Intercomparison of Microwave Radiative Transfer Models for Precipitating Clouds

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***Abstract*—An intercomparison of microwave multiple scattering radiative transfer codes used in generating databases for satellite rainfall retrieval algorithms has been carried out to ensure that differences obtained from retrieval techniques do not originate from the underlying radiative transfer code employed for the forward modeling.**

A set of profiles containing liquid water and ice contents of cloud and rain water as well as snow, graupel and pristine ice were distributed to the participants together with a black box routine providing Mie single scattering, atmospheric background absorption and surface emissivity. Simulations were to be carried out for nadir and off-nadir (53.1°) observation angles at frequencies between 10 and 85 GHz. Among the radiative transfer models were two-stream, multiple stream and Monte Carlo models.

The results showed that there were two major sources of differences between the codes. 1) If surface reflection/emission was considered isotropic, simulated brightness temperatures were significantly higher than for specular reflection and this effect was most pronounced at nadir observation and over ocean-type surfaces. 2) Flux-type models including delta-scaling could partially compensate for the errors introduced by the two-stream approximation. Largest discrepancies occured at high frequencies where atmospheric scattering is most pronounced and at nadir observation. If the same surface boundary conditions, the same multiple-stream resolution and the same scaling procedures are used, the models were very close to each other with discrepancies below 1 K.

***Index Terms*—Microwave radiative transfer, model intercomparison, precipitation retrieval.**

I. INTRODUCTION

IN THE last decade, there has been a growing interest in developing rain profile retrieval algorithms trained by cloud radiative databases [1]. This approach is based upon the use of radiative transfer models applied to cloud-resolving hydrometeor profile outputs. The appeal to develop fast inversion algorithms using pregenerated physically consistent cloud radiative databases has been largely exploited for spaceborne microwave radiometry of rainfall [2], [3]. Following this approach, the accuracy of rainfall estimates are basically linked to the accuracy of both forward and inverse models. In particular, the reliability and consistency of the various radiative transfer models, used for building retrieval databases, is a crucial problem to be investigated within this framework.

TABLE I
SPECIFICATION OF MODEL FEATURES

Model	Main author	Specifications	Surface
1: CU	K.F. Evans	two–stream Eddington	Fresnel
2: CU	K.F. Evans	two–stream Eddington, δ–scaling	Fresnel
3: FSU	E.A. Smith	two–stream Sobolev, δ–scaling	Fresnel
4: FSU	E.A. Smith	two–stream Sobolev, δ–scaling	Lambertian
5: IFA	F.S. Marzano	16–stream discrete ordinate	Lambertian
6: NASA	C.D. Kummerow	two–stream Eddington	Fresnel
7: NASA	L. Roberti	reverse Monte Carlo	Fresnel
8: ECMWF	P. Bauer	two–stream Eddington	Fresnel
9: ECMWF	P. Bauer	matrix operator	Fresnel

This intercomparison has been carried out to ensure that differences obtained from retrieval techniques do not originate from the underlying radiative transfer code employed for the forward modeling. A desired output of this intercomparison exercise is that the radiative transfer codes used by the different algorithms all produce nearly equivalent brightness temperature (TB) results for similar input. TB-differences should not be greater than a few degrees. This requires that the inputs to the models be identical, i.e., the ambient pressure-temperature-moisture profiles, the extinction and scattering coefficients, the asymmetry factors and the boundary conditions must be specified exactly in the same way.

The participating models introduced in Section II cover the range of complexity for the treatment of polarized radiative transfer in media where multiple scattering is important. Participitating institutions were the University of Colorado, Boulder (CU), the Florida State University, Tallahassee (FSU), the Institute for Physics of the Atmosphere, Rome, (IFA), the National Aeronautics and Space Administration (NASA), Greenbelt, and the European Centre for Medium-Range Weather Forecasts, Reading (ECMWF), represented by the authors of this article. Directions were provided for channel center frequencies, viewing angles, surface temperatures,

Manuscript received April 18, 2001; revised August 10, 2001.

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Publisher Item Identifier S 0196-2892(02)03270-9.

