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## RESEARCH ARTICLE

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## Key Points:

- Cloud scattering induces polarization difference of the order of 10 K at 157 GHz
- Particle orientation must be considered in rain and cloud microwave retrievals
- MADRAS radiometric sensitivities at 89 GHz and 157 GHz are below 1.2 K and 2.5 K

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## First observations of polarized scattering over ice clouds at close-to-millimeter wavelengths (157 GHz) with MADRAS on board the Megha-Tropiques mission

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**Abstract** Polarized scattering by frozen hydrometeors is investigated for the first time up to 157 GHz, based on the passive microwave observations of the Microwave Analysis and Detection of Rain and Atmospheric Structures (MADRAS) instrument on board the Indo-French Megha-Tropiques satellite mission. A comparison with time-coincident Tropical Rainfall Measurement Mission Microwave Imager records confirms the consistency of the coincident observations collected independently by the two instruments up to 89 GHz. The MADRAS noise levels of 1.2 K at 89 GHz and of 2.5 K at 157 GHz are in agreement with the required specifications of the mission. Compared to the 89 GHz polarized channels that mainly sense large ice particles (snow and graupel), the 157 GHz polarized channel is sensitive to smaller particles and provides additional information on the cloud systems. The analysis of the radiometric signal at 157 GHz reveals that the ice scattering can induce a polarization difference of the order of 10 K at that frequency. Based on radiative transfer modeling the specific signature is interpreted as the effect of mainly horizontally oriented ice cloud particles. This suggests that the effects of the cloud particle orientation should be considered in rain and cloud retrievals using passive radiometry at microwave and millimeter wavelengths.

### 1. Introduction

Satellite observations from the visible to the microwaves are used operationally by the weather centers for the characterization of cloud and rain. Passive microwaves are recognized to provide unique information about the hydrometeors, with their ability to penetrate the cloud structure, whereas infrared and visible observations from satellite usually provides properties of the top of clouds like cloud top height or cloud top phase [e.g., *Stubenrauch et al.*, 2013]. Satellite remote sensing at millimeter waves has been proven recently to show a high sensitivity to the cloud ice phase due to the strong scattering signal from the frozen particles at these wavelengths [*Evans et al.*, 2005; *Buehler et al.*, 2007; *Jimenez et al.*, 2007; *Defer et al.*, 2008]. This influenced the recent decision of having an Ice Cloud Imager (ICI) at frequencies between 170 and 670 GHz on board the next generation of operational satellites in Europe (MetOp-SG). The MetOP-SG mission will also carry the MicroWave Imager and the MicroWave Sounder, both operating at lower frequencies than ICI.

At low microwave frequencies (roughly below 60 GHz) microwave radiation is essentially sensitive to the emission from liquid clouds. At higher frequencies, scattering processes also take place and can provide additional information on the cloud ice phase. Changing the observation frequency will change the observed brightness temperature (TB) signal of the Earth's upwelling radiation via changes in the sensitivity to the interaction mechanisms. At high microwave frequencies the scattering by frozen hydrometeors increases and can depress the TB signal. This reduction in the observed TB signal can be used to detect and quantify ice and snow clouds in the microwave range as demonstrated for rain identification with scattering index [*Grody*, 1991].

Within this framework, understanding and quantifying the scattering signals from frozen clouds, and more generally the frozen phase, at millimeter waves are a necessity for an optimal retrieval of the ice cloud characteristics from the future satellite measurements. The interaction of millimeter radiation with frozen hydrometeors is complex and involves not only the ice quantities but also the size distribution of the particles, their dielectric properties, their shapes, and their orientation.

Polarized scattering signals from the frozen phase have been evidenced up to 90 GHz, from measurements with conical scanners such as the Special Sensor Microwave Imager or Tropical Rainfall Measurement

**Table 1.** Characteristics of the MADRAS Instrument on Board Megha-Tropiques<sup>a</sup>

Central Frequency (GHz)	Bandwidth (GHz)	Polarization	Cross-Track Resolution (km)	Along-Track Resolution (km)	NEDT (K)		NEDT (K)	NEDT (K)
					Goal	Required	Flight	Ground
18.7	±0.1	H	40	67	0.5	0.7	0.33	0.37
18.7	±0.1	V	40	67	0.5	0.7	0.38	0.44
23.8	±0.2	V	40	67	0.5	0.7	0.34	0.39
36.5	±0.5	H	40	67	0.5	0.7	0.28	0.32
36.5	±0.5	V	40	67	0.5	0.7	0.28	0.33
89	±1.35	H	10	17	1	1.1	0.38	0.41
89	±1.35	V	10	17	1	1.1	0.36	0.39
157	±1.35	H	6	10	2	2.6	1.01	1.08
157	±1.35	V	6	10	2	2.6	0.94	1.08

<sup>a</sup>Different radiometric sensitivities are given: the specification ones (Goal and Required) and the in-flight and ground estimates from CNES at nominal MADRAS operations [Karouche *et al.*, 2012; Goldstein and Karouche, 2013]. NEDT stands for Noise Equivalent Differential Temperature.

Mission (TRMM) Microwave Imager (TMI) [Prigent *et al.*, 2001, 2005; Galligani *et al.*, 2013]. It has been shown that this polarized scattering can be explained by the interaction of the radiation with nonspherical and oriented particles and can bring insight into the cloud microphysics. Up to recently, space-based polarized measurements over 90 GHz were not available. Current meteorological satellite observations are provided up to 190 GHz, but in cross-track mode without separate measurements of the two orthogonal polarized signals.

Recently, new space-based observations at 157 GHz along the two orthogonal polarizations have been performed thanks to the Megha-Tropiques (MT) mission. The MT mission [Desbois *et al.*, 2007] is a collaborative satellite project, developed by ISRO (Indian Space Research Organization) and CNES (Centre National d'Etudes Spatiales). The Indo-French satellite, launched in 2011, carries several instruments, including a microwave imager MADRAS (Microwave Analysis and Detection of Rain and Atmospheric Structures) and a microwave sounder SAPHIR (Sondeur Atmosphérique du Profil d'Humidité Intertropicale par Radiométrie). MADRAS is a conical scanner with frequencies between 19 and 157 GHz. Both orthogonal polarizations are measured for most frequencies, including at 157 GHz. In this study, space-based polarized scattering signals over ice clouds are observed and analyzed for the first time at a frequency above 100 GHz, where the sensitivity to cloud ice scattering is expected to be higher.

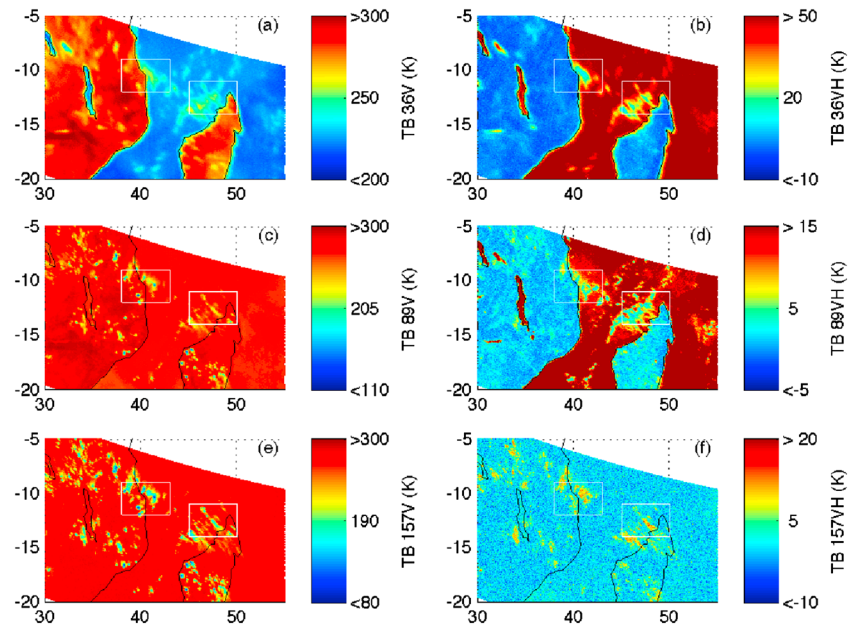
The MADRAS instrument is briefly described, insisting on the sensitivity of the high-frequency channels (section 2). The observed polarized scattering over ice clouds is then analyzed with special attention to its frequency dependence (section 3). Radiative transfer (RT) simulations help interpret the observations (section 4). Section 5 concludes this study.

