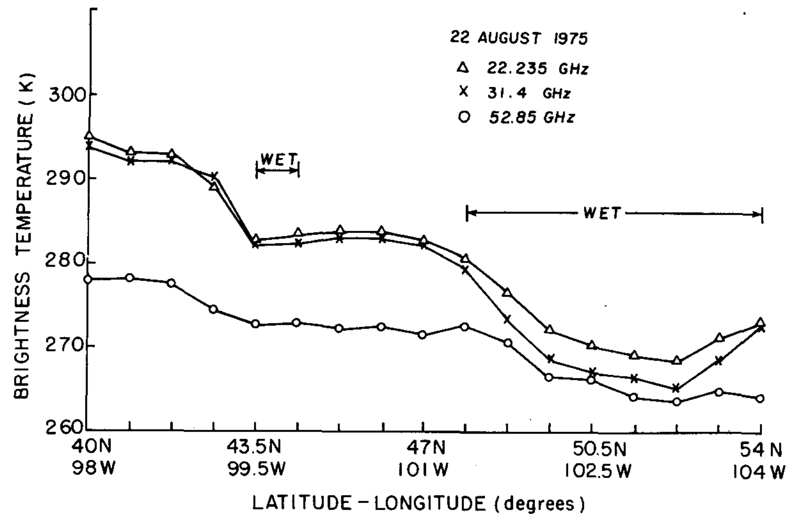

FIG. 2. Observed brightness temperatures for SCAMS channels 1, 2 and 3 along the Nimbus 6 satellite subtrack for 22 August 1975.

vapor amount were subsequently evaluated by means of the empirical-theoretical equations (2) and (3) with the coefficients for dry and wet conditions presented in Table 2.

The water vapor estimates for both days generally correspond within 15% of the RAOB data, and appear to be biased larger than the RAOB data. The SCAMS data scan at satellite subtrack forms a circle approximately 144 km in diameter, providing data averaged over this area, while radiosonde data represent point measurements taken along the balloon flight trajectory, and thus may not be representative of the atmosphere as a whole. Instrument inaccuracy for the radiosonde water vapor measurements is estimated to be approximately 20%.

The SCAMS liquid water measurements may be compared to the satellite photographs and the results obtained from infrared data by Feddes and Liou. The analysis in Fig. 1 for 22 August shows the effects of two overcast areas under the satellite pass. The Feddes and Liou results closely parallel the trend derived from the SCAMS data, but SCAMS data show higher liquid water contents in most cases. This is an expected result due to the capability of microwave to see through cloud layers, providing a better evaluation of lower cloud moisture levels. A similar result is shown in Fig. 3. Again, two cloud masses are shown. The southern mass

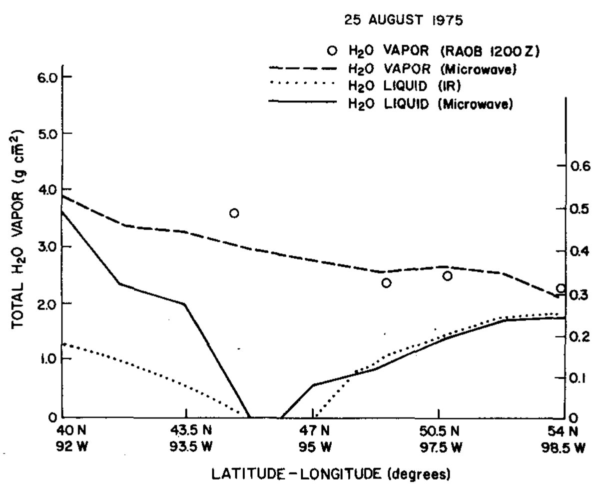

FIG. 3. As in Fig. 1 except for 25 August 1975.