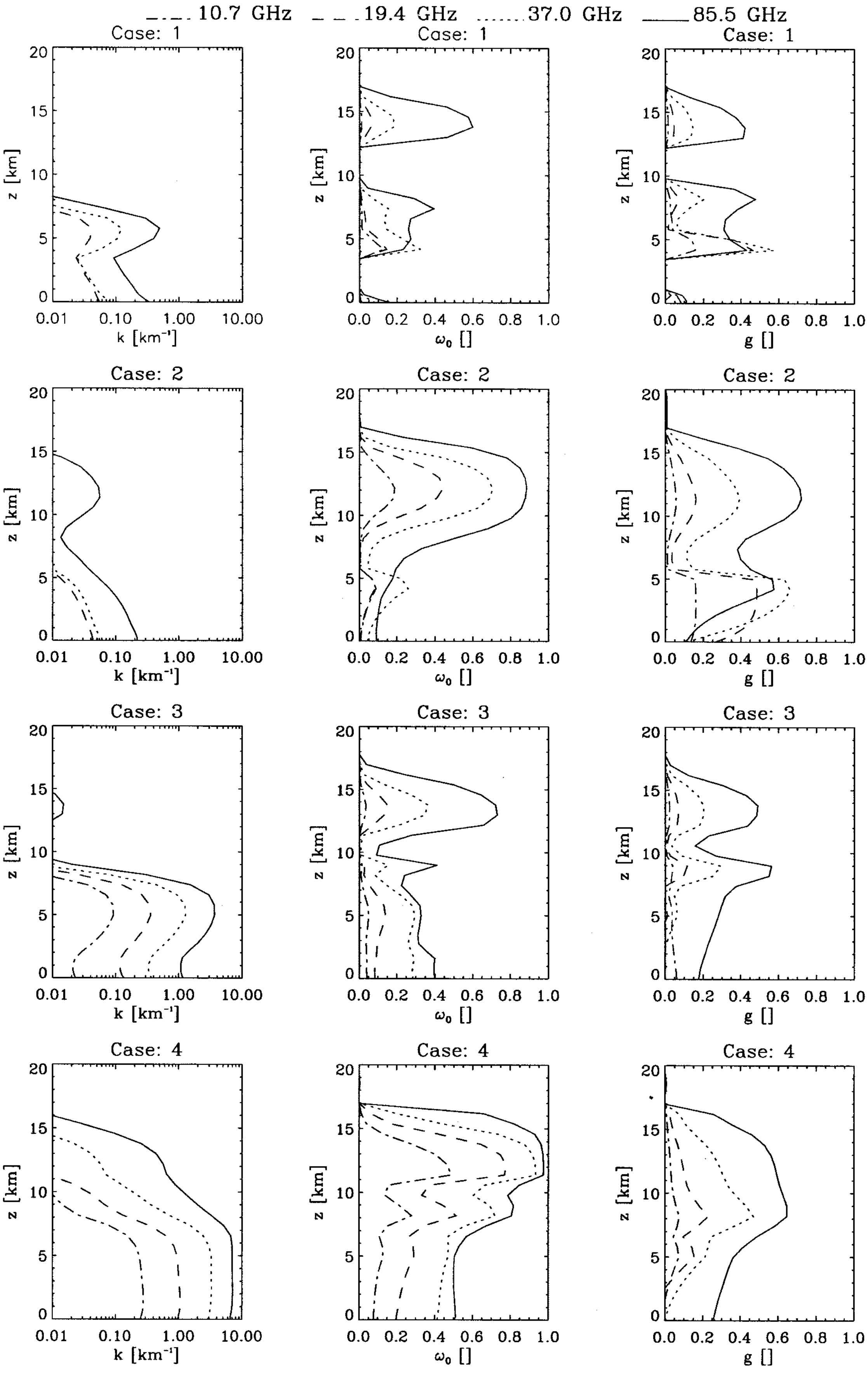

Fig. 1. Profiles of optical parameters for four cases (rows) and the corresponding extinction coefficients, k, single scattering albedos, ω_o, and asymmetry parameters, g, at four microwave frequencies (columns).

