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Microwave polarized signatures generated within cloud systems: SSM/I observations interpreted with radiative transfer simulations

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Abstract. Special Sensor Microwave /Imager (SSM/I) observations in cloud systems are studied over the tropics. Over optically thick cloud systems, presence of polarized signatures at 37 and 85 GHz is evidenced and analyzed with the help of cloud top temperature and optical thickness extracted from visible and IR satellite observations. Scattering signatures at 85 GHz ($TbV(85) \leq 250$ K) are associated with polarization differences ≥ 6 K, ~50% of the time over ocean and ~40% over land. In addition, over thick clouds the polarization difference at 37 GHz is rarely negligible. The polarization differences at 37 and 85 GHz do not stem from the surface but are generated in regions of relatively homogeneous clouds having high liquid water content. To interpret the observations, a radiative transfer model that includes the scattering by non-spherical particles is developed, based on the T-matrix approach and using the doubling and adding method. In addition to handling randomly and perfectly oriented particles, this model can also simulate the effect of partial orientation of the hydrometeors. Microwave brightness temperatures are simulated at SSM/I frequencies and are compared with the observations. Polarization differences of ~ 2 K can be simulated at 37 GHz over a rain layer, even using spherical drops. The polarization difference is larger for oriented non-spherical particles. The 85 GHz simulations are very sensitive to the ice phase of the cloud. Simulations with spherical particles or with randomly oriented non-spherical ice particles cannot replicate the observed polarization differences. However, with partially oriented non-spherical particles, the observed polarized signatures at 85 GHz are explained, and the sensitivity of the scattering characteristics to the particle size, asphericity, and orientation is analyzed. Implications on rain and ice retrievals are discussed.

1. Introduction

Passive microwave satellite observations have been extensively studied to estimate cloud properties and precipitation on a global scale. Depending on the observed wavelength and on the cloud and rain characteristics, the microwave radiation is affected by emission, absorption and/or scattering within the hydrometeor layers. During the emission/absorption process, liquid particles cause brightness temperatures to increase over a radiatively cold background like the ocean; the induced warming of the signal increases with frequency up to a saturation level. Retrievals of cloud liquid water paths over ocean are currently based on the emission signals measured between 19 and 85 GHz [e. g. *Greenwald et al.*, 1993; *Liu and Curry*, 1993; *Phalippou*, 1996; *Lin and Rossow*, 1994; *Prigent et al.*, 1997; *Wentz*, 1997]. Emission-based algorithms have also been developed to estimate precipitation [*Wilheit et al.*, 1977; *Prabhakara et al.*, 1992]. In contrast, scattering by large hydrometeors (particle dimensions $\geq$200μm) reduces the amount of radiation measured by the satellite, especially at higher frequencies. The scattering signal at 85.5 GHz has been used, for example, by *Spencer et al.* [1989], *Grody* [1991], *Ferraro et al.* [1996] and *Mohr et al.* [1999] to estimate precipitation over ocean and land. The emission signal originates in the liquid lower part of the cloud and rain whereas the scattering in the upper part of the cloud modulates the emission signal, especially at high frequencies. For each frequency, the radiation measured by the satellite radiometer is determined by the vertical structure of the hydrometeors, with their specific phase, size distribution, and shape. Modeling of the microwave radiative transfer in precipitating cloud systems, including emission and scattering processes, has been investigated to derive precipitation retrieval algorithms [e. g. *Smith et al.*, 1992; *Mugnai et al.*, 1993; *Kummerow and Giglio*, 1994]. Based on elaborate cloud microphysics obtained from cloud resolving models, radiative transfer calculations are performed for detailed hydrometeor profiles taking into account different hydrometeor phases and various size distributions that depend on the life stage of the cloud structure. The scattering properties of the particles are calculated from Mie theory assuming spherical hydrometeors. Although the emission from the earth surface can be polarized, these studies usually do not account for generation of polarization within the hydrometeor layers. To further understand the microwave signatures in cloud and precipitation, high resolution passive microwave observations have been performed from high-altitude aircraft [e. g. *Adler et al.*, 1990; *Fulton and Heymsfield*, 1991; *Turk et al.*, 1994; *MacGaughey et al.*, 1996], but because of the large resolution differences, the extrapolation to satellite observations is difficult [*MacGaughey et al.*, 1996]. *Panegrossi et al.* [1998] recently stressed the need for consistency between models and measurements for precipitation retrievals based on elaborate cloud microphysics. The cloud model and the associated radiative transfer model have to be able to explain and reproduce all the observed signatures.

Although the microwave radiative properties of clouds and rain have been widely explored from model simulations to observations from satellites and aircrafts, some features of the measured microwaves are still not fully explored. Polarized scattering signatures have already been observed in some cloud structures, both from satellite and aircraft measurements. *Spencer et al.* [1983] observed residual polarization at 37 GHz with the Scanning Multichannel Microwave Radiometer (SMMR) in precipitation areas but later attributed it to calibration problems [*Spencer et al.*, 1989]. However, they did observe polarization differences at 85 GHz with the Special Sensor Microwave/Imager (SSM/I) and related it to non-spherical particles with non-random orientations in stratiform regions, whereas in convective cores, the absence of polarization would be due to "irregularly shaped graupels tumbling in a turbulent environment". *Heymsfield and Fulton* [1994] also observed polarized scattering signatures at 85 GHz with SSM/I (up to 13 K difference between the vertical and horizontal brightness temperatures) in a few mesoscale systems over land and ocean. They also believe these are related to large non-spherical ice particles with a preferred horizontal orientation in the stratiform region of the mesoscale cloud, but they did no radiative transfer simulations to support their assumption. With the ER-2 aircraft over land *Adler et al.* [1990] observed residual polarizations of several kelvins at 37 and 18 GHz in convective areas.

Haferman [1999] thoroughly reviews the studies on the effect of non-spherical hydrometeors on microwave radiation. The various model studies show that oriented non-spherical hydrometeors are necessary to generate large polarized scattering signatures in the microwave domain. *Wu and Weinman* [1984] obtain small polarization differences at 37 GHz ($\sim$ 1 K) with spherical particles whereas incorporating non-spherical particles in the calculation could yield $\sim$ 10 K for the same frequency for large rain rate ($\geq$ 32mm/h). *Evans and Vivekanandan* [1990] concentrate on the radiative properties of horizontally oriented cirrus crystals (plates, columns, and needles) at 37, 85, and 157 GHz. *Turk and Vivekanandan* [1995] consider ice plates, oblate raindrops, and conical graupels and calculate large polarization differences at 37 and 85 GHz. *Czekala and Simmer* [1998] analyze the polarization difference generated by horizontally oriented spheroidal liquid particles on upward and downward brightness temperatures. Large polarization differences are simulated and are confirmed by ground-based observations at 37 GHz [*Czekala et al.*, 2000]. *Roberti and Kummerow* [1999] use a Monte Carlo code to simulate the effect of horizontally oriented non-spherical particles at 37 and 85 GHz. Using cloud profiles from atmospheric mesoscale model, they reproduce the observations by *Heymsfield and Fulton* [1994] when tuning the amount of non-spherical particles. However, the same matrices are used for horizontally oriented and randomly oriented particles, whereas angle dependent matrices should be calculated for oriented particles.

In this study, SSM/I microwave observations in cloud systems are analyzed over the tropics for several months, along with the International Satellite Cloud and Climatology Project (ISCCP) infrared and visible derived cloud products which include cloud top temperature and optical thickness (Section 2). The presence of strongly polarized scattering signatures at 85 GHz is examined with the help of lower frequency microwave measurements and ISCCP parameters: Their frequency of occurrence and their characteristics are statistically analyzed over land and ocean separately. At 37 GHz, residual polarization difference is observed, even over optically thick hydrometeor layers. A radiative transfer model that includes emission/scattering by non-spherical particles is developed, based on the T-matrix approach [*Mishchenko et al.*, 1991, 1993, 1999] and the formalism of gas absorption by *Pardo et al.* [2000b]. The radiative transfer is carried out using the doubling and adding method as described by *Evans and Stephens* [1995]. The code does not only treat randomly or perfectly oriented particles; it can also simulate partially oriented spheroidal particles. With plausible hydrometeor profiles, the microwave observations are reproduced and the scattering signatures are explained (Section 3). Section 4 concludes this study and stresses the importance of a good understanding of the emission/scattering mechanisms when developing rain and ice retrievals.

2. SSM/I observations of polarized scattering signatures generated by clouds

2.1. The satellite data

The Defense Meteorological Satellite Program (DMSP) satellites provide an almost complete coverage of the earth twice daily from near-polar, circular, sun-synchronous orbits. The SSM/I instrument on board these satellites senses the atmospheric and surface emissions at 19.35, 22.235, 37.0, and 85.5 GHz with both horizontal and vertical polarizations, except the 22 GHz frequency, which has vertical polarization only [*Hollinger et al.*, 1987]. The observing incident angle on the earth is close to 53° and the elliptical fields of view (the footprint at -3dB) decrease in size proportionally with frequency, from 43×69, 40×50, and 28×37 to 13×15 km for 19.35, 22.235, 37.0, and 85.5 GHz, respectively. An instrument evaluation has been performed by *Hollinger et* *al.* [1990] and an inter-sensor calibration has recently been completed by *Colton and Poe* [1999]. Results from the F10 and F11 satellites are presented.

In the ISCCP data, cloud parameters and related quantities are retrieved from visible (VIS, ~0.6 μm wavelength) and infrared (IR, ~11 μm wavelength) radiances provided by a set of polar and geostationary meteorological satellites [*Rossow and Schiffer*, 1991, 1999]. Among other variables, the ISCCP data set provides cloud top temperatures. During daytime, when visible reflectances are available, the cloud optical thickness in the VIS is also retrieved, assuming a cloud drop size distribution. For liquid water clouds (i. e. for cloud top temperatures above 260 K), an effective radius of 10 μm is assumed to estimate the cloud liquid water path, whereas for ice clouds (i. e. clouds with cloud top temperatures below 260 K), the effective radius of polycrystals is assumed to be 30 μm to retrieve the ice path. The pixel level data set (the DX data set) is used: It has a horizontal sampling of about 30 km and a sampling interval of 3 hours. A detailed description of the ISCCP data products is provided in *Rossow et al.* [1996].