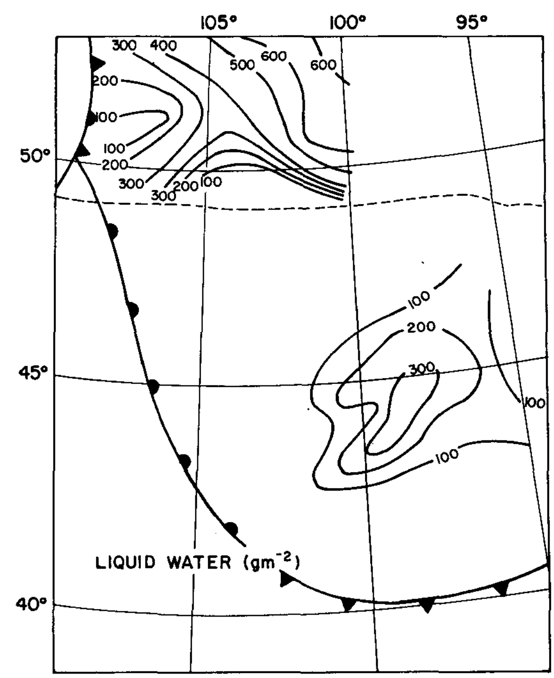

FIG. 4. A mesoscale cloud liquid water content mapping from SCAMS data based on the parameterized empirical-theoretical equations for 22 August 1975. The frontal position on this day is also shown.

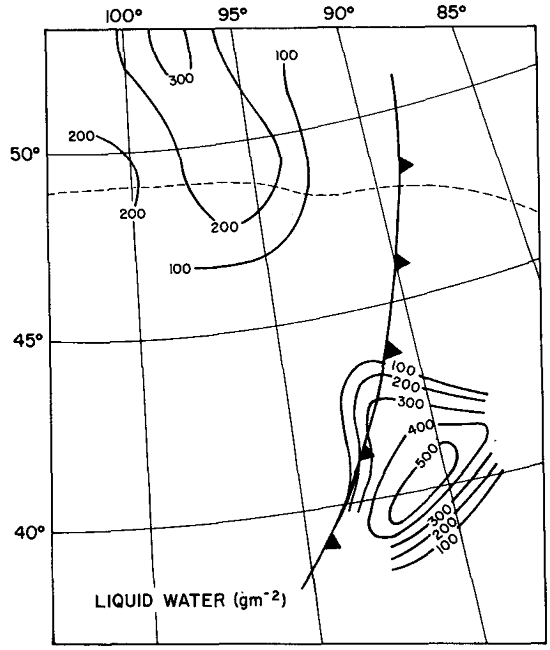

Fig. 5. As in Fig. 4 except for 25 August 1975.

appears on the satellite photographs as an area of cirrus, and shows as an area of low water content in the Feddes and Liou study. The SCAMS data are not affected by the cirrus and yield higher amounts of liquid water, revealing the area of active thunderstorms and rain under the cirrus clouds.

Figs. 4 and 5 display the analyzed SCAMS liquid water content values plotted on a polar projection. The two figures contain the analysis for 22 and 25 August, respectively. The isopleths are labeled with the liquid water content based on the theoretical-empirical calculations. Both figures show two distinct cloud masses. The analyses are quite similar to the results obtained by Feddes and Liou, with the modifications mentioned earlier. The smoothing effects of the larger scan results in only a minor loss of data compared with the results obtained by Feddes and Liou. In Fig. 4 of 22 August, the two cloud areas correspond well with the NOAA 4 satellite visible and IR photographs of the same time. Analysis of Fig. 5 also corresponds well to its matching satellite data. The line of thunderstorms in the southern cloud mass is hidden by the cirrus deck but is well documented by the surface observations. The sharp southern edge of this cloud mass is well defined on the satellite photographs. The southern edge of the northern cloud mass also shows a sharp moisture gradient which is evident on the surface weather map and satellite images.

4. Remarks

By means of the parameterized theoretical-empirical equation, two days of SCAMS data were used to derive and to map the liquid water content over mesoscale cloud systems. Liquid water content values obtained from the SCAMS data were compared to visible and infrared satellite photographs as well as to results derived by Feddes and Liou (1978) using HIRS data. The results compared favorably in both instances. It should be noted that the SCAMS data base from which the samples were taken was limited to a two-week period in August, and the effects of certain surface conditions, such as snow cover, mountain terrain and a combination of water and land surfaces, were not considered and examined. Thus, the success of the present investigation regarding the retrieval of the liquid water content over mesoscale land surfaces must be noted in the context of these limitations. It is clear, nevertheless, that the SCAMS data analyzed in this paper demonstrated a capability to sense liquid water hidden to infrared sensors by overlying cirrus layers and to provide a smoothed map of atmospheric moisture for a variety of atmospheric conditions. This technique would ideally be used in conjunction with other sensors. Infrared sensors, such as the HIRS instrument aboard Nimbus 6, could provide better resolution than the microwave radiometers and are capable of detecting cirrus clouds which are essentially transparent to the microwave spectrum. It would seem that a proper combination of infrared and microwave measurements could result in operationally significant data for vertical and horizontal moisture mapping.

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