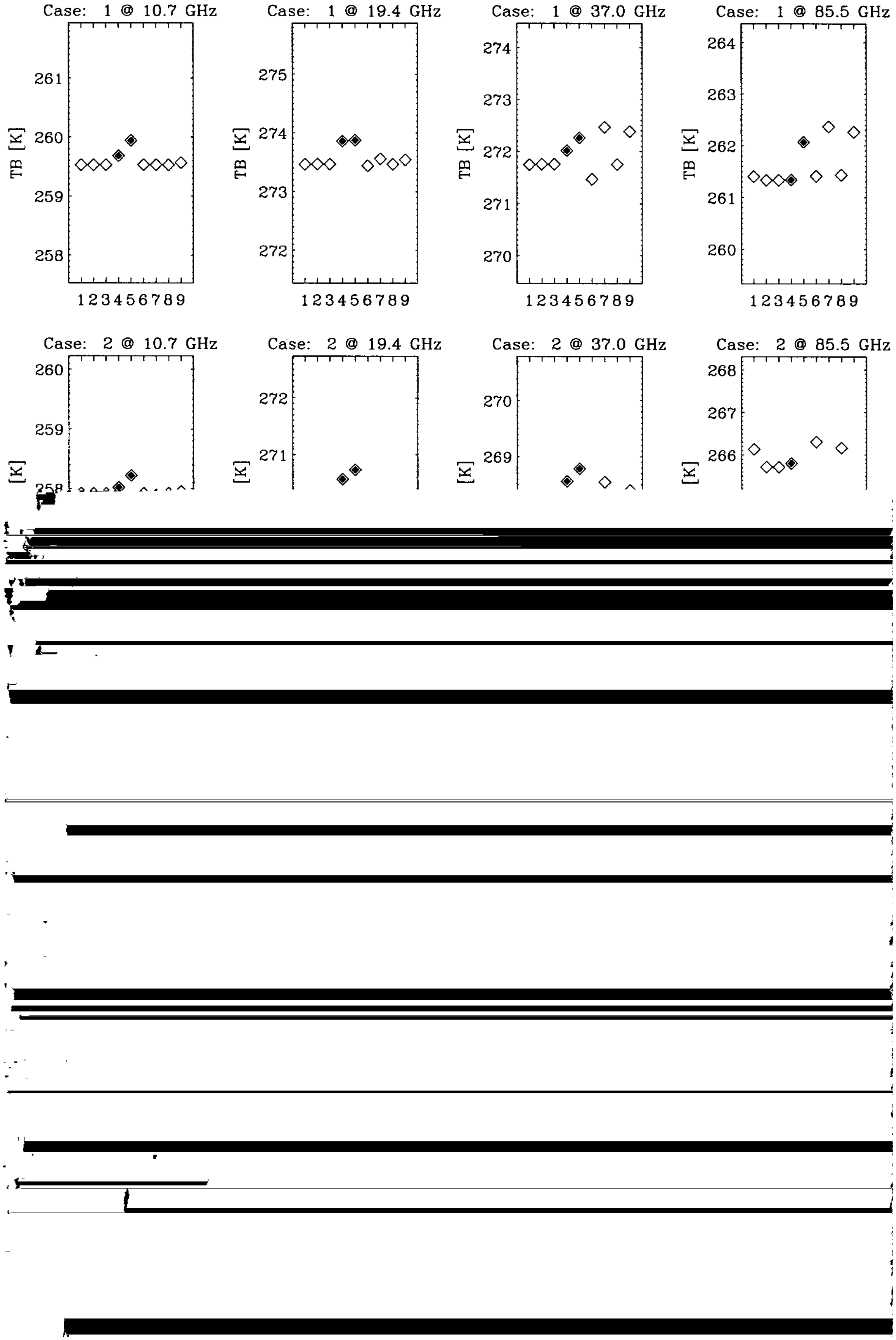

Fig. 2. TBs at 53.1° incidence over land surface for four cases (rows) and at 10.7, 19.4, 37, and 85.5 GHz (columns); filled symbols mark models which assume Lambertian surface reflection.