## 2. MADRAS on Board Megha-Tropiques

The objective of the MT mission is to study the water cycle in the intertropical region and to evaluate its influence on the energy budget [Desbois *et al.*, 2007]. The MT satellite was successfully launched by ISRO from the Sriharikota launch pad (India) and put on a circular orbit at 865 km, inclined by 20° to the equator. Thanks to this low-inclined orbit, MT is providing frequent observations over the tropics, between latitudes of ±23° and is part of the Global Precipitation Mission (GPM) constellation. MT carries two microwave instruments: SAPHIR, a cross-track humidity sounder with six channels around the H<sub>2</sub>O line at 183 GHz, and a conical imager with an incidence angle of 53.5°, MADRAS, with frequencies at 18.7, 23.8, 36.5, 89, and 157 GHz for both orthogonal polarizations (except at 23.8 GHz that is vertical only) [Karouche and Raju, 2010].

MADRAS conical scan consists in 54, 214, and 356 pixels at low (18 to 36 GHz), medium (89 GHz), and high (157 GHz) frequencies, respectively. To obtain the specified pixels with the required spatial resolution (Table 1) and achieve the requested radiometric sensitivity, data are oversampled on board in the cross-track direction as described in Karouche *et al.* [2013].

Table 1 lists the different specifications of the MADRAS instrument including the required and goal Noise Equivalent Differential Temperature (NEDT) set to 2.6 K and 2 K, respectively, at 157 GHz [Goldstein and Karouche, 2013]. Analysis performed by CNES on in-flight records indicated better sensitivity than the requirements (as listed in Table 1), with even better performances in flight compared to the assessment



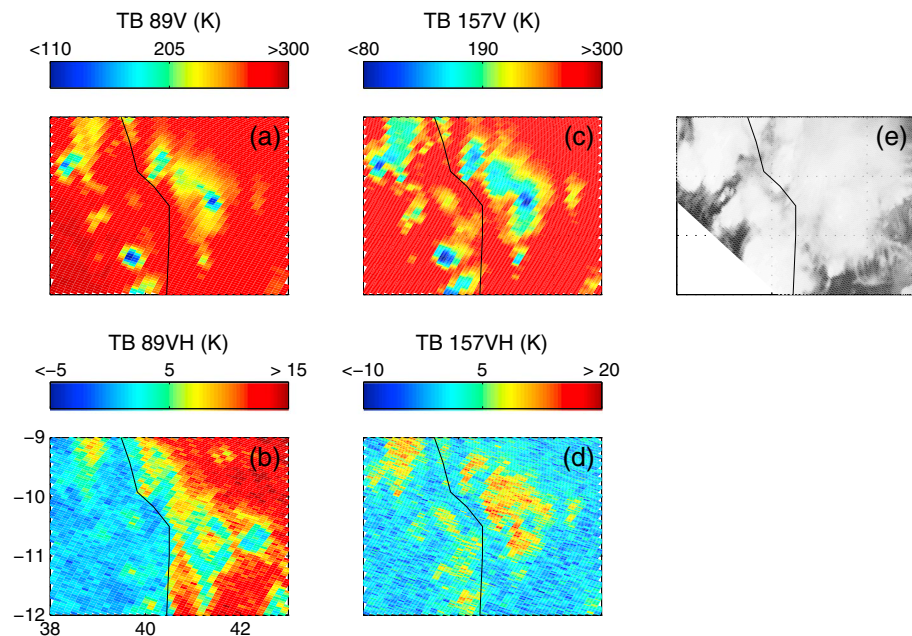
**Figure 1.** A scene from MADRAS on board Megha-Tropiques, off the east coast of Africa, on 9 December 2011, between 12:05 and 12:12 UT. (top to bottom) 36, 89, and 157 GHz, on the left the vertical polarization, on the right the difference between vertical and horizontal polarizations (TBVH). The two regions plotted in Figures 2 and 3 are also indicated.

performed on the ground during integration at ISRO [Goldstein and Karouche, 2013]. Details on CNES flight tests and calibration as well as long-term monitoring of MT payloads are available at [http://smc.cnes.fr/MEGHAT/Fr/A\\_recette\\_vol.htm](http://smc.cnes.fr/MEGHAT/Fr/A_recette_vol.htm).

The MADRAS V05 data set studied here covers an observational period from 13 October 2011 to 1 February 2013. Unfortunately, due to a serious anomaly observed in the MADRAS scan mechanism, the instrument is no longer operational and does not provide data since February 2013.

### 3. Analysis of the MADRAS Observations Over Ice Clouds

An example of MADRAS observations is shown in Figure 1, over both ocean and land, over the south east coast of Africa, at 36, 89, and 157 GHz, for the vertical polarization (left) and for the polarization difference (right). The ocean surface emissivities are rather low and polarized, contrarily to the land that usually has high emissivities with very limited polarization signatures. For the low-frequency channels, atmospheric opacity is low and therefore the contrast between ocean and land is large. At 157 GHz, the atmospheric opacity in these humid tropical regions almost completely masks the surface signal. Note the differences in spatial resolution from 36 GHz to 157 GHz (from 67 to 10 km, Table 1), with rather blurred structures at 36 GHz as compared to the higher frequencies. At 36 GHz, the liquid water emission in the clouds induces an increase of the TBs over the radiatively cold ocean but a decrease over the highly emitting land due to the colder cloud temperatures. The cloud emission also induces a decrease of the polarized surface emissions over ocean (Figure 1b). The observed large polarized signature, defined as the difference of the brightness temperature between the vertical polarization and the horizontal polarization (TBVH), over land at 37 and 89 GHz does not correspond to cloud structures, but to water surfaces (e.g., lake Malawi between 14°S–10°S and 34°E–35°E, lake Rukwa centered on 8°S and 32°E, or the south part of the lake Tanganyika around 7°S and 35°E). At 157 GHz, some cloud structures appear cold over both ocean and land, with TBs down to 80 K (Figure 1e), which is much lower than the physical temperature of the upper part of the clouds. This is due to scattering by the cloud ice phase. The low TBs are also associated with an increase in the TB157VH polarization signal (Figure 1f). This cannot be due to the surface contribution, as the cloud free areas at 157 GHz do not show any polarization. In addition scattering from spherical particles cannot generate a polarized signal of the order of 10 K. However, as already observed close to 85 GHz, nonspherical horizontally aligned particles can generate significant positive polarized signal [Prigent *et al.*, 2001, 2005; Galligani *et al.*, 2013]. These first polarized measurements at 157 GHz from MADRAS tend to show,



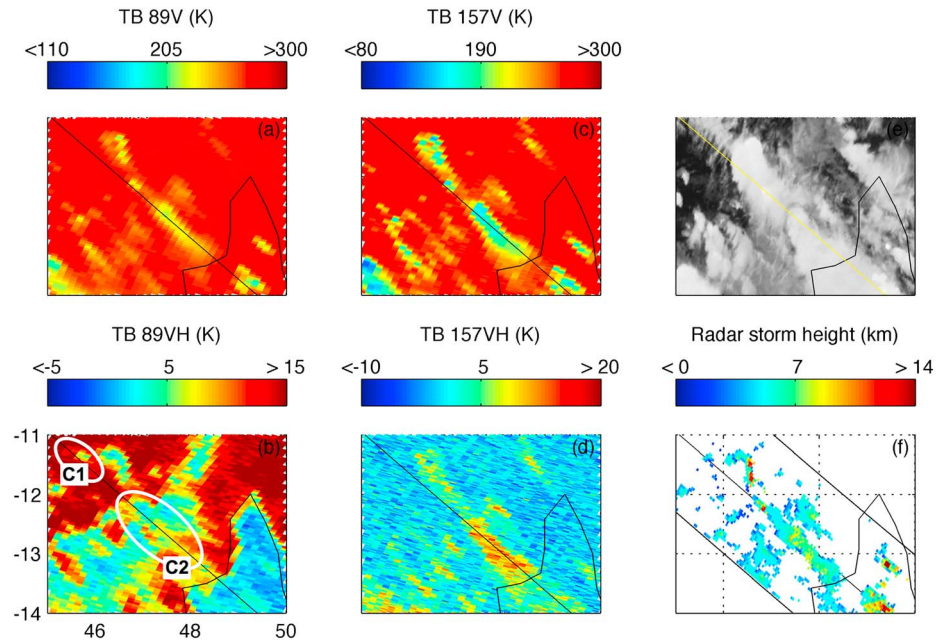
**Figure 2.** Zoom on one area of Figure 1 with (a) TB89V map, (b) TB89VH map, (c) TB157V map, (d) TB157VH map, and (e) almost time-coincident (see Appendix A) TRMM VIRS 12  $\mu\text{m}$  IR image.

and as discussed later in the paper, that polarized scattering by cloud systems is very common at 157 GHz, with larger polarization signal than at 89 GHz.

