SIX YEARS OF MICROWAVE RADIATIVE TRANSFER VALIDATION USING AIRBORNE RADIOMETERS

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1. INTRODUCTION

The UK Meteorological Office has operated a two-channel microwave scanning radiometer, MARSS, since 1990. MARSS measures microwave brightness temperatures at 89 and 157 GHz, close to the AMSU-B window channels. It is usually operated on a modified C-130 aircraft, from a position where it can view both up and down at angles from 0 to 40^{o}. In 1995 a second radiometer, Deimos, added channels at 23.8 and 50.1 GHz, close to AMSU-A channels 1 & 3, primarily to study surface emissivity. The MARSS radiometer has been operated on over 100 flights of the C-130, collecting over 1000 hours of data. Additional ground-based data have also been collected. Analysis of this dataset has led to new insight into radiative transfer errors at microwave wavelengths, prior to the launch of ATOVS. This paper summarises the results, many of which have been previously published. Ongoing measurements are now concentrating on land and ice surface microwave emissivity, in preparation for ATOVS.

2. AIRCRAFT INSTRUMENTATION

The C-130 aircraft is fitted with sensors to measure air pressure (pitot-static tube), temperature (standard Rosemount sensor), humidity (General-Eastern chilled mirror and Lyman-α total water) and total cloud liquid water content (Johnson-Williams hot wire probe). In addition there is an array of radiation, navigation, cloud microphysics and camera equipment, making it one of the best equipped aircraft of its type. The aircraft is shown in Figure 1. The MARSS can be seen to the right of the crew door, Deimos is located on the belly of the aircraft and the "nose" houses the major meteorological sensors. The MARSS mirror rotates through 360^{o} to allow nine views above and nine below the pod. At both ends of the pod are calibration targets, one heated to 60^{o}C the other allowed to float at ambient temperature. These allow continuous and very accurate calibration of the radiometer (to between 1-2K, *Jones 1995*). Deimos is accommodated in the underside of the aircraft, with 5 downward views. Deimos measures two polarisations (V & H in the forward (40^{o}) position) in each view. It includes a similar, independent calibration system, providing a 2-3K calibration accuracy.