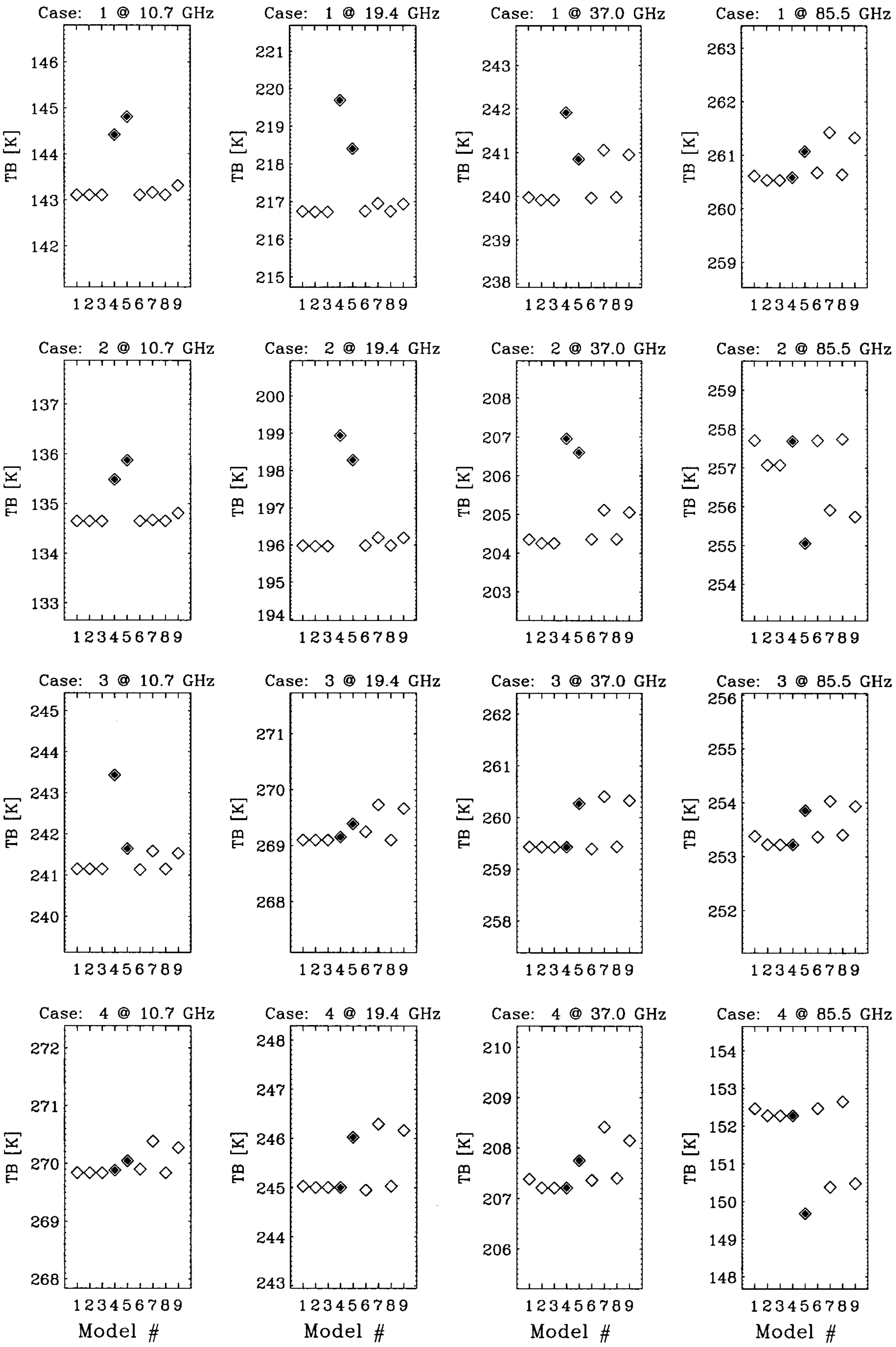

Fig. 3. TBs at 53.1° incidence over ocean for four cases (rows) and at 10.7, 19.4, 37, and 85.5 GHz (columns); filled symbols mark models which assume Lambertian surface reflection.