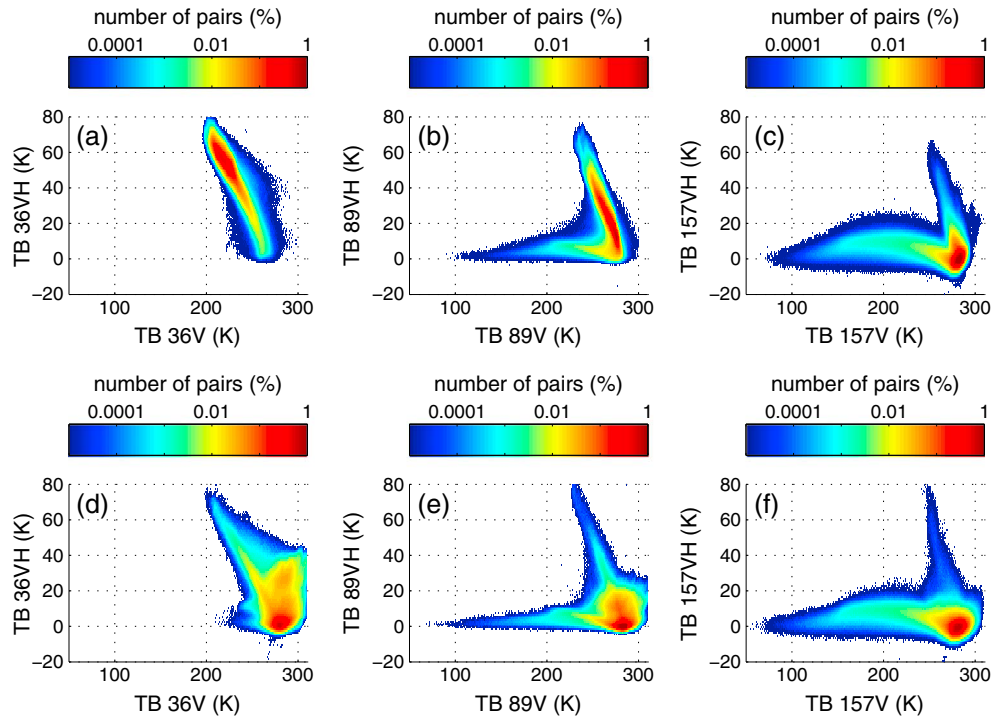
Figures 2 and 3 show almost coincident TRMM and MADRAS observations in two zones of interest of Figure 1 (TRMM observed the same region about 6 min after MT). As detailed in Appendix A, the comparison of the temporally and spatially coincident brightness temperatures confirms the spatial and radiometric consistencies of the MADRAS and TMI microwave records in the common wavebands. Additional TRMM instruments are considered here: it includes the Precipitation Radar (PR) and the Visible and Infrared Scanner (VIRS) [Kummerow *et al.*, 1998]. Figure 2 focuses on deep convective clouds that exhibit significant cold TBs at 89 and 157 GHz (Figures 2a and 2c). Convective and stratiform cloud regions already mapped at 89 GHz are also detected at 157 GHz (Figures 2a and 2c). The scattering signal measured at 157 GHz also emanates from the edges of convective and stratiform clouds and from partially transparent clouds at 89 GHz (Figures 2a and 2c). The 157 GHz channels therefore offer the possibility to characterize better the horizontal structure of the clouds and their inner properties at the origin of the scattering. The difference of polarization at 157 GHz tends to be of the order of 7–9 K in thick clouds and close to 0 K in convective cores that exhibit cold TBVs (Figure 2d). Figure 3 zooms on another region of Figure 1 that was also sampled by TRMM PR (Figure 3f). Compared to Figure 2, the sampled clouds are less convective. The radiometric responses at 89 and 157 GHz are coherent between each other and with the IR records (Figure 3e). Except for few PR pixels, the precipitation measured along the PR swath was flagged as stratiform with the presence of bright band (not shown). The 157 GHz polarization difference exceeds 7 K in the precipitating clouds and covers a more extended area than at 89 GHz (Figures 3d and 3e).

The previous section focused on examples of typical radiometric signals and their characteristics at the cloud scale. In the following we summarize the main scattering features based on TBs collected over 14 days of MADRAS records selected during the studied period (i.e., 13 October 2011 to 1 February 2013) over the full tropical region covered by MADRAS. Figure 4 presents the relationship between MADRAS brightness temperature polarization differences (TBVH) and brightness temperatures in vertical polarization (TBV). These observations passed additional in-house verification simultaneously performed on the radiometric signals at 89 GHz and 157 GHz. The ocean and land cases are treated separately according to CNES surface-type categorization. Due to the different sampling rates, the number of quality-controlled pixels at 157 GHz is approximately twice the number of quality-controlled pixels at lower frequencies. The emission and scattering regimes can be easily distinguished, especially over ocean. Over ocean, at 36, 89, and 157 GHz,

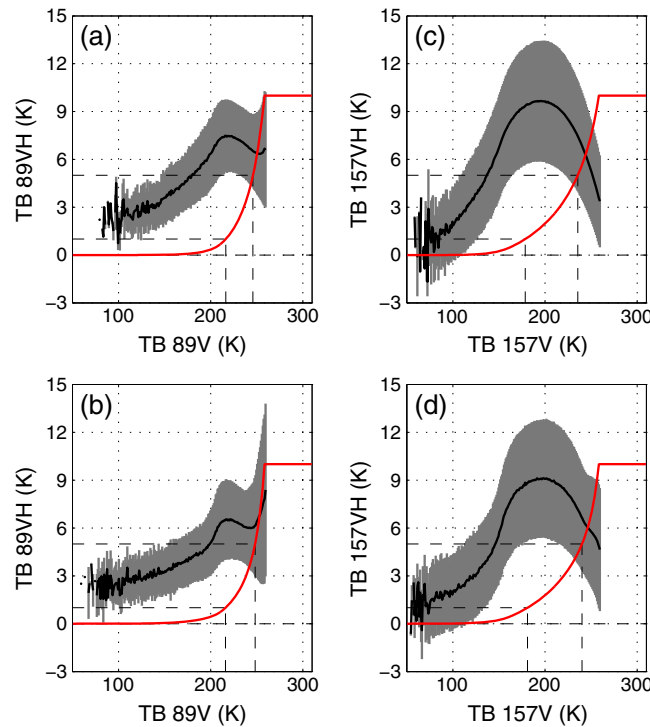




**Figure 3.** Same as Figure 2 but for another region with in addition (f) almost time-coincident TRMM PR storm height. The solid lines in Figure 3f delineate the borders of the PR swath. The yellow line in Figure 3e and the black line in the other panels locate the transect of interest used in section 4.3. C1 and C2 indicate the regions of interest investigated in section 4.3.



**Figure 4.** The brightness temperature polarization differences (TBVH) versus the brightness temperature in vertical polarization (TBV), for (a–c) ocean and (d–f) land, for 36, 89, and 157 GHz from left to right. For each 1 K by 1 K box, the color indicates the relative number of TBV-TBVH pairs, with respect to the total number of TBV-TBVH pairs considered in the analysis. More than 235 (80) million of observations at 157 GHz were used over ocean (land). The number of samples at 36 and 89 GHz is about half the number of 157 GHz samples.



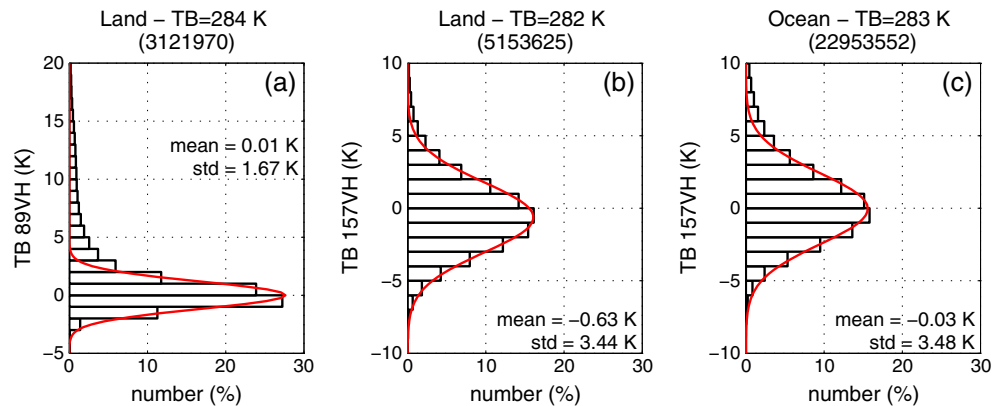
**Figure 5.** Most probable polarization difference (solid black lines) and its standard deviation (in grey) at 89 and 157 GHz for (a–c) ocean and (b–d) land in the scattering regime (see text for the methodology to identify the scattering regime). The red curve shows the cumulative distribution of the number of samples (rescaled between 0 and 10 K) with the dashed lines corresponding to 0, 10, and 50% of the sample population in the scattering regime.

clear sky and thin clouds have low TBV with significant polarization difference (the lower the frequency, the larger the polarization difference) but when the cloud opacity increases, TBV increases and the polarization difference decreases. At 157 GHz, even under clear sky conditions, the opacity related to the water vapor in tropical region can be high (large TBV) and masks the polarized surface signal (low TBVH). At 89 and 157 GHz, in the presence of clouds with frozen hydrometeors, TBV decreases due to scattering by ice particles and can reach very low values.