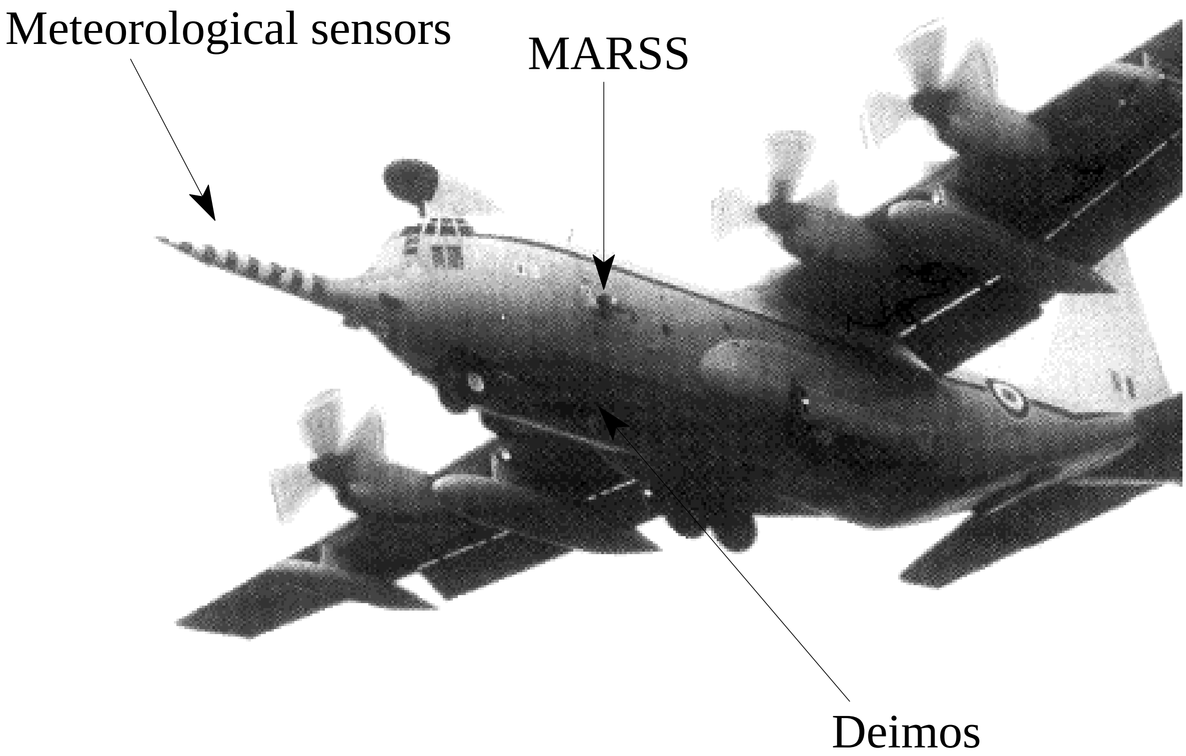

Figure 1: The UK Meteorological Office C-130 showing the location of the microwave radiometers and meteorological sensors used in this study.

3. RESULTS

3.1 Water vapour absorption

The MARSS radiometer is well designed for studying water vapour absorption. Its channels, at 89 and 157 GHz, are in a window region with substantial residual water vapour absorption, sufficient to lift the 157 GHz weighting function off the surface in moist atmospheres. Equally importantly it has the ability to look up at a range of heights from surface to 9km. Looking up has two advantages. Firstly cold space is a fixed, known background, unlike the Earth's surface with its variable temperature and emissivity. Secondly, because cold space emits with an effective blackbody temperature of 2.7K, nearly all the radiation measured by the radiometer originates from gaseous emission. It is therefore sensitive to very small changes in water vapour emission. Finally, because the radiometer is aircraft mounted, it can fly at very high altitude. Therefore water vapour emission can be measured at temperatures from -50^{o}C to +25^{o}C. Existing laboratory measurements of water vapour emission predict different temperature dependence of the absorption coefficient. The aircraft measurements offer an effective source of validation of this term.

Measurements have been made in tropical, middle latitude and arctic atmospheres, in order to cover a global range of conditions. Column water vapour burdens (WVB) from 0.5cm to 4.5cm have been experienced (obtaining clear air conditions at higher WVBs was difficult) with surface temperatures from -5^{o}C to +30^{o}C but high altitude temperatures well below -50^{o}C. Validation results are shown in Figures 2a (89 GHz) and Figure 2b (157 GHz).