2.2. Polarized scattering signatures over optically thick clouds

An analysis of SSM/I observations along with collocated ISCCP data is first conducted. Because polarized scattering signatures over clouds do not occur frequently, a statistical analysis is better suited to understand their dominant features. Three months (July 1992, October 1992 and January 1993) have been examined. Only observations over tropical areas are presented here. Mid-latitude and polar regions have also been studied but are not shown in this paper: Polarized signatures from clouds are less frequent and much weaker in these areas and confusions can arise from scattering and reflection by snow and ice surfaces. Two specific situations are considered in the tropics, one over ocean the other over land.

For July 1992 and the latitudinal band from 30°S to 30°N, Figure 1 presents scatterplots of the SSM/I brightness temperatures in the vertical polarization (TbV) Figure 1 versus the brightness temperature polarization differences ($TbV - TbH$). This is done for three SSM/I frequencies (19, 37, and 85 GHz) and for cloudy pixels only (cloudiness is determined by the ISCCP pixel closest in time and space). The sea and land cases are treated separately. For each 1×1 K box, the color indicates the mean cloud top temperature as given by ISCCP. Contours limit regions where the pixel population in the 1×1 K boxes is larger than 0.01% and 0.002% of the total population for a month. In Figure 1, the emission and scattering regimes are easily recognizable over ocean. The two lower frequencies respond primarily to emission/absorption processes. In the emission regime over the ocean cold background, thiner clouds show rather low microwave brightness temperatures with large polarization differences caused by the ocean surface. As cloud opacity increases, usually associated with a decrease of the cloud top temperature, the microwave brightness temperatures increase and the polarization differences progressively decrease. In the scattering regime, which is only clearly observable at 85 GHz for clouds with cold top temperatures, the brightness temperatures decrease due to scattering by larger cloud particles. Scattering signatures at 37 GHz are not obvious, although for low cloud top temperature, $TbV(37)$ decreases with non-zero polarization differences. Over land, large differences in surface emissivities (from low emissivities over wet soil to emissivity $\sim$1 over dense vegetation) make the interpretation of the scatterplots more difficult. In general the much larger emissivities reduce the polarization difference produced by the land surface that can be sensed through optically thin clouds. However, the cloud scattering signal at 85 GHz is still easily recognized, associated with high opacity clouds that are likely to block any signal from the surface. The relative population of pixels for $TbV(85) \leq 220$ K is larger over land than over ocean (see the population contours in Figure 1).

At 85 GHz where scattering dominates the signal, the polarization difference is clearly greater than zero. In the scattering regime, Figure 2 presents the statistically most probable polarization difference versus the vertically polarized brightness

Figure 2

temperature, both observed at 85 GHz over ocean and land. With decreasing $TbV(85)$, the mean polarization difference first increases up to ~7 K for $TbV \sim 230$ K and decreases down to zero. For 200 K$\leq TbV(85) \leq 260$ K, the most probable polarization difference is ≥ 5 K, both over ocean and land. Scattering signatures ($TbV(85) \leq$250 K) are associated with polarization differences ≥ 6 K, for ~50% of the time over ocean and for ~40% over land.

To better characterize the scattering signatures at 85 GHz, Figure 3 focuses on the scattering regime at 85 GHz and presents histograms of the ISCCP cloud top temperatures for each 10 K TbV and 3 K ($TbV - TbH$) interval at 85 GHz, for July 1992 over the tropics. Ocean (solid lines) and land (dashed lines) cases are treated separately. Histograms are only presented when the number of pixels falling in the interval is larger than 70 during the month. While $TbV(85)$ changes drastically from 240 K to 140 K, the corresponding cloud top temperatures do not undergo significant changes, with mode values around 210 K when 85 GHz falls below 240 K, both over ocean and land, decreasing to ~200 K when $TbV(85)$ gets below 190 K. The IR radiation is not sensitive to the mechanisms that induce large differences in the 85 GHz brightness temperature and polarization differences. The numbers in each box indicate the ratio of population density over land versus population density over ocean. The number of strong scattering cases ($TbV(85) \leq 150$ K) is more than twice as large over land than over ocean while the number of scattering cases at 85 GHz (190 K$\leq TbV(85) \leq 240$ K) associated with large polarization difference (6 K $\leq TbV - TbH(85) \leq 12$ K) is at least twice smaller over land than over ocean. Figure 3

Is the polarization difference at 85 GHz generated within the cloud or is it related to some contribution from a polarized underlying surface? If the polarization difference emanates from the surface for these situations, the 37 GHz channel, which is less sensitive to absorption by cloud and rain particles, should also receive a significant contribution from the surface and be at least as polarized as the 85 GHz signature. The

37 GHz channel field-of-view (FOV), being also more than four times the size of the 85 GHz (FOV), should also be more affected by spatial inhomogeneities. As in Figure 3, Figure 4 presents histograms of the TbV and $TbV - TbH$ at 37 GHz for each 10 K TbV and 3 K ($TbV - TbH$) interval at 85 GHz. When the emission regime dominates ($TbV(85) > 250$ K and $TbV - TbH(85) >3$ K), histograms of $TbV(37)$ over ocean and land are different because of the different emission properties of the surfaces. However, in areas of significant scattering at 85 GHz ($TbV(85) < 230$ K), the histograms of $TbV(37)$ and $TbV - TbH(37)$ over ocean and land are much closer, suggesting that only a small fraction of the radiation comes from the surface. This is even true when the polarization difference at 85 GHz is large (6 K $\leq TbV - TbH(85) \leq$ 12 K); the $TbV(37)$ histograms then show a narrow peak at $\sim$ 260 K, which over the radiatively cold ocean indicate large emission/absorption. For $TbV(85) \leq 190$ K, whatever the underlying surface, $TbV(37)$ histograms peak around 250 K with broader left pointing tail, indicating that the 37 GHz radiation either comes from a very cold emitting cloud layer or has undergone scattering. The $TbV - TbH$ histograms at 37 GHz show that in areas of dense clouds (based on ISCCP) the polarization difference does not reach zero at this frequency, even over land (histograms over land peak around 3 K for $TbV(85) \leq$ 240 K). The histograms at 19 GHz (not presented here) are always different over land and ocean, even when the optical thickness at 37 GHz is large enough to obscure the surface. Two factors contribute to this effect, the lower absorption by liquid particles at 19 GHz and the poorer spatial resolution at this frequency. Figure 4

While the lower frequency channels are sampled every 25 km, the 85 GHz channel is sampled every 12.5 km [*Hollinger et al.*, 1987]. The spatial standard deviation of the 85 GHz channel is calculated for each $1/4^o \times 1/4^o$ and the histograms of the standard deviation are presented in Figure 5, for each 10 K TbV and 3 K ($TbV - TbH$) at 85 GHz within the scattering regime. Scattering at 85 GHz ($TbV(85) \leq$240 K) with large polarization differences (6 K$\leq TbV - TbH(85) \leq$ 12 K) occurs in regions of rather Figure 5 low spatial standard deviations at 85 GHz (mode values close to 5 K) as compared to areas where scattering is associated with low polarization differences. *Anagnostou and Kummerow* [1997] proposed using a similar "variability index" to classify stratiform and convective rainfall with the SSM/I 85 GHz channel and this idea is further developed by *Hong et al.* [1999].

The ice optical thickness derived from the ISCCP data has also been examined in correlation with the scattering signatures at 85 GHz (not shown here). Although scattering signatures at 85 GHz are always associated with large ice optical depths ($\geq$10), there are no noticeable changes in the ice optical depth between moderate ($TbV(85) \sim 230$ K) and strong ($TbV(85) \sim 180$ K) scattering at 85 GHz. This is due to the relative insensitivity of visible scattering to the larger precipitation-sized particles.

Observations from July 1992 have been presented so far. The analysis of the two other months we studied (October 1992 and January 1993) show very similar results.

Two particular situations, one over ocean and one over land, are examined closer to emphasize what has been revealed by the statistical analysis.

Figure 6a shows a cloud system over the Pacific ocean on January, 12, 1993 at 0721 as seen from the F10 satellite by SSM/I at 19, 37 and 85 GHz for vertical and horizontal polarizations. The cloud top temperature contour at 220 K (also shown on Figure 6a) is associated with $TbV(19)$ and $TbV(37)$ larger than 220 K and 240 K respectively, and also corresponds to a decrease of the $TbV(85)$ below 250 K. Centered on 10S and 153W, a region of depressed $TbV(85)$ indicates the presence of scattering at 85 GHz and is associated with $TbV(19)$ larger than 270 K, implying heavy precipitation. The polarization difference in this area is higher at 85 GHz than at 19 and 37 GHz. As also shown on the profile in Figure 6b, between 600 and 700 km and between 1000 and 1100 km from point A(5S 156W), $TbV - TbH$ minima at 19 and 37 GHz coincide with polarization difference maxima at 85 GHz, proving that the polarized signatures at 85 GHz do not stem from the polarized surface but from the cloud structure itself. Figure 6

A mesoscale convective system is observed with SSM/I on board the F11 satellite on January, 25, 1993 at 0811 over south east Australia (Figure 7a). The surface emissivity in this area shows large values with negligible polarization differences close to the coast and higher emissivity polarization difference farther inland (see the emissivity atlas described in *Prigent et al.* [1998, 2000]). The cloud structure centered at 32.5S and 148E is easily detectable not only at 85 GHz but also at 37 GHz, as TbV which is usually very warm over the land surface is depressed by the presence of cold emitters and/or scatterers. A profile through this cloud structure (Figure 7b) shows a sharp decrease of the $TbV(85)$ at 1000 km from A(25S 140E) that also corresponds to an increase in the polarization difference at the same frequency. The polarization difference at 85 GHz cannot be attributed to the surface which is not polarized. For 150 km, the signatures are stable and then $TbV(85)$ decreases again over a small area along with the 37 and 19 GHz. The polarized scattering signals associated with $TbV(85)$ around 220 K are located in the stratiform region of the system, while in the convective core very low TbV are observed at 85 and 37 GHz and are associated with a decrease of the polarization difference at 85 GHz. Figure 7

Our analysis of the scattering signature at 85 GHz suggests the following conclusions:

- "Strong" and spatially variable scattering signatures at 85 GHz ($TbV(85) \leq 190$ K) are associated with small polarization difference (mean $TbV - TbH(85) \leq 3$ K) and are observed more frequently over land than over ocean. They coincide with low cloud top temperatures ($Tc \sim 200$ K) that characterize deep convection. They are also associated with low $TbV(37)$ (≤ 250 K) implying emission by cold hydrometeors and/or scattering at 37 GHz. This suggests that these scattering signatures are concentrated in the convective cores of the cloud system where large vertical motions take place, especially over land. The proportion of ocean and land deep convective cases identified in this way in the SSM/I data is compatible with *Machado and Rossow* [1993] analysis of IR satellite measurements who also found higher occurrence of deep convection over land than over ocean.