Derived from Figure 4, Figure 5 represents the most frequent polarization difference at 89 and 157 GHz versus TBV in the scattering regime for ocean and land separately. The scattering regime was identified from a basic filtering applied on TBV and TBVH values, i.e.,  $TBV < 260$  K and  $|TBVH| < 20$  K. Mean value and standard deviation of TBVH are computed as a function of TBV per bin of 1 K for any observation in the scattering regime. Ten percent of the TBV values recorded in the scattering

regime are below 217 K for sea and land at 89 GHz and below 179 and 182 K over sea and land, respectively, at 157 GHz. In the scattering regime, for TBV decreasing, the mean polarization difference first clearly increases up to 6–7 K at 89 GHz (Figures 5a and 5b), and up to 9–10 K at 157 GHz (Figures 5c and 5d), and then decreases for TBV below 200 K. Larger standard deviations of TBVH are observed at 157 GHz compared to 89 GHz with a maximum of ~3.5 K. Figures 5a and 5b also show that colder brightness temperatures are recorded over land than over ocean, which is consistent with deeper convection over continent than over ocean. There is only 0.6 K difference at 200 K between the most probable polarization differences over ocean and land at 157 GHz. This confirms that the surface contribution to the polarization signal here is very limited, and it is likely that this difference is related to a difference in the cloud microphysics above land and ocean.

As shown in Figures 4d–4f, the maximum of the 2-D distribution over land is located at high TBV and close to 0 K polarization for all frequencies. This is expected: the land emissivity is only weakly polarized on average, and atmospheric emission processes are not polarized. At 157 GHz (Figure 4f) a significant number of pixels corresponding to high TBV show negative polarization differences. We argue that the distribution of the polarization difference at the maximum density of points for high TBV over land can provide an estimate of the instrument noise. This is also possible at 157 GHz over ocean, due to the high atmospheric opacity at this frequency. For these conditions, the dispersion of the TBVH around the mean value (close to 0 K) is an approximation of the noise on the polarized difference  $\sigma_{V-H}$ . With  $\sigma_{V-H}^2 = \sigma_V^2 + \sigma_H^2$  and assuming that  $\sigma_V = \sigma_H$ , one can deduce an estimate of the instrument noise. Figure 6 shows the histograms of the TBVH at the TB value corresponding to the maximum density of points in Figure 4. This maximum density corresponds to TBV equal to 284 and 282 K over land at 89 and 157 GHz, respectively, and 283 K over ocean at 157 GHz. At 157 GHz (Figures 6b and 6c), the maximum of the distribution is at -0.6 K (respectively, 0 K) over land (respectively, ocean) with a standard deviation of 3.4 K (respectively, 3.5 K), while at 89 GHz over land (Figure 4a), the histogram peaks at 0 K with a standard deviation of 1.7 K. From the



**Figure 6.** Distribution of the polarization difference at the maximum of the distributions shown in Figure 4 over land at (a, b) 89 and 157 GHz and over ocean at (c) 157 GHz. The brightness temperature that corresponds to the maximum is given at the top of each panel as well as the number of TBV-TBVH pairs with that maximum brightness temperature.

previous equation, and assuming a standard deviation of 3.5 K, i.e., the mean of ocean and land standard deviations (Figures 6b and 6c) for the polarization difference at 157 GHz, we deduce that the instrument noise at 157 GHz is 2.5 K, whereas the instrument noise is 1.2 K at 89 GHz. These estimates are above the values provided by CNES (Table 1), but they are in agreement with the required instrument specification (9% above the required specification at 89 GHz, 4% below the required specification at 157 GHz).

#### 4. Confirmation of the Interpretation of the Polarized Scattering With Radiative Transfer Simulations

Radiative transfer simulations were performed with the Atmospheric Radiative Transfer Simulator (ARTS) [Eriksson *et al.*, 2011]. ARTS is a freely available, well-documented, open source software package. ARTS handles scattering with a full and efficient account of polarization effects. It provides different methods to solve the radiative transfer equation and the Discrete Ordinate Iterative method is used in this study [Emde *et al.*, 2004]. The single scattering properties are calculated using the T-matrix code [Mishchenko, 2000] that allows the treatment of oriented spheroids. The dielectric properties of the material, the particle size distribution, their shape, and orientation are all subject to large uncertainties that can translate into significant differences in terms of simulated brightness temperatures [e.g., Wiedner *et al.*, 2004; Surussavadee and Staelin, 2006; Meirolt-Mautner *et al.*, 2007; Kulie *et al.*, 2010]. Recently, Galligani *et al.* [2013] used ARTS to explore the impact of changes in hydrometeor phase around the melting layer on the upwelling polarized radiation for frequencies below 100 GHz. Two different sets of simulations are performed here to explore the polarized scattering up to 157 GHz. First, simplified thermodynamic and hydrometeor profiles are used to carefully analyze the polarized radiation sensitivity to the particle characteristics (phase, size, shape, and orientation). Second, more realistic simulations of the observed signals by MADRAS are conducted by exploiting the coincidence of TMI and MADRAS observations along a transect, in the middle of the PR swath presented in Figure 3f. This allows using the profiles of water and ice species estimated from the 2A12 TMI GPROF-based product (version v7) available for that specific TRMM overpass. The focus for both simulations is on the impact of variations of the different frozen phase microphysics on the microwave polarized scattering signals observed by MADRAS.

##### 4.1. Hydrometeor Microphysical Properties

The scattering properties of hydrometeors are related to their dielectric properties, their size distribution, their shape, and their orientation. For pure water, the dielectric properties are relatively easy to estimate with limited uncertainties, for instance, using Liebe *et al.* [1991]. For pure ice, Matzler *et al.* [2006] model is commonly adopted, but for other frozen species, the density is a key parameter in the calculation of the dielectric properties. Mesoscale cloud models (Meso-NH for instance) [Lafore *et al.*, 1998] usually provide the mass content ( $\text{kg/m}^3$ ) of the species per atmospheric layer and the size distribution of the maximum dimension of the particle. However, the density and the shape of the species are not explicitly provided by



the microphysical scheme. In Meso-NH for instance, the mass of each hydrometeor category is derived from a relation of the type  $m = aD^b$ , with  $a$  and  $b$  specified for each type of hydrometeor, but the shape of the particle and as a consequence its volume and density are not explicitly given for all particles. For liquid clouds and rain, the particles are assumed to be spheres with  $m$  proportional to  $D^3$ . Graupel and small ice crystals are not strictly spheres ( $b = 2.8$  and  $b = 2.5$ , respectively) but are approximated so in the radiative transfer in the microwave as there is no real justification for a more complicated treatment. Graupel species are rimmed particles for which it is reasonable to assume a spherical shape. Small pure ice crystals can be approximated by spheres for microwave radiative transfer calculation as their scattering is very limited. However, for snow, with  $m$  proportional to  $D^{1.9}$ , the particles are clearly not spheres. For passive microwave signals, it is viable to focus on the bulk aspect of particles as characterized by its aspect ratio, neglecting the simulation of individual complicated particle shapes [Matrosov *et al.*, 2005]. Aspect ratios between 1 and 2 will be tested, and a value of 1.6 is considered realistic from aircraft observations (A. J. Heymsfield, personal communication, 2012). The particle density for ice crystal is that of pure ice ( $0.917 \text{ g/cm}^3$ ). The density of snow and graupel particles is derived from the mass-size relationship intrinsic to the Meso-NH microphysical scheme. In terms of dielectric properties, snow and graupel are heterogeneous media, made of ice and air (dry snow and graupel) and possibly ice, air, and water (wet snow). The dielectric properties for heterogeneous media can be calculated with a number of mixing formulas. The most common, and the one used in this study, is the Maxwell Garnett formula that gives the effective dielectric constant of a mixture as a function of the dielectric constants of the host material and inclusions (see applications of this formula in, e.g., Battaglia *et al.* [2003] and Olson *et al.* [2001a, 2001b]). For dry snow and graupel, the host is air and the inclusion is ice. For wet snow, the Maxwell Garnett Formula is applied twice, once to calculate dry snow and a second time to mix dry snow and water.