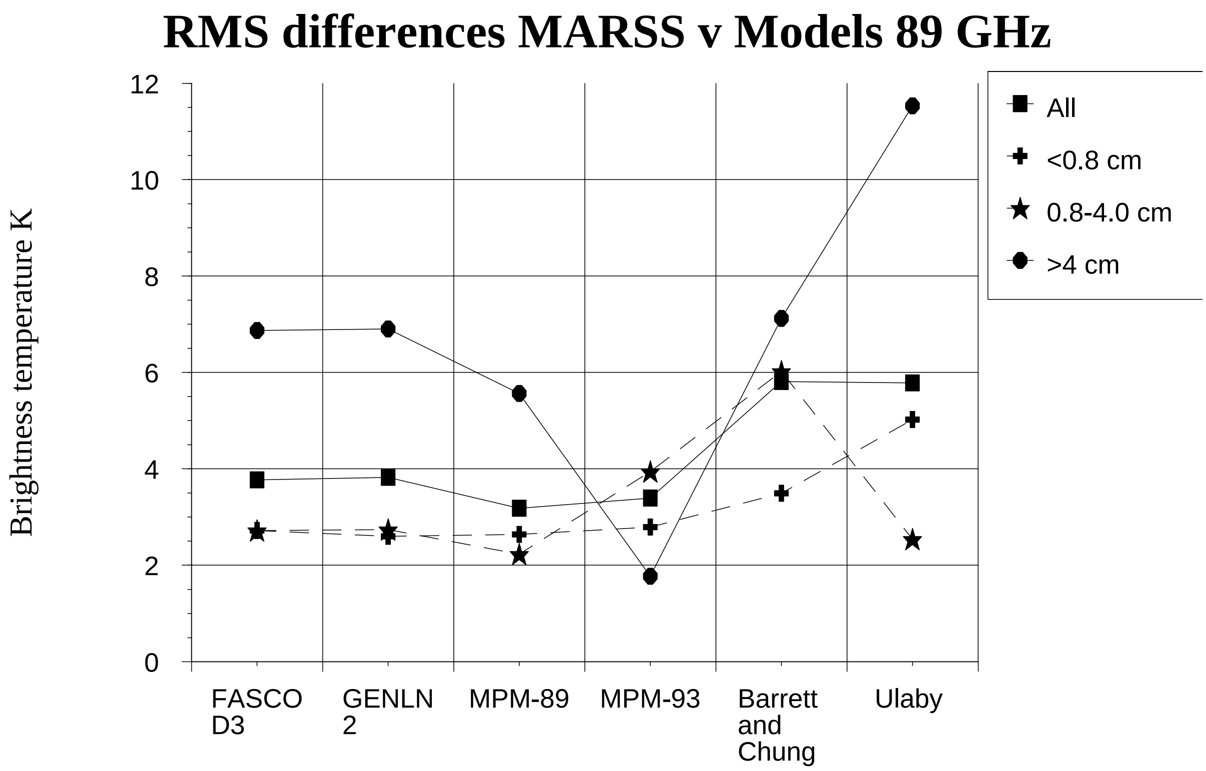

Figure 2a: Validation results of a range of line by line radiative transfer models against MARSS observations at 89 GHz partioned by integrated water vapour burden (WVB). The dashed line with stars represents normal conditions (0.8-4.0cm WVB). The dashed line with small crosses denotes extremely dry and cold atmospheres (<0.8cm WVB). The continuous line with circles denotes extreme tropical atmospheres (<4.0cm) and the continuous line with squares denotes all atmospheres. Liebe MPM-89 gives the closest fit to the observations.

In middle latitude conditions a number of radiative transfer models give good results, most notably *Liebe (1989)*. In extreme conditions most models do less well, but *Liebe 1989* still gives good results as do the general purpose line by line models, GENLN2 (*Edwards 1988*) and FASCOD3 (*Clough 1989*). In warm, moist tropical atmospheres most models underestimate water vapour absorption, sometimes by as much as 10%. It is notable that while the more recent code of *Liebe (1993)* gives excellent results in the tropics, it gives poor agreement with observations at high frequency for middle latitude and arctic profiles. A complete account of these validation results is given by *English et al. 1994* and *English et al. 1995.*

3.2 Oxygen absorption

Oxygen absorption is not negligible in the spectral window between the oxygen complex centred on 60 GHz and the isolated line at 118 GHz. A pure Van Vleck Weisskopf line shape would predict around 15% transmission loss from surface to space at 89 GHz. However the effect of line coupling is to reduce this to around 5%. Nonetheless in dry atmospheres this is comparable with absorption by around 0.5cm of column water vapour, such that in dry atmospheres above 850hPa oxygen absorption