- "Moderate" and less spatially variable scattering signatures with $TbV(85)$ between 220 and 250 K are associated with large polarization differences $TbV - TbH(85)$ that can reach $\sim 12K$. These signatures are more frequent over ocean. For scattering situations with $TbV(85) \leq 250$ K, polarization differences larger than 6 K represent ~50% of the situations over ocean and ~40% over land. The polarization differences do not stem from the surface but are generated within clouds with top temperatures $\sim$ 210 K, optical thicknesses above 10 in the VIS, high liquid water contents (small polarization difference at 37 GHz associated with $TbV(37) \sim 260$ K). These characteristics are likely to be observed in the stratiform anvil of the convective cloud system as discussed by *Machado and Rossow* [1993] in their study of the average cloud properties in tropical convective systems from ISCCP data. *Machado and Rossow* also indicate that stratiform anvil clouds represent about 80% of the tropical convective systems, and that one third of the anvil cloud may be associated with stratiform precipitation. These large proportions are consistent with the percentage of "moderate" scattering signatures at 85 GHz.

At 37 GHz, the polarization difference rarely is never negligible in regions of optically thick clouds. Given that similar signatures are observed over land and ocean, this polarization difference is unlikely to emanate from the surface alone.

Polarized microwave signatures in clouds could be associated with the "bright band" observed by radar. In precipitating stratiform clouds, the radar detects a strong increase in reflectivity associated with the melting layer due essentially to change in particle permittivity and water coating effects at the onset of melting. This hypothesis will have to be investigated using collocated passive and active measurements from the Tropical Rainfall Measurement Mission (TRMM). Studies of the melting layer in the passive domain has recently motivated simulation studies [*Bauer et al.*, 1999] but no satellite investigation has been undertaken so far.

3. Development of a radiative transfer model and interpretation of the observations

We have developed a radiative transfer model to explore the physical conditions that can explain the observed signatures.

Our model combines into a single code T-matrix routines to calculate the scattering by non-spherical particles, "doubling and adding" polarized radiative transfer through plane parallel layers composed of such particles, and a very up-to-date model of the microwave gas absorption in the atmosphere. It can be used to simulate radiances (including satellite viewing) in the longwave domain (up to 3 THz at present). The pure gas absorption of the atmosphere is taken from recent works by *Pardo et al.* [2000b].

3.1. Description of the model

The equation describing the transfer of radiation through an atmosphere that may contain scatterers is as follows:

$$\mu\frac{dI(z,\mu,\varphi)}{dz} = K(z,\mu,\varphi)I(z,\mu,\varphi) - \int_{-1}^{1} d\mu' \int_0^{2\pi} d\varphi' Z(z,\mu,\varphi,\mu',\varphi')I(z,\mu',\varphi') - \sigma(z,\mu,\varphi)B[T(z)] \quad (1)$$

where:

I=(I,Q,U,V)^T is the Stokes vector column describing the radiation field. T denotes the transposed vector;

K is the 4×4 extinction matrix;

Z is the 4×4 phase matrix;

σ is the 4×1 emission column vector;

$B(T)$ is the blackbody radiance at temperature T;

μ=cos(ϑ) where ϑ is the nadir angle;

φ is the azimuth angle;

z is the vertical coordinate in a plane-parallel atmosphere with z=0 at the surface.

The frequency dependence of I, K, Z, σ, and B is implicit. The extinction and phase matrices and the emission vector are related according to

$$K_{i1}(z,\mu,\varphi) = \int_{-1}^{1} d\mu' \int_{0}^{2\pi} d\varphi' Z_{i1}(z,\mu,\varphi,\mu',\varphi') + \sigma_i(z,\mu,\varphi), i = 1, ..., 4, \qquad (2)$$

which is a consequence of the detailed energy balance [*Mishchenko et al.*, 1999].

We will briefly introduce here the three basic parts of the model: The absorption by atmospheric gases, the scattering calculations for spherical and non-spherical hydrometeors, and the radiative transfer through an atmosphere with plane parallel layers in which different hydrometeors and/or atmospheric gases coexist.

The absorption coefficient for the resonant spectrum of the different gases present in the atmosphere is calculated according to the following equation:

$$(\kappa_\nu)_{lu} = \frac{8\pi^3\nu}{3hc}[\frac{N_l}{g_l} - \frac{N_u}{g_u}] \,|< u \mid \vec{\chi} \mid l >|^2 \, f(\nu, \nu_{u-l}) \qquad (3)$$

where:

$\vec{\chi}$ is the quantum mechanical operator associated to the dipole moment of the transition;
ν_{u-l} is the resonant frequency;
$< u \mid$ and $< l \mid$ are the eigenfunctions associated to the energy levels E_u and E_l whose degeneracies are g_u and g_l. The populations of these levels are N_u and N_l per unit of volume:
$f(\nu, \nu_{u-l})$ is the Van Vleck-Weisskopf line shape function.

The details about the calculation of all the parameters in this equation for different atmospheric gases are given in *Pardo et al.* [2000b]. Recent broadband Fourier Transform Spectroscopy measurements from the ground covering frequencies up to 1.6 THz [*Pardo et al.*, 2000a; *Matsushita et al.*, 1999; *Paine et al.*, 2000] have validated the longwave gas absorption model in the troposphere.

The far-field scattering by single non-spherical particles is computed using T-matrix codes developed by *Mishchenko* [1991, 1993, 2000]. Two different codes have been used. First, the case of non-spherical randomly oriented axially symmetric particles is treated by means of very fast routines TMD (T-Matrix Double precision routines) [*Mishchenko*, 1991, 1993]). The calculations are the fastest available for the considered case thanks to the use of analytical solutions. The second set of routines treats the case of totally oriented non-spherical particles (T-matrix for single oriented particles [*Mishchenko*, 2000]). The use of these routines provides exactly the same result as the TMD routines if the phase matrices are integrated over all possible orientations, but the calculations typically take 10-100 times longer. However, these routines allow the simulation of scattering by an ensemble of partially oriented particles. Water droplets falling in the gravitational field or ice cloud particles aloft are examples of partially oriented non-spherical particles. For the integration over all possible orientations to be possible, it is necessary to be in the independent scattering regime where each particle is in the far-field zone of the others. This implies that the average distance between particle centers is larger than four times their radius [*Mishchenko et al.*, 1995]. This requirement is usually satisfied by both cloud and precipitation particles. The scattered fields are then incoherent and their Stokes parameters can simply be added.

We have introduced a degree of orientation of the spheroid particles without breaking the azimuthal symmetry of the problem. This is possible by considering a random orientation of the projection of the particle axis in the azimuthal plane but limiting its vertical orientation to a given range with respect to the zenith direction. We have considered sphericities ([a=b]/c) larger than 1 (oblate particles) with axis tilting randomly from $\frac{\pi}{2} - \alpha_0$ to $\frac{\pi}{2}$ with respect to the horizontal plane because that favors the more realistic case of the two larger particle axis being in or near the horizontal plane instead of in the zenith direction.

The assumptions described in the last paragraph allow the use of a simplified radiative transfer equation (that describes the behavior of the system from a macrophysical point of view) such as equation (1). In our simulations, the plane parallel geometry is assumed with thermal emission as the only source of radiation. The hydrometeors can be either totally randomly-oriented or at least azimuthally randomly oriented. In that case, the radiation field is azimuthally symmetric [*Evans and Stephens*, 1995] leading to vanishing Stokes parameters U and V; thus, the dimension of the vectorial equation (1) is reduced to two:

$$\mu \frac{dI^0(z,\mu)}{dz} = K(z,\mu)I^0(z,\mu) - 2\pi \int_{-1}^{1} d\mu' Z^0(z,\mu,\mu')I^0(z,\mu') - \sigma(z,\mu)B[T(z)], \tag{4}$$

where the superscript 0 denotes the zeroth azimuthal harmonic of the respective quantity, all matrices represent the upper left 2×2 blocks of the respective 4×4 matrices appearing in Eq. (1), and all column vectors have the dimension 2 and are composed of the upper two elements of the respective 4-element column vectors.

The 2x2 radiative transfer equation is integrated using the quite standard method called doubling and adding, introduced in our model following *Evans and Stephens* [1995]. Three properties, the reflection matrix (R), the transmission matrix (T) and the source vectors (S), are used in this method for the calculations. R and T have to be defined for each pair of "in" and "out" directions and S for each incident angle. A quadrature description is thus used for the zenith angle in the integration. All three properties are derived for a layer of infinitesimal thickness (Δz) from K, M and σ by a discrete finite difference of equation (1).

3.2. Simulations and interpretation of the observations

The model allows the calculation of the Stokes parameters I and Q or brightness temperatures in two independent linear polarizations in the phase plane (usually linear horizontal and linear vertical). Fresnel or Lambert like surfaces can also be introduced in the calculations, and a large number of parameters can be varied. Those parameters are listed below:

-frequency;

-observation nadir angle;

-surface type;

-atmospheric humidity and temperature profiles;

-hydrometeor vertical distribution;

-particle size and distribution;

-dielectric constant of the hydrometeors;

-particle asphericity;

-degree of orientation of the hydrometeors (angle α_0 introduced above).