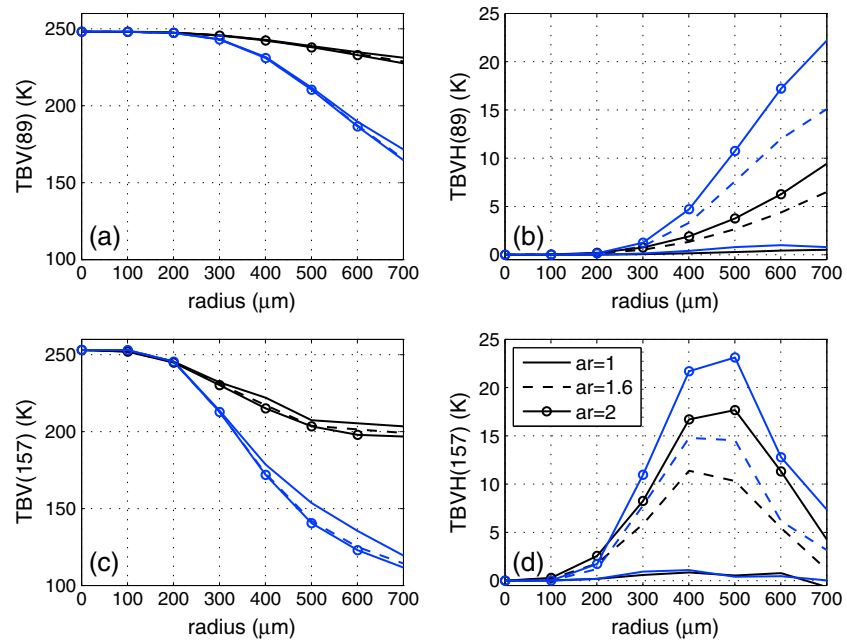
By analyzing the scattering properties from accurate Discrete Dipole Approximation modeling of snow particles, Liu [2004] observed that snow has scattering and absorption properties between those of a solid ice equal mass sphere of diameter  $D_0$  and an ice-air mixed sphere with a diameter equal to the maximum dimension of the particle  $D_{\text{max}}$ . For each frequency and particle shape, a softness parameter  $SP = (D - D_0)/(D_{\text{max}} - D_0)$  is derived that gives the diameter of the best fit equal mass sphere. For each particle shape, this is actually equivalent to the use of a frequency-dependent effective density along with modified diameters. This approach has already shown a high efficiency in reproducing real observations [Meirolid-Mautner *et al.*, 2007], and it will also be tested here.

Both randomly oriented and perfectly horizontally aligned particles are considered in our calculation. In the case of horizontally aligned particles, most particles are likely to suffer particle tumbling related to turbulence. The effect of tumbling has already been evaluated in Prigent *et al.* [2001]. Xie *et al.* [2012] showed that the simulated difference is of the order of 0.2 K in TBs between perfectly horizontally aligned particles and horizontally oriented particles with a standard deviation of  $10^\circ$ . We will concentrate on perfectly horizontally aligned particles for practical reasons.

#### 4.2. Simulations With Idealized Profiles

These simulations involve a tropical standard atmosphere from the Fast Atmospheric Signature Code database [Anderson *et al.*, 1986], with a total column water vapor of  $33 \text{ kg/m}^2$ , a surface temperature of 300 K, and a land surface emissivity set to 0.9 for both polarizations (to avoid any polarized contributions from the surface itself). The incidence angle of the simulated satellite observations is set to  $53^\circ$ , similar to TMI and MADRAS observation geometries. A single cloud layer (2 km thick from 6 to 8 km) is considered and populated with hydrometeors with varying Ice Water Path (IWP). A monodisperse particle size distribution of spheroids is assumed, with radius of  $50 \mu\text{m}$  to  $800 \mu\text{m}$  (note that radius here refers to the radius of the sphere with equivalent mass, i.e., the effective radius).

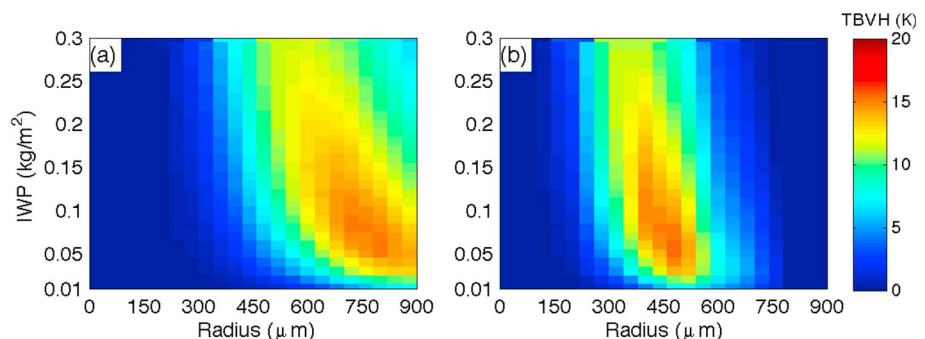
Figure 7 presents the sensitivity of TBV and the polarization difference TBVH to the particle size at 89 and 157 GHz, for pure ice and for dry snow, for a fixed Ice Water Path (IWP) of  $0.2 \text{ kg/m}^2$ , for horizontally aligned spheroids of different aspect ratios (aspect ratio of 1 corresponds to spheres). The TBV depression is very limited at 37 GHz (not shown), even for very large particles, but strongly increases with frequencies (Figures 7a and 7c). TBV depression increases with particle size for dry snow and ice particles. For dry snow the scattering effect is stronger than for pure ice, because of the larger number of particles to reach the same IWP for snow than for ice (the density of ice is  $0.917 \text{ g/cm}^3$  compared to a minimum density of  $0.1 \text{ g/cm}^3$



**Figure 7.** The sensitivity of the vertical brightness temperature (TBV) and the polarization difference (TBVH) at 89 GHz and 157 GHz to the particle aspect ratio as a function of the effective radius for a mono disperse distribution of pure ice (black) and dry snow (blue) horizontally aligned spheroids (fixed IWP at 0.2 kg/m<sup>2</sup>). The parameter “ar” stands for aspect ratio and corresponds to the ratio of the longest to the shortest axis of the spheroids.

for dry snow). As expected, the different aspect ratios do not have a large impact on TBV and the larger the aspect ratios produce slightly more scattering. In terms of the polarization difference, randomly oriented spheroids of aspect ratio of 1.6 or 2 produce only very limited polarized scattering signals (not shown). However, horizontally aligned spheroids, as expected, simulate significant polarization differences. The polarization difference increases with frequency (Figures 7b and 7d). At 157 GHz, TBVH reaches saturation around 500 μm. The different aspect ratios have a significant impact on TBVH. Note that for a realistic aspect ratio of 1.6, a polarization difference between 9 and 15 K is obtained at 157 GHz (between 4 and 7 K at 89 GHz), depending on the density of the particle (pure ice or dry snow). Such results from idealized profiles, but nonetheless realistic simulations, can explain the MADRAS observations at these two frequencies.

To further understand the MADRAS observations, Figure 8 shows the sensitivity of the polarization difference at 89 and 157 GHz to the IWP and particle radius for horizontally aligned spheroids only (aspect ratio of 1.6). Large polarization differences are simulated at 157 GHz for rather low IWP and limited radius. As observed in Figures 7 and 8, both an increase of ice water content (IWC) and particle size can result in the saturation of the polarization difference. This saturation is reached at lower sizes and lower IWP



**Figure 8.** The sensitivity of the polarization difference (TBVH) at (a) 89 GHz and (b) 157 GHz for a monodisperse distribution of dry snow horizontally aligned spheroids, as a function of the IWP and as a function of the particle (effective) radius.

at 157 GHz than at 89 GHz. This saturation feature has been reported before [Miao *et al.*, 2003; Xie and Miao, 2011] when a large number of scattering events occur. In that case, the  $V$  and  $H$  orthogonal streams of radiation tend to the same value, and their difference reaches zero.