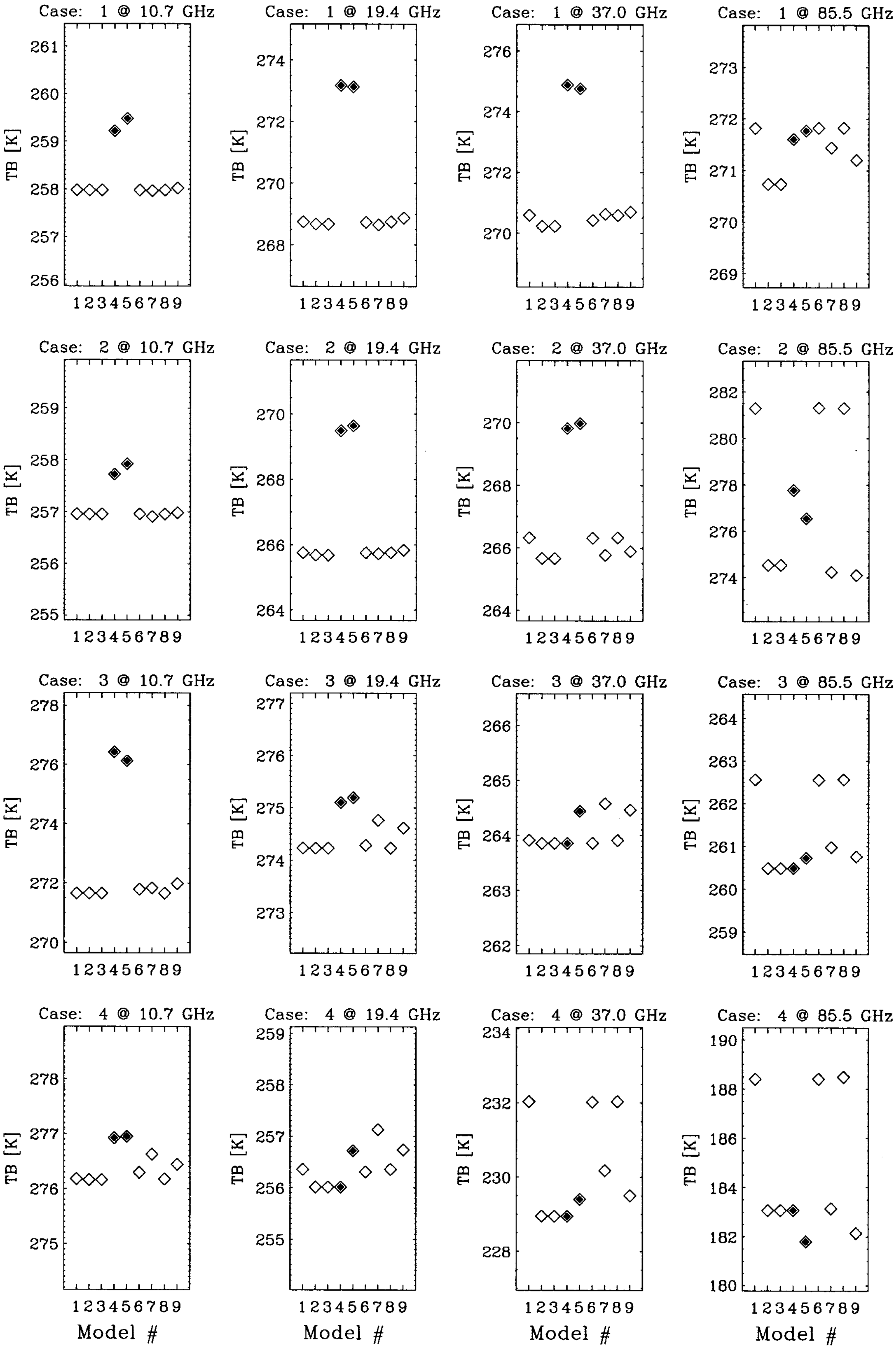

Fig. 4. TBs at 0° incidence over land surface for four cases (rows) and at 10.7, 19.4, 37, and 85.5 GHz (columns); filled symbols mark models which assume Lambertian surface reflection.