In this study we do not intend to fully explore the whole range of variations of all the hydrometeor parameters and their impact on all the SSM/I channels. Instead, we focus on the investigation of the parameters that are relevant to the explanation of the range of the observed polarized scattering signatures in the microwave. Atmospheric profiles with plausible characteristics are selected as inputs to the radiative transfer model. The effects of realistic variations of the relevant hydrometeor parameters are analyzed.

A tropical Standard Atmosphere profile is used. It contains 45.5 kg/m^2 of water vapor and has a surface temperature of 299 K. The surface type changes in the simulations to illustrate how the surface is seen at the different SSM/I frequencies. The land surface emissivity is set at 0.95 for both polarizations and the ocean is treated as a perfect Fresnel surface. The nadir angle of the simulated satellite observation is 50° which is close to the SSM/I scanning angle.

A number of simulations were performed to identify situations that compare well with the observed polarized scattering signals described earlier. Our analysis confirms the *Mugnai et al.* [1993] study of weighting functions in clouds. The 19 GHz channels are essentially sensitive to the rain layer, whereas the contribution of the liquid cloud is large for the 37 GHz channels and the 85 GHz radiation does not sound below the thick ice layer when present.

Four plane-parallel hydrometeor layers are considered in our simulations, separately or in different combinations:

1) a rain layer located between 0 and 5 km with a Marshall-Palmer drop size distribution;

2) a layer of liquid droplets between 5 and 6.5 km containing a liquid water path of 0.8 kg/m^2 with single-size spherical particles of 20 μm radius;

3) a layer of ice particles between 6.5 km and 8 km with characteristics that will vary for the different simulations;

4) a layer of ice particles between 8 km and 13 km with an equivalent water path of 0.1 kg/m^2 and single-size spherical particles of 30 μm radius.

Results for different combinations are presented in Table 1. For the rain and cloud liquid water layers, the simulated brightness temperatures are similar over ocean and land at 37 and 85 GHz because the extinction is high enough to prevent the reception of radiation from the surface (compare rows 1-2 and 3-4). A polarization difference of $\sim$ 2 K is calculated at 37 GHz over both land and ocean for simulations with rain and cloud liquid layers (rows 1 to 4). It is compatible with the polarization differences observed with SSM/I over optically thick clouds with mode values of $\sim$ 3 K. No significant polarization difference is simulated at 85 GHz for these cases (rows 1 to 4). The polarization difference at 37 GHz is produced within the rain layer by scattering on spherical rain drops. Attenuation within the cloud is not large enough at 37 GHz to eliminate the polarization difference. Figure 8 shows the variation of the polarization difference at 37 GHz with rain rate: the polarization difference saturates around 2 K when using spherical rain drops. With ramdomly oriented non-spherical particles, very similar results are obtained. However, for non-spherical oriented particles, the polarization difference increases with rain rate and with the degree of orientation of the particles. Using different rain particle shapes and orientations, *Czekala et al.* [1998, 1999, 2000] have also simulated large polarization differences at 37 GHz. However, given the spatial resolution of the SSM/I instrument at 37 GHz, the observed polarization difference in the scattering regime at 37 GHz never reaches large values. Although the

Table 1

Figure 8

particle size is not large enough to produce a significant scattering that can significantly depress the brightness temperature, the induced polarization difference is large enough to be detectable. At 19 GHz, the rain and cloud liquid water layers do not totally block the surface radiation (not shown): Simulations over ocean and land are different and over ocean the polarization difference generated at the surface is not completely masked by the hydrometeor layers.

Addition of an ice layer to the hydrometeor profile has a limited effect on the brightness temperatures at 19 GHz and 37 GHz, because of very low absorption and scattering by ice at these frequencies. At 37 GHz, an ice water path of 0.4 kg/m^2 with 200μm effective radius reduces the brightness temperatures by no more than 2 K in both polarizations. In contrast, the 85 GHz channels strongly react to the presence of the dense ice cloud and its impact is highly dependent upon the ice quantity and the particle characteristics. For spherical ice particles, the polarization difference is $\leq$ 0.5 K (rows 5 to 7); non-spherical randomly oriented particles do not generate high polarization difference either (row 8). Simulations are then performed to allow random orientations of the particle axis in the horizontal plane but restricting those orientations to a given range of α in the vertical plane. When the ice particles have an orientation restricted to $-\alpha_0 < \alpha < \alpha_0$ (with α_0 <90°), the polarization difference increases as α_0 decreases reaching values observed with SSM/I at 85 GHz above cold clouds (row 9 in Table 1). Figure 9 (top) shows the sensitivity of the 85 GHz brightness temperatures to the sphericity and orientation of the particles. For particle shapes close to spheres (asphericity=1.1), the polarization difference does not increase much as the particles become more oriented, whereas it can reach large values for highly oriented particles. The effect of particle size in this ice layer is also presented in Figure 9 for an asphericity of 1.4 and different values of the parameter α_0. Polarization differences from 6 to 10 K appear for an effective radius of $\sim$ 350-450 μm and $\alpha_0 \leq 40^\circ$ for the same ice water path of 0.4 kg/m^2.

Figure 9

The fourth cloud layer made of small ice particles only increases the microwave radiation at 85 GHz but does not affect much the polarization difference. This cloud layer is necessary to fit the mean 210 K cloud top temperature observed in the IR. Its ice water content of 0.1 kg/m ^{2} for effective particle radius of 30 μm corresponds to an optical thickness of 10 [*Rossow et al.*, 1996], similar to the ISCCP estimates in the areas of polarized scattering signatures at 85 GHz. From SAGE II and ISCCP estimates, *Liao et al.* [1995] have shown that in the tropics, 70% of the thick clouds have an extinction coefficient that gradually increases over a substantial vertical extent. The physical cloud top is usually located near the tropopause. The two ice layers schematically represent this phenomenon in our simulations.

These simulations support the SSM/I observations described in Section 2 that correspond to scattered brightness temperatures of $\sim$ 240 K and polarization differences $\geq$ 6 K at 85 GHz. Simulations at 37 GHz also fit the measurements for these same cases, with averaged brightness temperatures $\sim$ 260 K over both ocean and land, and polarization differences $\geq$ 2 K. Other combinations of rain and liquid cloud layers could reproduce the microwave signatures present in the observations. However, whatever the liquid hydrometeor layers below, an ice layer with oriented, large, non-spherical particles is required to explain the large polarization signatures at 85 GHz.

4. Conclusion

SSM/I microwave observations of convective cloud systems in the tropics are studied for several months. A thorough analysis of the observed polarized scattering signatures is conducted with the help of cloud top temperatures and optical thicknesses extracted from visible and IR observations. Strong scattering signatures at 85 GHz with very low brightness temperatures ($TbV(85) \leq 190$ K) correspond to small polarization difference ($TbV - TbH(85) \leq 3$ K). They coincide with low cloud top temperatures, happen in areas of large spatial heterogeneity, and are observed more frequently over land than over ocean. This suggests that these scattering signatures are concentrated in the convective cores of the cloud system where large vertical motions take place, especially over land. Moderate scattering signatures ($TbV(85) \sim 230$ K) are generally associated with mean polarization differences over ~ 6 K. They occur more often over ocean. In the scattering regime at 85 GHz ($TbV(85) \leq 250$ K), we showed that polarization differences ≥ 6 K, occurs ~50% of the time. The polarization difference does not stem from the surface but is generated within relatively homogeneous clouds having rather high liquid water content and cold cloud tops. These characteristics are observed in the stratiform anvils of convective cloud systems. In addition, the polarization difference observed at 37 GHz is never negligible over dense clouds whereas simple absorption/emission models for cloud and rain predict zero polarization difference over optically thick clouds.

To interpret these observations, a radiative transfer model that includes the scattering by spheroidal particles is developed, based on the T-matrix approach and using the doubling and adding method. It does not only treat randomly or perfectly oriented particles but also simulates partially oriented spheroidal hydrometeors. Microwave brightness temperatures are calculated at SSM/I frequencies and are compared to the observations. A polarization difference of ~2 K at 37 GHz is generated by emission/scattering in the rain layer even when using spherical particles; with oriented spheroidal particles, larger polarization differences can be simulated. The 85 GHz simulations are very sensitive to the ice phase of the cloud. Simulations with randomly oriented, large, spheroidal particles cannot replicate the observed polarization differences at 85 GHz, but oriented non-spherical particles can account for the observed signatures. Variations of the polarization difference with the degree of particle orientation are analyzed.

A large number of rain algorithms rely on the scattering signal at 85 GHz to detect and quantify rain rate. Recent developments include studies by *Combs et al.* [1999] or *Liu and Curry* [1998]. These algorithms derive from radiative transfer calculations with simplified scattering schemes that assume spherical particles, i.e. negligible polarization differences generated in the hydrometeor layers. Several of them are based on indices like the polarization-corrected temperature defined by *Spencer et al.* [1989] (PCT=1.818TbV(85)-0.818TbH(85)). The magnitude of the polarized scattering signatures and the fact that it occurs almost 50% of the time in the scattering regime cannot be neglected when generating rain rate retrieval schemes based on the scattering properties of the hydrometeor layers. Although a full radiative transfer model may not be efficient in an operational implementation, the development of rain-rate algorithms should take this feature into account to avoid systematically biased retrievals. Efforts are also directed toward retrieval of ice water amount in clouds from microwave observations, based on radiative transfer simulations for up to sub-millimeter frequencies [e. g. *Evans et al.*, 1998; *Liu and Curry*, 1999; *Weng and Grody*, 2000], but great care must be exercised to fully represent the complexity of prevailing scattering signatures, such as described in this study.