Even though the atmospheric state was rather simplified in the simulations presented here, the sensitivity analysis reveals the impact of the microphysical properties on the polarization signal and their stronger effects with increasing frequency. The simulations so far could explain MADRAS observations, and in fact show consistency in terms of a qualitative comparison between TBV and TBVH values for 89 and 157 GHz. For example, considering particles of a specific size (450  $\mu\text{m}$ ) and a realistic aspect ratio (1.6), the TBVH at 157 GHz as presented in Figure 8 shows values between 10 and 15 K, while at 89 GHz TBVH is between 5 and 10 K, with TBV values at 157 GHz being considerably colder than at 89 GHz (not shown). This is in agreement with the order of magnitudes presented in Figure 5. The next section uses more realistic atmospheric parameters for the simulations and explores further the consistency of the simulations with the MADRAS observations.

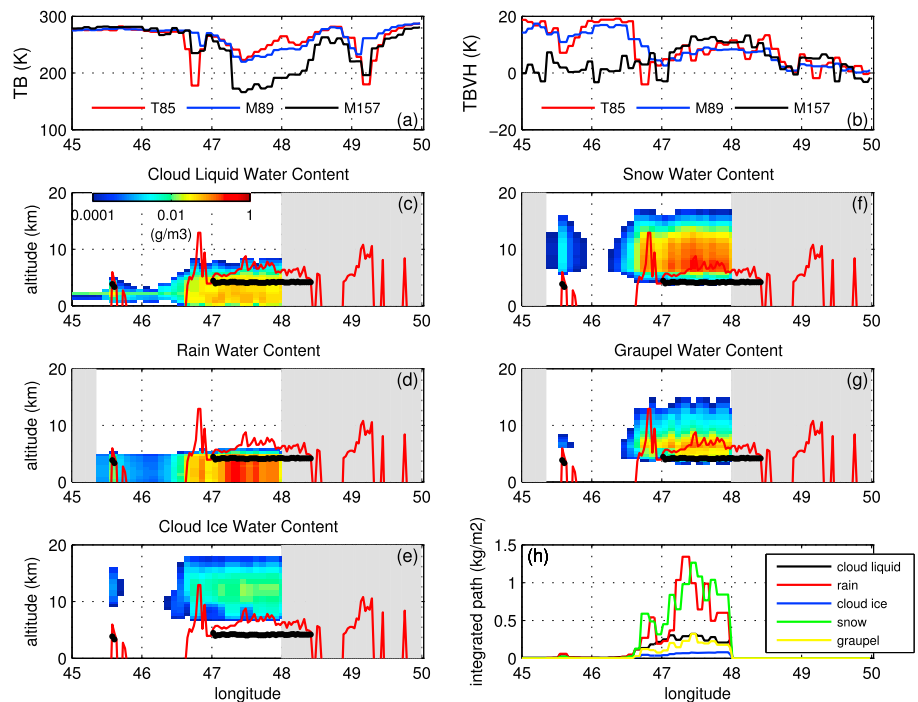
### 4.3. Simulations With Observational-Based Hydrometeor Profiles

We focus on the system off the coast of Madagascar in Figure 3, with large TBVH differences observed by both MADRAS and TMI. The PR nadir swath crosses this system and a longitudinal transect in the middle of the PR swath is selected for our analysis of coincident MADRAS and TMI observations. The profiles of water and ice contents retrieved from TMI (the v7 2A12 TMI product) are adopted along with coincident European Center for Medium-Range Weather Forecasting (ECMWF) reanalysis.

The PR 2A23 rain product [Awaka *et al.*, 1998; Iguchi *et al.*, 2000] provides information on the presence and location of a melting layer, on the rain type (i.e., stratiform, convective, or other), on the freezing height, and on the cloud top height, as detected by the PR. Note that the accuracy of these estimates by the PR is directly related to the PR sensitivity. The v7 TMI 2A12 based on Goddard profiling algorithm (GPROF) generates surface rainfall and vertical hydrometeor profiles of five species (snow cloud water, cloud liquid water, ice, graupel, and rain) from the TMI brightness temperatures. It is derived from a Bayesian retrieval, and it gives the most probable structure of the hydrometeor profiles, given the TMI observations [Kummerow *et al.*, 2011].

Figure 9 shows the measured brightness temperatures and the polarization signals recorded at 85 GHz by TMI and 89 and 157 GHz by MADRAS, along with the v7 TMI 2A12 product, for the transect of interest. Each radiometric observation located along the transect was paired to one PR beam using a minimum distance criteria. The GPROF vertical profiles (only available over ocean) map two different vertical cloud structures: C1 centered around 45.6°E (see Figure 3b) mainly composed of snow and ice with some precipitation and C2 from 46.5°E to 48°E with much higher hydrometeor contents and a convective tower located on the western part. This convective tower is clearly observed by TMI (Figure 9a) with a significant depression of brightness temperatures at 85 GHz. Note that the corresponding 2A12 hydrometeor content is rather limited with respect to the large TB85V TMI depression. The depression is less strong for the MADRAS 89 GHz observations due of a larger footprint but is significant at 157 GHz along the entire transect (down to 160 K on Figure 9a). Finally, the TMI depression at TB85V located around 49.2°E (Figure 9a) corresponds to deep convection: it is also observed by PR with a cloud top around 10 km (Figure 9c). Both 89 and 157 GHz MADRAS measurements show TB depressions in that part of the transect but slightly shifted in latitude and amplitude because of the observation matching methodology and the different sampling geometries for the two radiometers. Figure 9b shows an average TB157VH positive polarization signal of 10 K over C2, while at lower frequencies the polarization signal average is around 7 K. Galligani *et al.* [2013] reported positive polarization signal at 85 GHz in stratiform regions and in presence of bright band that can be explained by horizontally oriented hydrometeors. Finally, the vertical structure of C2, as described with GPROF products, shows a vertical distribution of graupel centered mainly between 5 and 8 km (Figure 9g) while the concentration of ice particles is more pronounced above 8 km (Figure 9f). On the average, the vertically integrated snow content is more than 3 (10) times higher than the vertically integrated graupel (ice) as shown in Figure 9h.

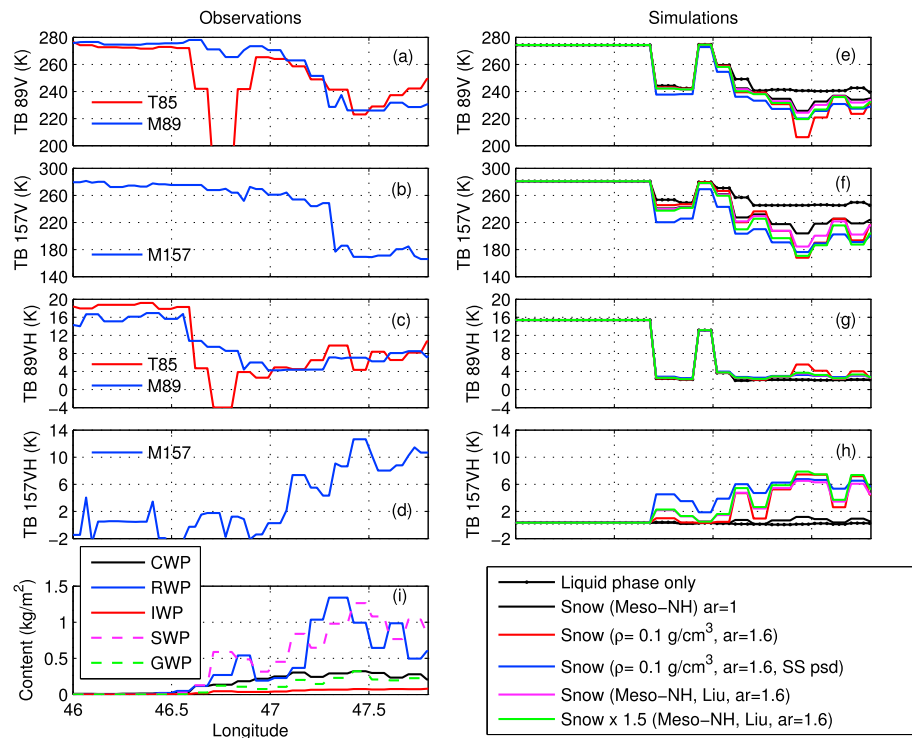
The RT calculations depend not only on the hypothesis on the microphysical properties of the hydrometeors (see sections 4.1 and 4.2) but also on the ability of the TMI 2A12 algorithm to retrieve accurate hydrometeor contents. The hydrometeor contents are provided with the TMI spatial resolution that is different from



**Figure 9.** Brightness temperatures and the retrieved v7 TMI 2A12 hydrometeor profiles along the transect of interest: (a) TMI 85 GHz (T85) TBV and MADRAS 89 GHz (M89) and 157 GHz (M157) TBV, (b) TMI 85 GHz TBVH and MADRAS 89 GHz and 157 GHz TBVH, (c) the cloud liquid water content (CWC), (d) the rain water content, (e) the cloud ice water content (IWC), (f) the snow water content (SWC), (g) the graupel water content and (h) the hydrometeor integrated paths. Note that the PR bright band height (black dots) and the PR cloud top height (solid red curve) are overlaid, while 2A12 TMI profiles with bad quality flag are plotted in grey. TMI 2A12 retrieval is not available over land (east of 48E).