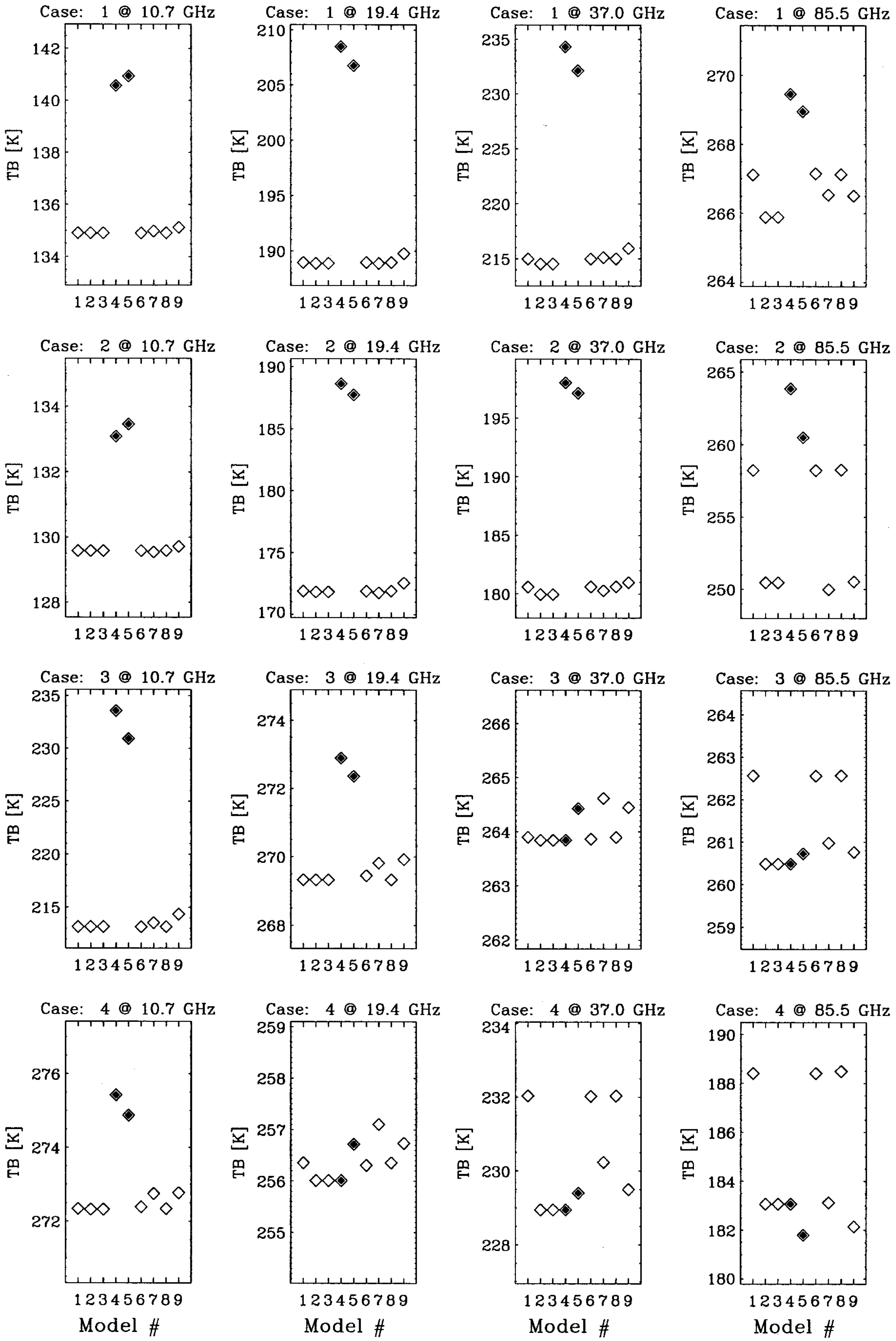

Fig. 5. TBs at 0° incidence over ocean for four cases (rows) and at 10.7, 19.4, 37, and 85.5 GHz (columns); filled symbols mark models which assume Lambertian surface reflection.

surface emissivities and cosmic background temperature. In Section III, the input data, i.e., profiles of height, temperature, pressure, specific humidity, hydrometeor densities of several species given in terms of equivalent liquid water contents are described along with the set-up of those routines used to calculate single scatter parameters and gaseous absorption coefficient. From these, the investigators were asked to provide simulations of upwelling radiances (in terms of TBs) at the top of the atmosphere for each model result. There were 16 sets of model calculations required (four cases, each of which includes four separate profiles). An analysis of these results is presented in Section IV followed by conclusions.

II. MODELS

Nine different models participated in the intercomparison representing flux-type, multiple stream and Monte Carlo techniques. Table I gives an overview of the main model features. Principally, the more streams are used the better the representation of the angle dependence of the phase function is and therefore the more accurate the multiple scattering calculations are. Also, the Monte-Carlo model may be considered a reference since all scattering angles and multiple scattering configurations occur given that enough photons are used.

In the original instructions, it was requested that the surface emissivity was to be fixed at all frequencies without specification whether the surface was to be taken as a Fresnel or Lambertian reflector. Since this led to some discrepancies in how each of the models was run, the FSU model was run with both Fresnel and Lambertian surfaces for each of the water and land cases. All other modelers used Fresnel reflectors while IFA only assumed Lambertian, i.e., isotropic surface reflection. This will explain some of the discrepancies observed in the results.