Further analysis of cold cloud observations is planned using measurements from the Tropical Rainfall Measurement Mission (TRMM) satellite. Joint analysis of the passive and active measurements are projected, along with radiative transfer calculations for both active and passive modes. The TRMM microwave imager (TMI) has frequencies similar to SSM/I plus a 10.7 GHz channel and it has enhanced spatial resolution compared to SSM/I (30$\times$18 and 7$\times$4 km at 19 and 85 GHz respectively). The radar at 13.8 GHz has a spatial resolution of 4 km. For a given hydrometeor profile, the radiative transfer code that has been developed will be used to generate simultaneously microwave brightness temperatures and backscattering coefficients that will be compared to the observations from the two instruments. Use of the two instruments, along with a synthetic radiative transfer code will help better constrain the estimation of the hydrometeor characteristics and improve our understanding of the processes in the clouds. Special attention will be paid to the analysis of the passive measurements when radar "bright bands" are observed.

Using a large set of meteorological satellite data in the visible and the IR, *Machado et al.* [1998] developed a method to analyze the evolution of cloud properties over the life cycles of deep convective systems. We plan to study the passive and active microwave satellite responses, using the *Machado et al.* method to infer information about the life stage of the cloud system. This will facilitate our understanding of the growth, maturation and decay processes that dominate the cloud life cycles and precipitation processes.

A future paper will be devoted to a detailed description of the radiative transfer model itself and to an extensive exploration of the multidimensional space defined by all its parameters. Another interesting application of the model will be to simulate the effect of different types of clouds on ground-based observations. Ground-based radioastronomy uses the brightness temperature of the sky to calculate the opacity, and thus its transmission, in order to apply a correction to the intensity of cosmic sources. The estimation relies on radiative transfer models that consider only gases and so are known to fail when observations are attempted in presence of clouds. The effect can corrupt maps of cosmic sources that take many hours, even days to obtain. In general, the presence of clouds will change the ratio of the sky opacity at two different frequencies (that is rather constant at a given site for clear sky conditions), thus providing means to identify situations where astronomical observations should not be attempted.

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Figure 1. Scatterplots of the SSM/I brightness temperatures in the vertical polarization (TbV) versus the brightness temperature polarization differences ($TbV - TbH$), at 19, 37, and 85 GHz in July 1992 over the Tropics for cloudy pixels only. The sea (upper panel) and land (lower panel) cases are treated separately. For each 1×1 K box, the color indicates the mean cloud top temperature. Contours limit regions where the pixel population in the 1×1 K boxes is larger than 0.01% and 0.002% of the total population for a month.

Figure 2. Statistically most probable polarization difference at 85 GHz versus the 85 GHz vertically polarized brightness temperature over ocean and land.

Figure 3. Histograms of the ISCCP cloud top temperatures for each 10 K TbV and 3 K $TbV - TbH$ box at 85 GHz, for July 1992 over the Tropics. Ocean (solid lines) and land (dashed lines) cases are treated separately.

Figure 4. Same as Figure 3 for the TbV and $TbV - TbH$ at 37 GHz.

Figure 5. Same as Figure 3 for the standard deviation of the TbV at 85 GHz calculated for each $1/4^\circ \times 1/4^\circ$.

Figure 6. a) A cloud system over the Pacific ocean on January, 12, 1993 at 0721 as seen from the F10 satellite by SSM/I at 19, 37 and 85 GHz for vertical and horizontal polarizations. The ISCCP cloud top temperature contours at 220 K are also shown. b) Cross-section along A(5S 156W) B(15S 150W).

Figure 7. Same as Figure 6 but for a cloud system observed by the F11 satellite on January, 25, 1993 at 0811 over south east Australia.

Figure 8. Sensitivity of the 37 GHz polarization difference to the orientation of the non-spherical rain drops. The asphericity of the rain drop is 1.5.

Figure 9. Top: Sensitivity of the 85 GHz polarization difference to the asphericity and orientation of the ice particles in the ice layer considered in the simulations (see text). Bottom: Effect of ice particle size on the 85 GHz polarization difference.

Table 1. [1] The 4 parameters given in column 2 are: Equivalent water path (kg/m^2), particle size (μm), asphericity, orientation parameter in degrees (the orientation of the particle axis is random in the azimuthal plane and limited to [-$\alpha_0 < \alpha < \alpha_0$] in the vertical direction, α is the angle with respect to the azimuthal plane). Input parameters that change in one row with respect to the previous are indicated in bold.

Surface Hydro. layers	Characteristics of layer 3[1]	TbV(37) TbV-TbH(37)	TbV(85) TbV-TbH(85)
Land		249.49	254.20
1		2.75	1.29
Ocean		248.40	253.93
1		3.51	1.39
Ocean		263.24	265.31
1+2		2.34	0.08
Land		264.02	265.35
1+2		1.78	0.07
Land	**0.2/400**	262.19	246.60
1+2+3	**1.0/90**	2.05	0.40
Land	**0.4**/400	261.41	228.68
1+2+3	1.0/90	2.04	0.48
Land	0.4 /**200**	262.79	261.84
1+2+3	1.0/90	2.05	0.18
Land	0.4 /**400**	261.48	230.15
1+2+3	1.4/90	2.04	0.48
Land	0.4 /400	261.65	232.87
1+2+3	1.4/**20**	2.43	8.50
Land	0.4 /400	261.91	239.30
1+2+3+**4**	1.4/20	2.35	7.30

Fig1

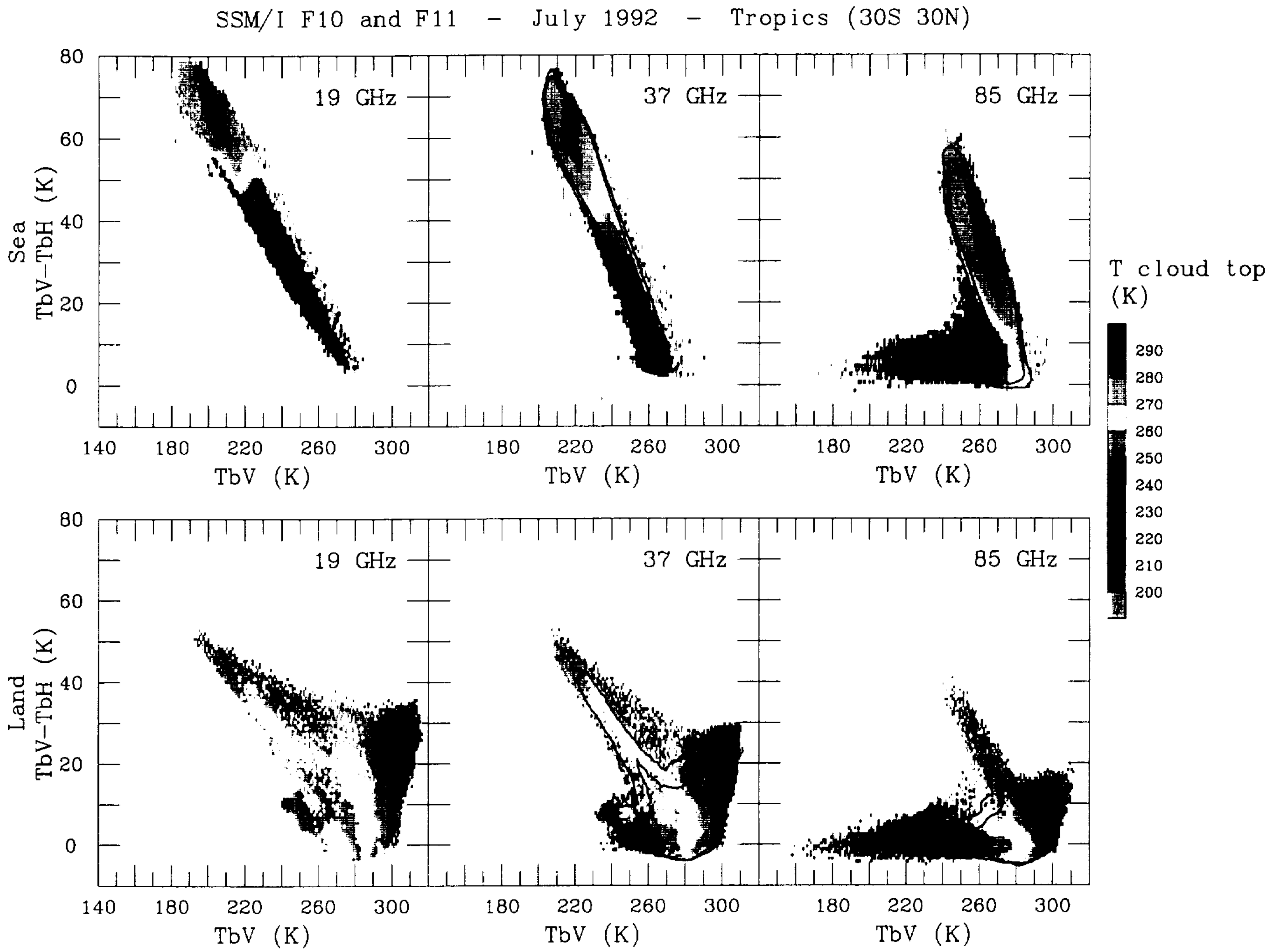

SSM/I F10 and F11 - July 1992 - Tropics (30S 30N)
19 GHz
37 GHz
85 GHz
Sea
TbV-TbH (K)
Land
TbV-TbH (K)
TbV (K)
80
60
40
20
0
140
180
220
260
300
T cloud top
(K)
290
280
270
260
250
240
230
220
210
200