MADRAS (see Table 1). The RT simulations are conducted using realistic ocean emissivities derived from FASTEM [English and Hewison, 1998] using information on surface wind and surface skin temperature from coincident ECMWF reanalysis. As the hydrometeor contents are provided according to the highest TMI spatial resolution, simulated TBs at MADRAS frequencies are already expected to be different to the observed MADRAS TBs as the spatial resolutions are different for the two radiometers.

Figures 10a–10d shows in blue the MADRAS observations along the transect of interest. Note that TMI 85 GHz observations (red lines) are also shown for reference since the v7 TMI 2A12 hydrometeor profiles are provided according to the highest TMI spatial resolution, as mentioned earlier. Figures 10e–10h summarizes the results of the sensitivity analysis to different microphysical assumptions. Finally, Figure 10i shows the vertically integrated mass content of the different hydrometeor species as retrieved from the 2A12 algorithm along the transect of interest. The first simulation configuration (black line) corresponds to the initially selected parameters where the particle size distribution and the intrinsic mass for all species are specified according to those of the microphysical scheme in the cloud mesoscale model Meso-NH. All species, including snow, are assumed to be perfect spheres (i.e., aspect ratio of 1). The dielectric properties of the snow and graupel species retrieved from the 2A12 profiles are calculated using the Maxwell Garnett mixing formula for dry snow with an ice volume fraction,  $f = \rho(\text{snow})/\rho(\text{ice})$ , where  $\rho(\text{snow})$  is the density of snow and graupel as deduced from the Meso-NH parameterization of the mass of these species. Note that the dielectric properties are calculated for dry snow, and not for wet snow, as it is considered that the temperatures of the snow profiles are too low to consider a wetness degree ( $W(\%) = 0$  for  $T < 258.15$  K;  $W(\%) = T - 258.15$  for  $258.15 < T < 273.15$  K;  $W(\%) = 15$  for  $T > 273.15$  K from Skofronick-Jackson *et al.* [2002]). This configuration results in very limited scattering with small TB depression (too warm TBV), evidenced in Figures 10e–10f, and the limited polarization, evidenced by the low positive values in TBVH in Figures 10g–10h. Another configuration where only the liquid phase is taken into account is also shown (black dotted lines) for reference in Figures 10e–10h to emphasize the importance of the scattering signal of the ice phase at 89 and especially at 157 GHz, as discussed throughout this study.



**Figure 10.** The TBV and TBVH signals at 89 and 157 GHz (a–d and i) observed by MADRAS including TMI 85 GHz records and (e–h) simulated with ARTS under different microphysical properties of dry snow species, for the transect of interest. In Figure 10i CWP, RWP, IWP, SWP, and GWP stand for cloud water path, rain water path, ice water path, snow water path, and ice water path, respectively.

Changing the aspect ratio, the orientation or the PSD (to that of the Meso-NH PSD parameterization for graupel for instance for the dry snow particles), but using the same density parameterization as given by Meso-NH does not have any impact on TBV or TBVH (not shown). Multiplying the snow content by 1.5 in each layer decreases the simulated TBVs at most by 5 K at 157 GHz (not shown). Snow particle sizes that are likely to scatter and polarize the radiation at 89 and 157 GHz have very low density under the Meso-NH mass size parameterization, affecting the dielectric properties via the ice volume fraction, and as a consequence are almost transparent to the microwaves (already seen in, e.g., *Meirolid-Mautner et al. [2007]*).

Assuming the Meso-NH particle size distribution for snow species but calculating the dielectric properties for dry snow particles with a fixed density of  $0.1 \text{ g/cm}^3$  (a value that is often selected for snow) has an important impact on the single scattering properties via the ice volume fraction and thus on the TBVs. Randomly oriented spheres result in simulated TBVs closer to those observed than the assumptions previously discussed (not shown) but do not polarize the scattering signal. In contrast, oblate horizontally oriented snow particles with an aspect ratio of 1.6 (solid red line, Figures 10e–10h) lead to more realistic TBVs and polarization signals of the order of those observed by MADRAS at 157 GHz. At 89 GHz, however, this assumption can generate excessive scattering (as shown here locally Figure 10e and as observed in other situations).

For the same configuration, the Meso-NH snow PSD was replaced by the *Sekhon and Srivastava [1970]* (SS) PSD (blue lines, Figures 10e–10h), thus assuming fewer large particles and more numerous smaller ones. With the SS PSD the TBVs and TBVHs are closer to observations at 89 GHz than the previous assumption but a slight deterioration is observed at 157 GHz.

The *Liu [2004]* parameterization of the scattering properties of snow is then tested, with the nominal PSD and density of the Meso-NH model (pink line, Figures 10e–10h). It provides TBV depressions and TBVH polarizations within the observed values, without any additional fine-tuning. Finally, the sensitivity to the snow water content (SWC) is then analyzed by multiplying the snow content by 1.5 in each atmospheric layer for the previous configuration with Liu’s approximation (green lines), configuration labeled Liu (SWC × 1.5)



in the remainder of the discussion. The scattering effect is significant, especially in terms of TB depression and polarization difference at 157 GHz. The snow quantities provided by the TMI inversion are realistic, and adding more snow does not improve the agreement between simulations and observations.

A number of points from Figure 10 need to be emphasized before concluding that MADRAS observations could be explained by applying the Liu (SWC  $\times$  1.5) assumptions. First of all, TBV and TBVH simulations at 89 GHz and 157 GHz are of the same order of magnitude as the observations, meaning that the assumptions are consistently constraining the RT simulations successfully. Note that the strong depression measured by TMI in Figure 10a around 46.5°W corresponds to the convective tower previously mentioned but “missed” by MADRAS mainly due to its larger footprint size. The Liu (SWC  $\times$  1.5) simulation does not fully reproduce the observed strong brightness temperature depressions. This is possibly due to an underestimation of the actual hydrometeor contents from the 2A12 algorithm for that specific convective tower. In terms of the TBVH, west of 47°W, TBVH simulations are observed to peak at 85 GHz up to 13 K, in disagreement with MADRAS and TMI observations. In fact, the simulated TBVHs and TBVs are similar to MADRAS observations at clear sky conditions (e.g., west of 46.5°W). These RT simulations are clear evidence that the retrieved species contents are underestimated in this region. Otherwise, the atmosphere would be opaque enough to mask the surface emissivity polarization that is simulated at 85 GHz for TBVH, for example. This is not the case for TBVH at 157 GHz since at this frequency we are not so sensitive to surface emissivity.

Considering the previous discussion, it appears that with realistic profiles and hydrometeors characteristics, and keeping in mind that there are still uncertainties on the scattering properties of the cloud microphysics, it is thus possible to explain consistently the polarized scattering signals observed at 89 and 157 GHz. This further extends the validity of our previous interpretation of the signals up to 90 GHz, with additional stringent constraints imposed by the higher frequency.

## 5. Conclusion

The MADRAS instrument launched at the end of 2011 on board the Megha-Tropiques mission offers for the first time measurements of the two orthogonal polarizations at high microwave frequencies. Analysis of available quality-controlled MADRAS data reveals that the radiometric sensitivity at 89 and 157 GHz are in agreement with the required instrument specifications. Further analysis of the MADRAS observations also revealed that the instrument was very stable.