The CU simulations produced two sets of results using a two-stream Eddington model [4], one in unscaled form and the other in δ-scaled form, specifying Fresnel surfaces for both water and land. FSU submitted two sets of results from a two-stream Sobolev model with δ-scaling for the two-stream case ([2]; it is equivalent to a δ-Eddington model), in which the water and land surfaces were first taken as Fresnel and then as Lambertian reflectors. The IFA model uses a discrete ordinate approach with 16-stream resolution with δ-scaling specifying Lambertian surfaces for water and land [5]. NASA submitted two sets of results, one for a two-stream Eddington model without δ-scaling [6] and one for their reverse Monte Carlo model [7], again specifying Fresnel surfaces for both water and land. Finally, both ECMWF models use Fresnel surfaces, one model being an 8-stream doubling-adding code [8], the other an Eddington model [9].

III. INPUT DATA

The directions and constants needed for making the calculations were specified as follows.

- Microwave frequencies for output at 10.7, 19.4, 37, 85.5 GHz, satellite zenith angles of 53.1° and 0° corresponding to the spaceborne Special Sensor Microwave/Imager (SSM/I) and the airborne Advanced Microwave Precipitation Radiometer (AMPR), respectively. Surface temperature of 300 K, surface emissivities of 0.85 for land and 0.4 for ocean and cosmic background temperature of 2.7 K were prescribed.
- All calculations were to be polarization independent, that is also for Fresnel reflection the polarization of incident unpolarized radiation was neglected.
- Four profiles were provided, representing four configurations of cloud states: 1) low water, low ice content (associated rainrate of 0.94 mm/h), 2) low water, high ice content (associated rainrate of 0.34 mm/h), 3) high water, low ice content (associated rainrate of 9.46 mm/h), and 4) high water, high ice content (associated rainrate of 90.23 mm/h).
- Profile information served as input to a Mie "black box" which generated volume extinction and scattering coefficients as well as asymmetry factors, plus total volume extinction and scattering coefficients (km^{-1}), total asymmetry factor and combined gaseous absorption coefficients for oxygen and water (km^{-1}) given for 41 layers. The latter were obtained from the millimeter propagation model (MPM) of [10]. For those models requiring phase functions, the Henyey-Greenstein approximation was prescribed to be obtained from the asymmetry factors.

The profiles had been selected from a mesoscale nonhydrostatic cloud model [11] simulation of a continental storm system during the Cooperative Huntsville Meteorological Experiment (COHMEX) in 1986. The profiles had 42 levels, the lowest level corresponding to the surface. At each level, the variables were height (km), temperature (K), pressure (hpa), specific humidity (g/kg), vertical velocity (m/s), cloud and rain liquid water content (LWC) as well as graupel, pristine ice crystal, snow and aggregate ice water contents (IWC) (all in g/m^3). An exponential formulation had been used to specify drop size distributions (DSD) for rain, graupel, snow and aggregates. It is of the form

$$N(D) = A \cdot \exp(-B \cdot D) \tag{1}$$

where D is the mean diameter of a hydrometeor in units of mm. At each level and for each of these hydrometeors, the parameters A in units of m^{-3}mm^{-1} and B in units of mm^{-1} were given. Cloud droplets and pristine ice crystals were assumed monodisperse with diameters of 0.01 mm and 0.1 mm, respectively. Fig. 1 summarizes the input profiles of volume extinction coefficient, k, single scattering albedo, ω_o and asymmetry parameter, g, at 10.7, 19.4, 37, and 85.5 GHz, respectively. At 85.5 GHz, the extinction profile follows the rain liquid water distribution while ω_o indicates nicely the precipitating ice (snow and graupel) concentrations. The total ice amounts of cases two and four are about the same while case four shows multiple maxima.

Each investigator's output had to contain four TB-vectors (one for each profile) for each of the following cases: SSM/I-land, SSM/I-ocean, AMPR-land, AMPR-ocean, i.e., 16 datasets all together.

IV. RESULTS

Figs. 2–5 summarize the results from all sensor and surface combinations. For convencience, only the four window frequencies where atmospheric absorption is small compared to hydrometeor contributions are presented. Over land (Figs. 2 and 4) and between 10.7 and 37 GHz, all those models using Fresnel surface reflection produce almost identical results. The assumption of isotropic reflectors increases the upwelling radiances significantly by 1–5 K at 0° incidence and by $<$ 2 K at 53.1° incidence. These differences might be partially compensated if parameterizations for rough surfaces are accounted for in Fresnel reflection.