Fig 2

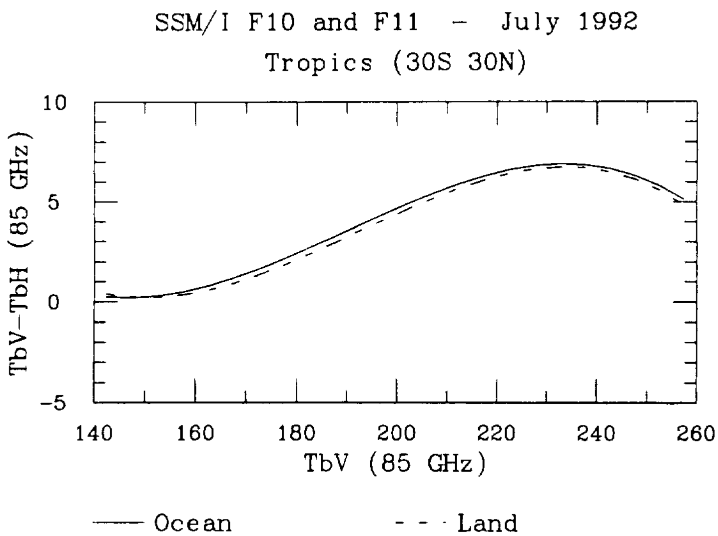
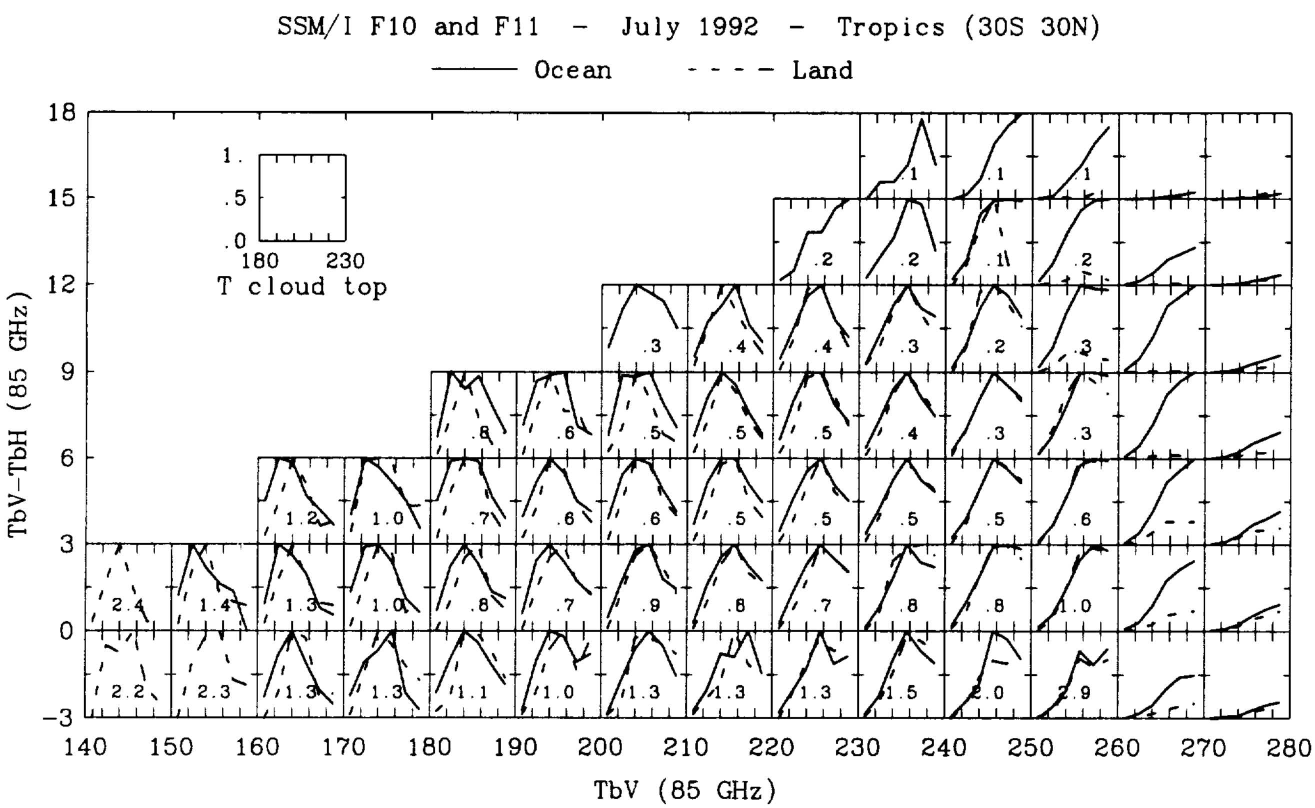

SSM/I F10 and F11 - July 1992
Tropics (30S 30N)
TbV-TbH (85 GHz)
10
5
0
-5
140
160
180
200
220
240
260
TbV (85 GHz)
Ocean
Land

Fig 3



SSM/I F10 and F11 - July 1992 - Tropics (30S 30N)
Ocean
Land
T cloud top
TbV-TbH (85 GHz)
TbV (85 GHz)

Fig 4

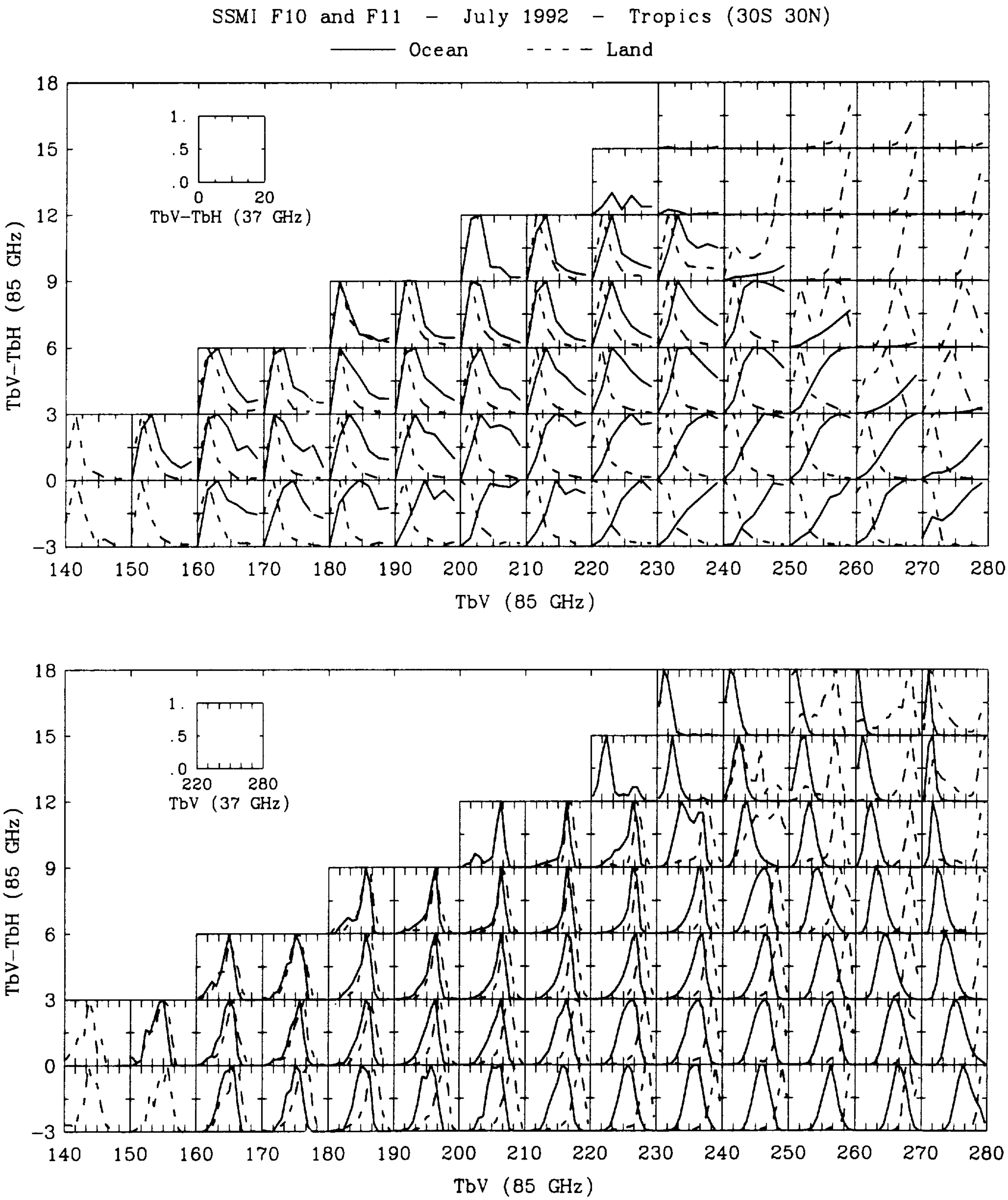

SSMI F10 and F11 - July 1992 - Tropics (30S 30N)
Ocean
Land
TbV-TbH (37 GHz)
TbV-TbH (85 GHz)
TbV (85 GHz)
TbV (37 GHz)
TbV-TbH (85 GHz)
TbV (85 GHz)