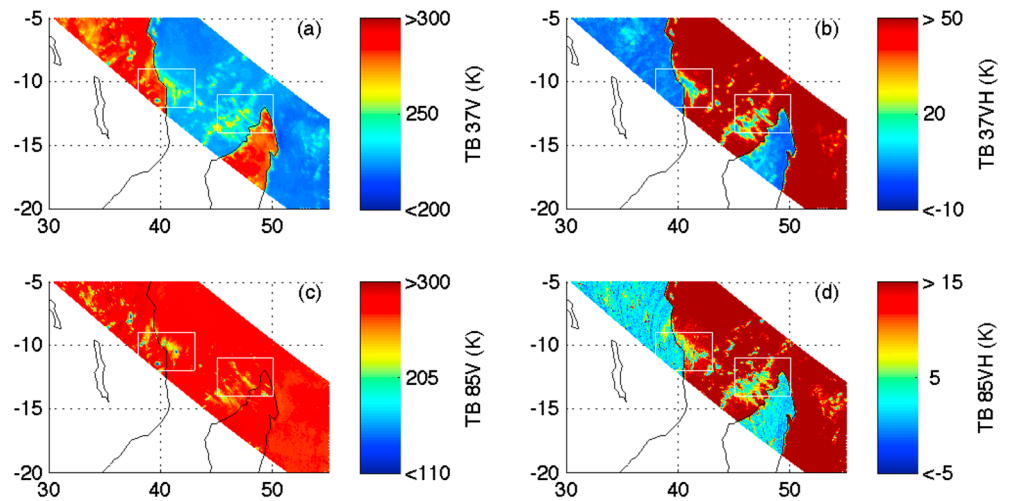
We observed that at 157 GHz, scattering by clouds is polarized with TBVH larger than 8 K in 50% of the cases for TBV below 250 K, as compared to 5.5 K in 50% of the cases at 89 GHz. Simulations confirm that this is due to horizontally oriented oblate particles in the cloud frozen phase. This polarized scattering signal at 157 GHz is consistent with the polarized signatures previously observed around 85 GHz, and as expected it is more common and stronger at higher frequencies. The large occurrence of the polarized scattering in the observations as well as the magnitude of the polarization suggest that horizontally oriented oblate particles are very frequent in the cloud ice phase.

This significant polarized scattering has to be taken into account in the development of the retrieval of precipitation and cloud properties from microwave radiometry, such as the GPM algorithms that are presently under development. Especially over land, most passive microwave retrievals for precipitation are based on the scattering signal at frequencies above 80 GHz. The effect of these oriented particles has to be accounted for, at least as an additional source of noise, if not explicitly.

With the recent decision of flying an Ice Cloud Imager between 183 to 664 GHz on board the next generation of European operational meteorological satellites, relating the observed scattering from the ice phase to accurate measurements of the cloud properties is a key challenge. The analysis of the measurements provided by MADRAS contributes to the preparation of this promising instrument, with polarimetric measurements at 170 and 670 GHz for a better description of the frozen hydrometeors.

## Appendix A: Comparison With Coincident TMI Observations

Nearly coincident MADRAS and TMI observations are available for the scene shown in Figures 1 and A1, respectively. The time difference is 6 min. Despite the different spatial resolutions and slightly different frequencies, the observations of the two radiometers are quite similar in terms of radiometric range and

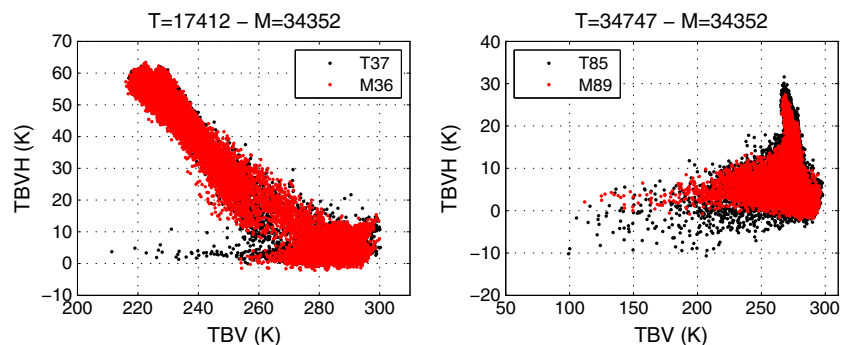


**Figure A1.** Same as Figure 1 but with TMI records for the period 12:10 to 12:18 UT on 9 December 2011.

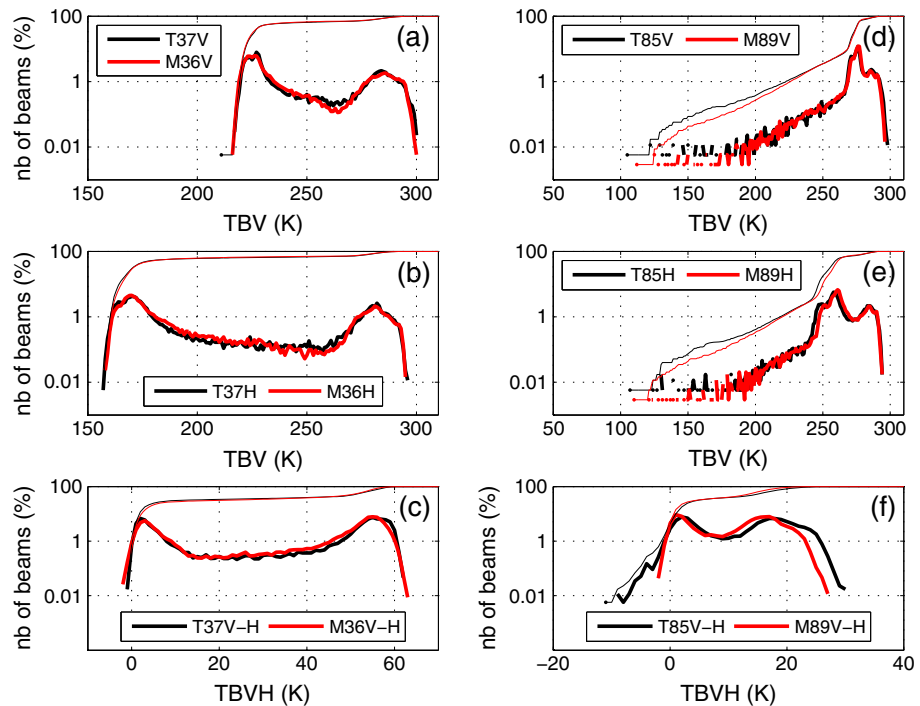
sensitivity over land and ocean. MADRAS measurements are very stable along a given scan and from a scan to the next at high frequencies. No clear jump between scan lines is observed on the images of the polarization differences at 89 or 157 GHz, whereas at 85 GHz with TMI, a large noise is evident on the polarization difference maps, within a scan and from one scan to the next.

Figure A2 shows the scatter plots of TBs and polarization differences for the common spectral bands (ocean and land together). At 35–37 GHz, the observations from the two radiometers span over the same radiometric domain even if TMI reported more convection-related scattering because of a better spatial resolution (9 km × 16 km for TMI [Kummerow *et al.*, 1998] and 40 km × 67 km for MADRAS as listed in Table 1). At 85–89 GHz, even if the number of pixels from two radiometers is almost the same, more negative polarization differences are reported by TMI, while the distribution of MADRAS polarization difference at TBs lower than 200 K seems to be centered around 5 K. This pinpoints to the need for thorough investigations of the calibration of each radiometer if their observations have to be used jointly.

Figure A3 shows the histograms and the cumulative distributions of the brightness temperatures for all surfaces together, for common radiometric band and polarization of the two radiometers. These histograms are computed from the radiometric measurements shown in Figures 1 and A1 but for the common area defined by the intersection of MADRAS and TMI swaths. At 37 GHz, both radiometers provide rather similar histograms for both sides of the distributions (Figures A3a and A3b). At 85 GHz, for both polarizations, differences exist at cold brightness temperatures, i.e., for convective clouds (Figures A3d and A3e).



**Figure A2.** Scatter plots of brightness temperatures and polarization differences at the studied bands for the two instruments for ocean and land beams together for the common area delineated by the intersections of MADRAS and TMI swaths shown in Figures 1 and A1. T and M stand for TMI and MADRAS, respectively.



**Figure A3.** (a–f) Histograms (in solid lines) and cumulative distributions (in thin lines) of the brightness temperatures mapped in Figures 1 and A1 for common radiometric bands. Only beams located within the common area defined by the intersections of the overpasses of the two swaths were used to produce the plot. T and M stand for TMI and MADRAS, respectively.

Those discrepancies could be explained by the different spatial resolutions between the two radiometers, the viewing geometry of the convective clouds depending on the orientation of the radiometer beams relative to the cloud structure, and the natural evolution of the sampled clouds between the two overpasses (delay of 6 min). While the histograms of the polarization difference at 37 GHz are rather similar (Figure A3c), some differences are observed at 85 GHz (Figure A3f): TMI recorded negative-to-null polarization differences while MADRAS did not, and smaller positive difference polarizations are recorded by MADRAS. These discrepancies could be explained by the different spatial resolutions of the two radiometers and by the different radiometric sensitivities between the instruments (see Table 1 for MADRAS. TMI noise levels are 0.36 K, 0.31 K, 0.52 K, and 0.93 K for 37 GHz V, 37 GHz H, 85 GHz V, and 85 GHz H channels, respectively [Kummerow *et al.*, 1998]).

From these comparisons, we can conclude that MADRAS performs well, with results very similar to TMI for their common (or close) channels.

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