Once scattering in the atmosphere becomes important (at 85.5 GHz, in particular for cases two and four), the influence of the model treatment of multiple scattering overrides the surface effect. Those two-stream models which do not include δ-scaling, i.e., do not account for the more extreme peak of the phase function in forward scattering direction, produce higher TBs. Models 4 and 5 (Lambertian surface) still overestimate TBs with respect to the other models but to a lesser extent than the unscaled models. The difference between multiple-stream and Monte Carlo models (models five, seven, and nine in case four at 85.5 GHz) always remains below 1 K where the surface has no effect. At nadir incidence, δ-scaling does not fully compensate the two-stream simplification because δ-scaling is most accurate where the observation angle corresponds to the zeroth order discrete angle in the quadrature formula [12].

Over oceans, the lower surface emissivities produce larger differences since both emission and scattering in the atmosphere are detectable in the response of TBs to cloud condition. The surface emission treatment becomes even more relevant. At nadir incidence, the Lambertian models produce TBs which are 20 K too high. For 53.1° incidence, this limit is reduced to 5 K. Again, the multiple-stream and Monte Carlo models are very close for opaque and strongly scattering atmospheres.

In summary, we have the following.

- δ-scaling makes little difference for SSM/I incidence angle (worst case 0.5 K for land at 85.5 GHz, 0.75 K for ocean), but large difference for nadir incidence (7–8 K at 85.5 GHz, 3 K at 37 GHz).
- Switching from Fresnel to Lambertian boundary conditions at fixed emissivity makes little difference at SSM/I incidence over land, but over 2 K for water at 10.7 GHz; at nadir incidence over land, differences are 3–5 K across all frequencies, while over ocean differences are approximately 20 K over the 10.7–37 GHz range.
- Going from two-stream to 16-stream for Lambertian boundary conditions produces worst case differences at 85.5 GHz of around 2.5 K for SSM/I incidence, while at nadir incidence worst case differences at 85.5 GHz are around 1 K over land and 3.5 K over ocean.
- The worst case differences between two-stream and reverse Monte Carlo are 2.5 K at SSM/I incidence and half that for nadir incidence.
- As would be expected, the differences between 16-stream and reverse Monte Carlo are smaller than the differences between two-stream and reverse Monte Carlo—where these comparisons can be made (only when the upwelling TBs are insensitive to surface boundary conditions since the IFA calculations used a Lambertian surface and the NASA Monte Carlo calculations used a Fresnel surface).
- The FSU and CU scaled two-stream calculations are almost identical, which is not surprising since they represent a similar approximate solution to the radiative transfer equation, although the codes were developed independently.

V. CONCLUSIONS

The emergence of an increasing number of physical rainfall retrieval algorithms based on radiative transfer simulations has raised the issue of modeling accuracy given different surface and atmospheric conditions. In this intercomparison effort, it was attempted to provide guidance to model users and algorithm developers on which model configuration to use and on how to interpret apparent differences between retrievals and training databases. For this purpose, hydrometeor profiles representing moderate and intense convection were provided to radiative transfer model developers with strictly prescribed directions to evaluate the technical differences of their solution to the radiative transfer in scattering atmospheres.

From the results, it is concluded that in semi-transparent atmospheres, the treatment of surface reflection/emission is extremely important. If surface reflection is considered isotropic, top-of-the-atmosphere TBs can be as much as 20 K higher than for Fresnel reflection. These differences are most pronounced over ocean but still significant over land. Since over ocean the surface reflection is rather specular, the assumption of isotropic reflection may lead to large inaccuracies.

The model formulation of multiple scattering becomes effective in nearly opaque and strongly scattering atmospheres. Multiple-stream and Monte Carlo models may be regarded most exact due to the angular resolution in the vertical plane. The δ-scaling approach for two-stream models can partially compensate the reduction to representative radiance streams at one zenith angle if scattering is strong. In any case, δ-scaling never reduces the accuracy.

In conclusion, if the same surface boundary conditions, the same multiple-stream resolution and the same scaling procedures are used, the models will be very close to each other with discrepancies below 1 K. These results provided the assurance that retrieval differences are not explained by the radiative transfer models included in this study. Thus all models presented here are not the major source of retrieval discrepancies by virtue of these tests.

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