Fig 5

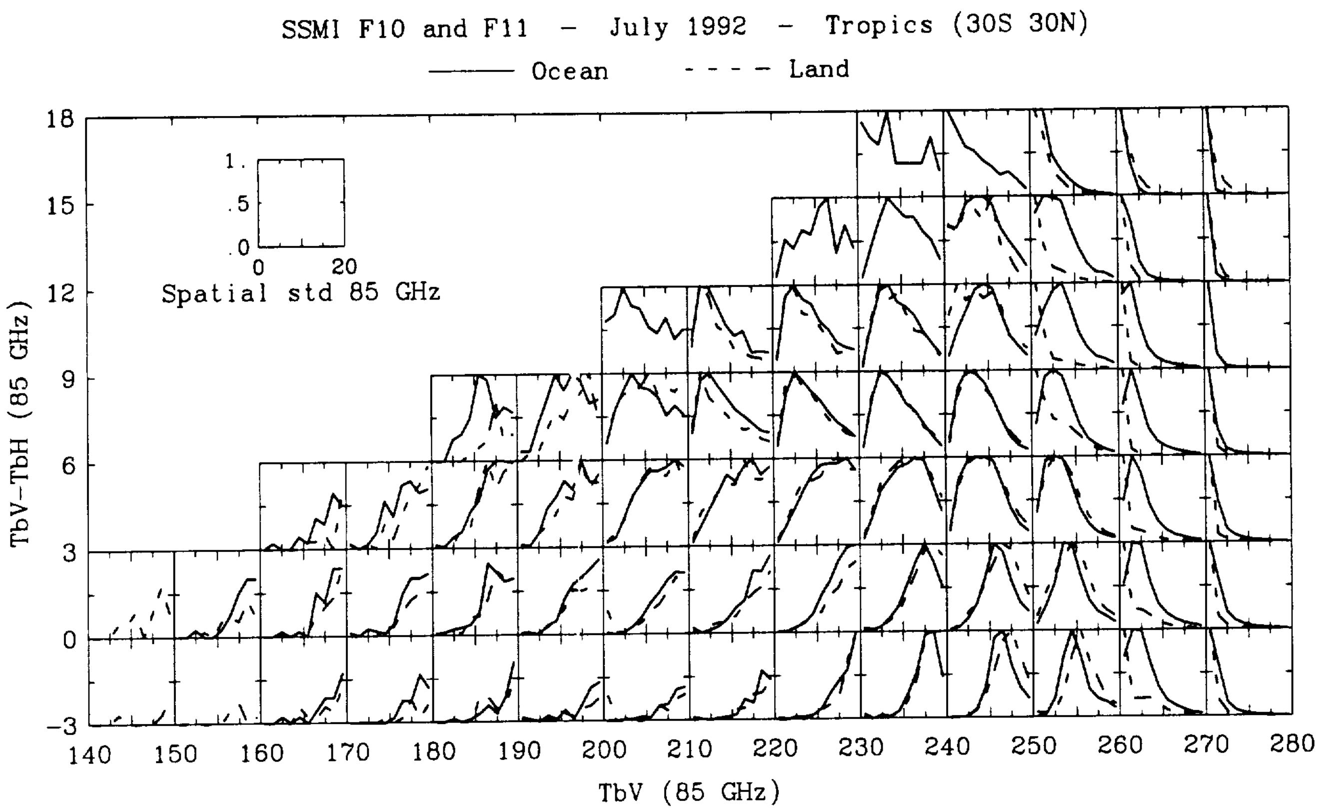

SSMI F10 and F11 – July 1992 – Tropics (30S 30N)
——— Ocean - - - - Land
Spatial std 85 GHz
TbV-TbH (85 GHz)
TbV (85 GHz)
18
15
12
9
6
3
0
−3
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
1.
.5
.0
0
20

Fig 6a

SSMI F10 01/12/1993 0721

contours for T cloud top at 220 K

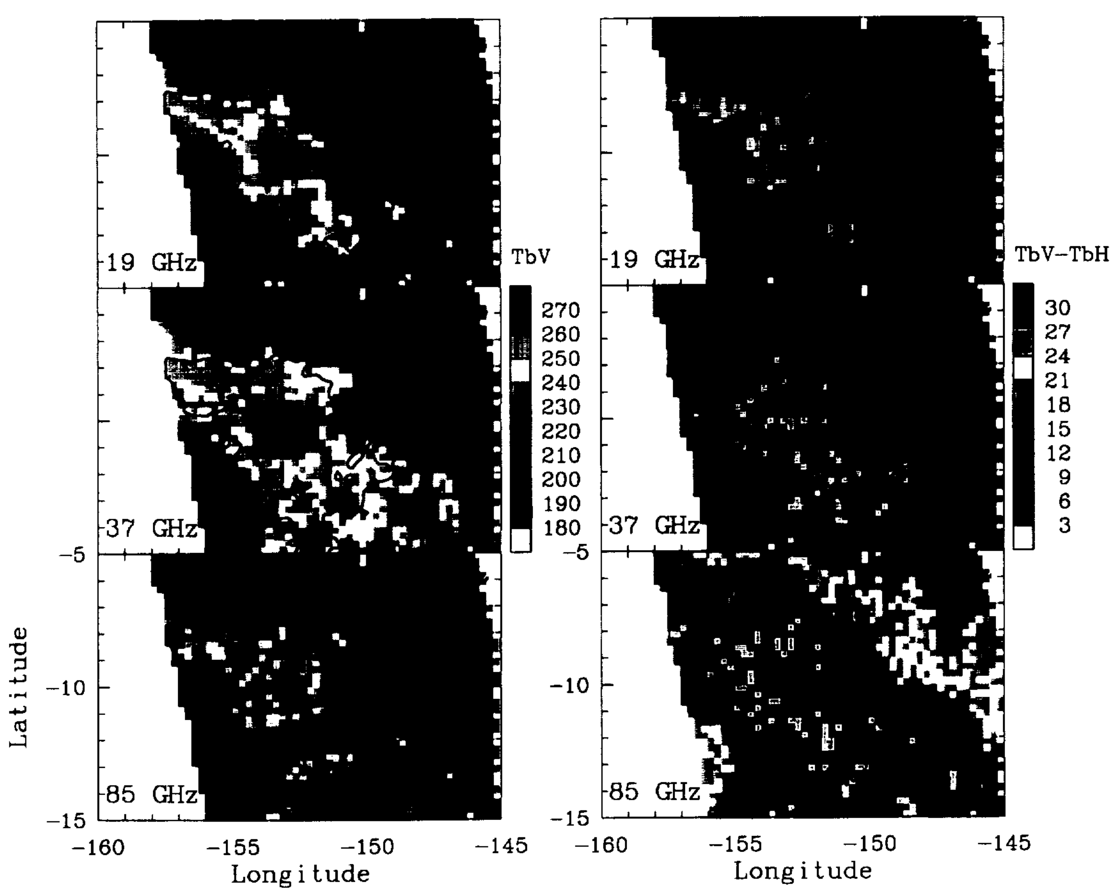


Fig 6B

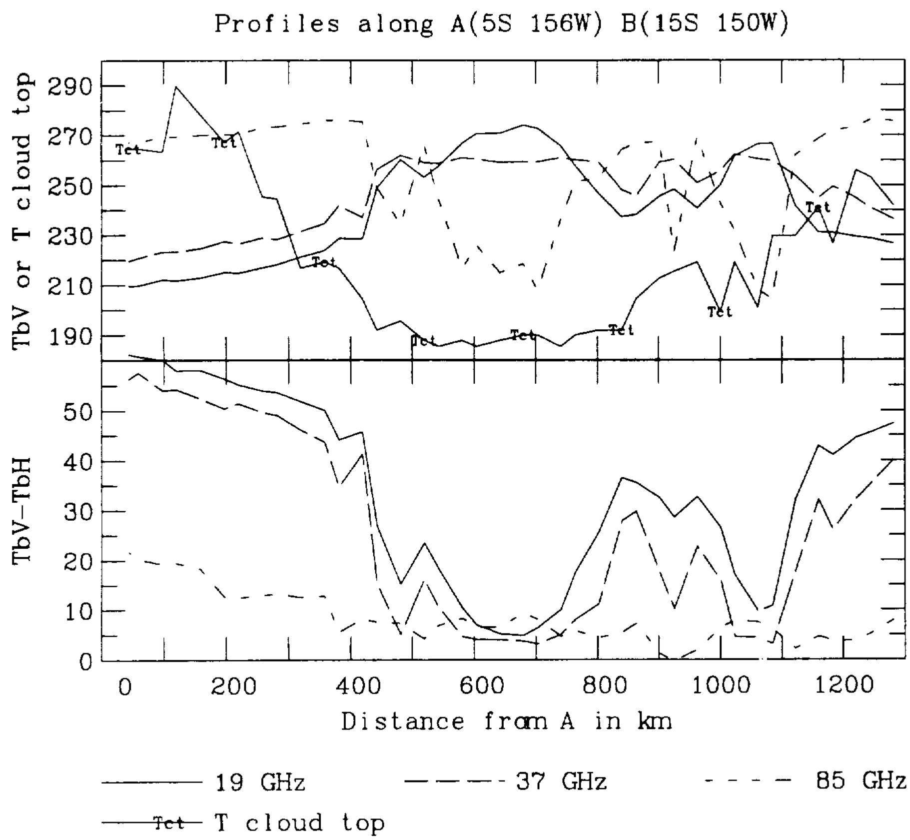

Profiles along A(5S 156W) B(15S 150W)
TbV or T cloud top
290
270
250
230
210
190
TbV-TbH
50
40
30
20
10
0
0
200
400
600
800
1000
1200
Distance from A in km
Tct
19 GHz
37 GHz
85 GHz
T cloud top

Fig 7a

SSMI F11 01/25/1993 0811

contours for T cloud top at 220 K

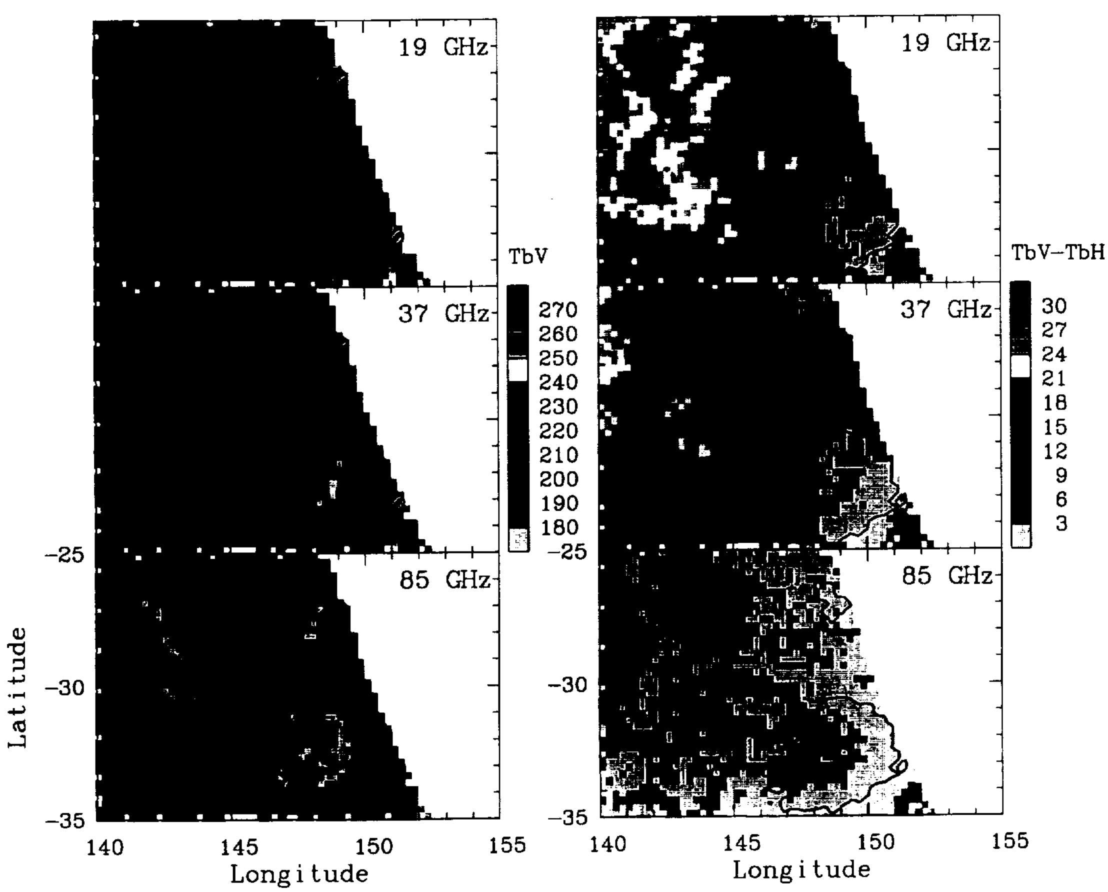


Fig 7e

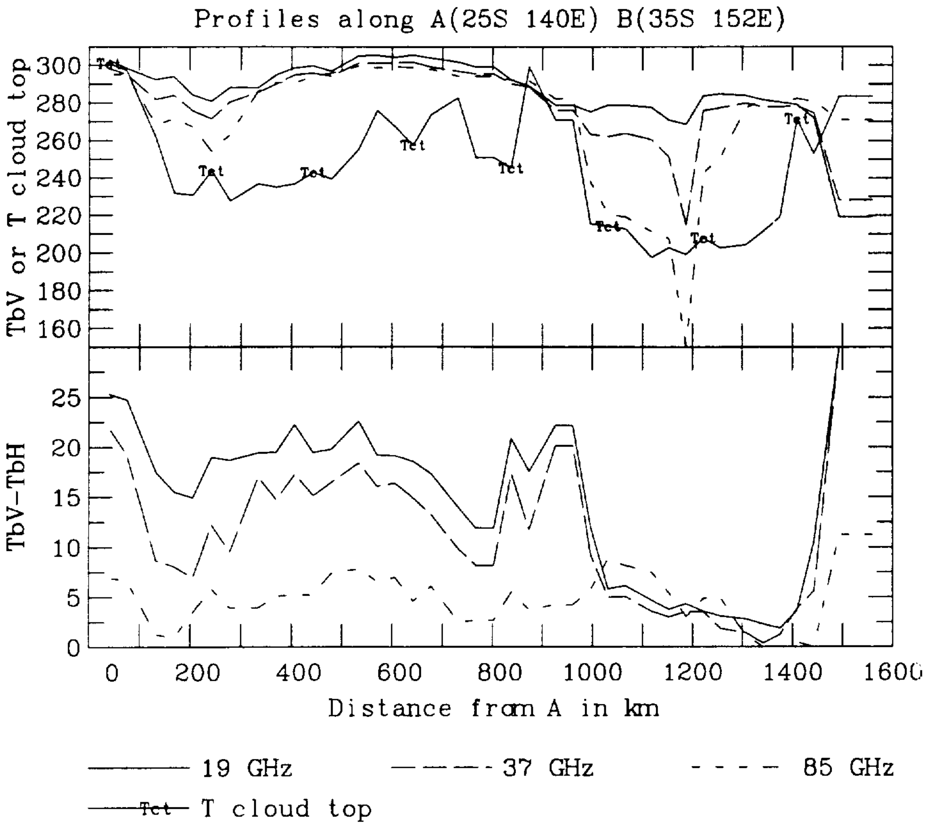
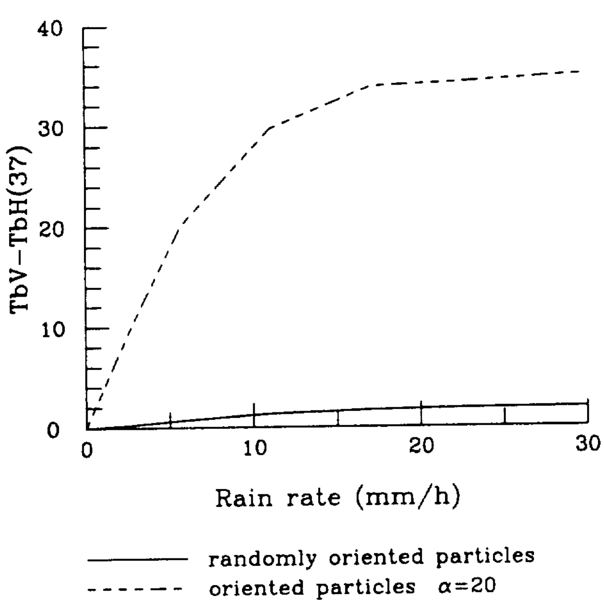
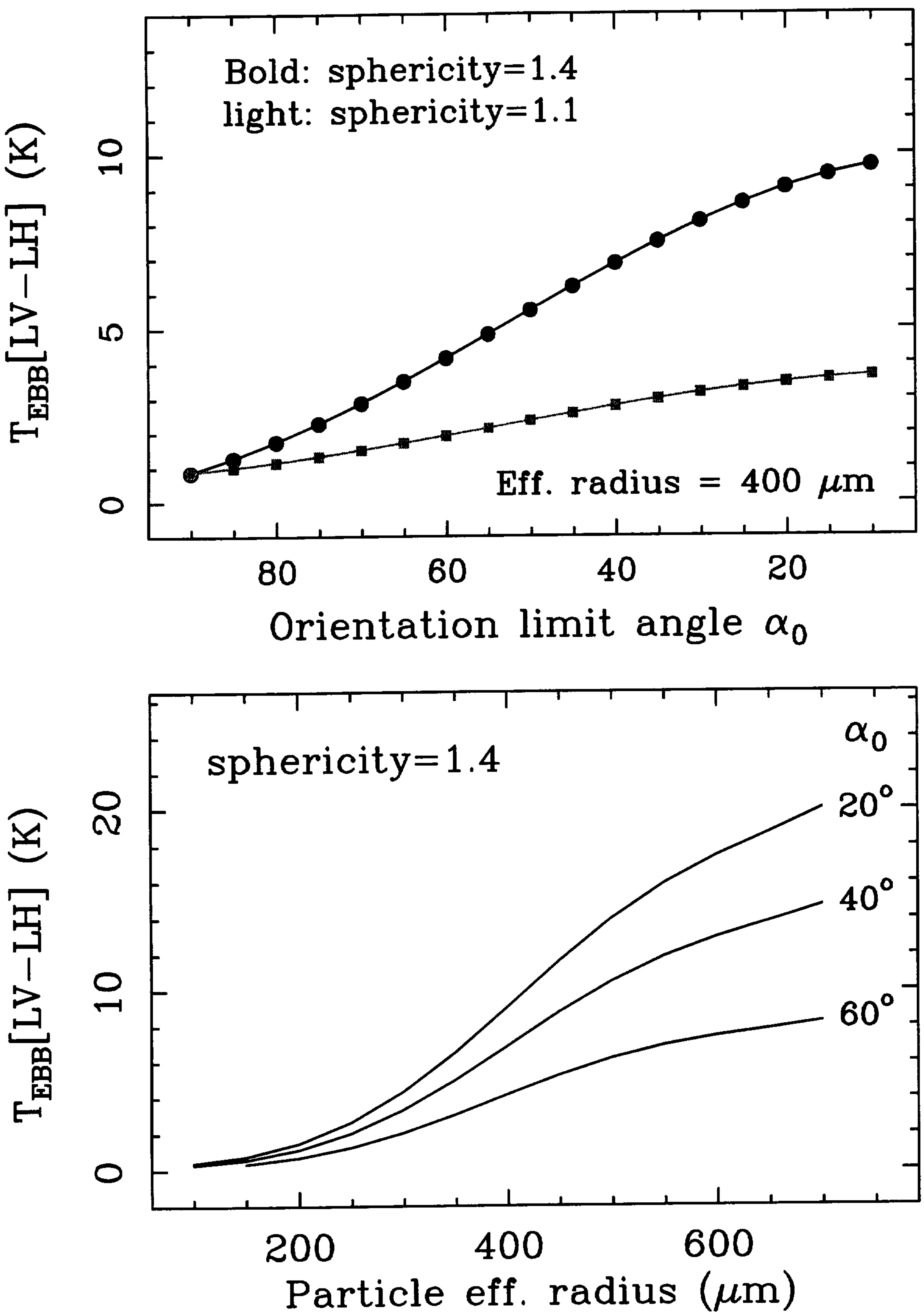

Profiles along A(25S 140E) B(35S 152E)
TbV or T cloud top
300
280
260
240
220
200
180
160
Tct
TbV-TbH
25
20
15
10
5
0
0
200
400
600
800
1000
1200
1400
1600
Distance from A in km
19 GHz
37 GHz
85 GHz
T cloud top

Fig 8



40
30
20
10
0
TbV-TbH(37)
0
10
20
30
Rain rate (mm/h)
randomly oriented particles
oriented particles α=20

Fig 9



Bold: sphericity=1.4
light: sphericity=1.1
Eff. radius = 400 μm
T_{EBB}[LV−LH] (K)
0
5
10
80
60
40
20
Orientation limit angle α_0
sphericity=1.4
α_0
20°
40°
60°
T_{EBB}[LV−LH] (K)
0
10
20
200
400
600
Particle eff. radius (μm)