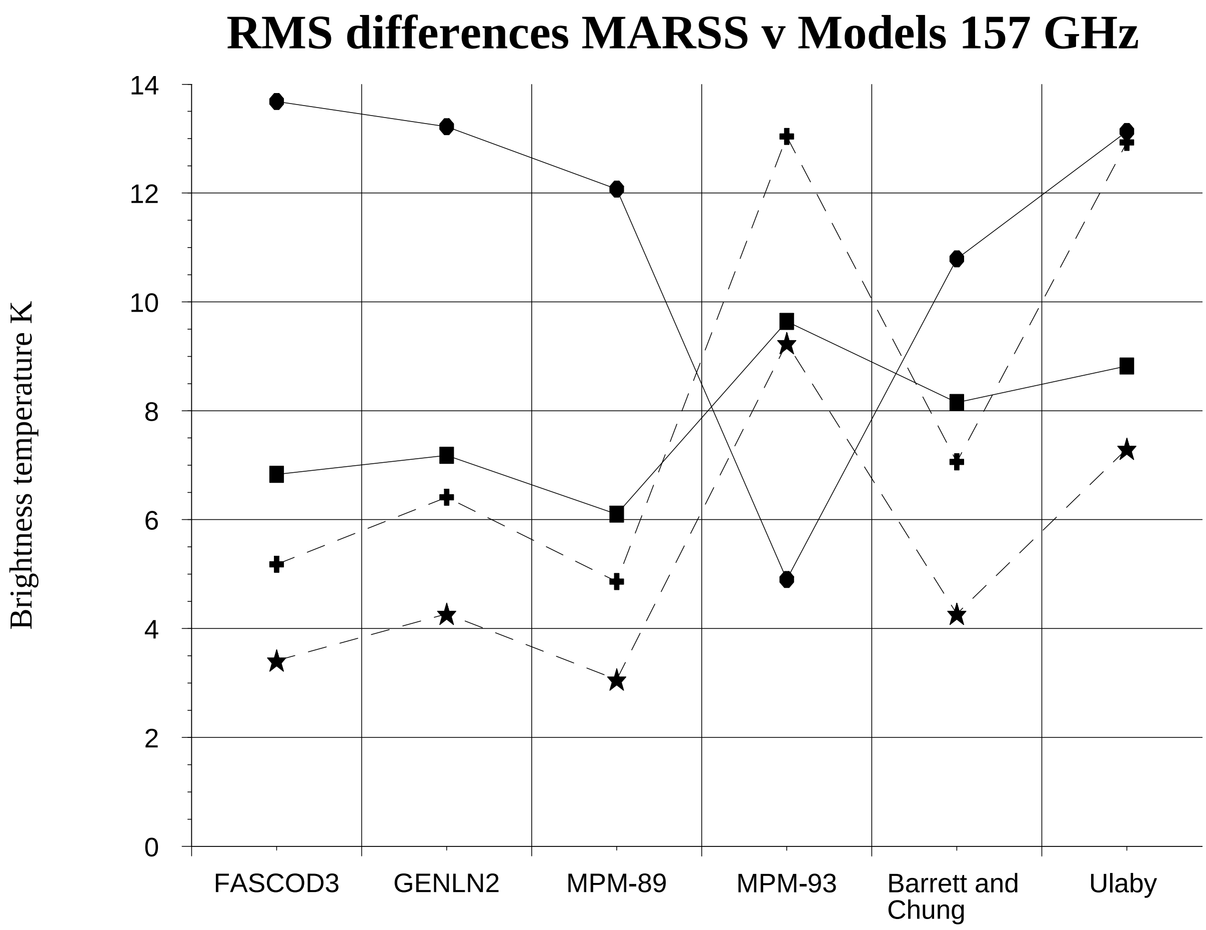

Figure 2b: As Figure 2a but for 157 GHz. MPM-89 again gives closest fit to the observations. Note the extremely poor agreement of the Liebe MPM-93 code with the MARSS observations outside the tropics.

will dominate the downwelling radiance at 89 GHz. The Deimos channel at 50.1 GHz is very sensitive to oxygen absorption (surface to space transmission loss is around 30%).

Data from the 50.1 GHz channel (aircraft and ground based) and the 89 GHz channel in cold, dry atmospheres have been analysed. The results show that the predicted absorption is very sensitive to the assumptions made in the treatment of line coupling, especially its temperature dependence. For example the implementation of line coupling in GENLN2 at the UK Met. Office, based on *Rosenkranz (1975)*, was found to underestimate absorption by between 5% and 20% at 50 GHz, although this implementation has only been used at UKMO. Other implementations (FASCOD3 (*Clough 1989*), *Liebe 1989, 1993*, *Rosenkranz 1975, 1989*) cluster more closely to each other and the observations. However comparisons by *Pardo et al. (1995)* showed biases between model and against observations of 1-4K for SSM/T-1 and MSU colocations. At the UK Met. Office GENLN2 has been coded to use line coupling coefficients from either of the Liebe or Rosenkranz models. At 89 GHz the measured absorption was less than that predicted by most models for dry atmospheres where water vapour absorption is small. It is planned to adapt Deimos to make measurements throughout the 50 GHz band during 1997.

3.3 Cloud liquid water

Validation of liquid water path (LWP) retrievals from spaceborne microwave radiometers (e.g. SSM/I, *Prigent et al. 1997*) is difficult as the satellite cannot resolve the features sampled by *in situ* measurements. Comparing retrievals of liquid water path from the airborne radiometer with *in situ* measurements made by the hot wire probe on the aircraft reduces the number of degrees of freedom in the study.

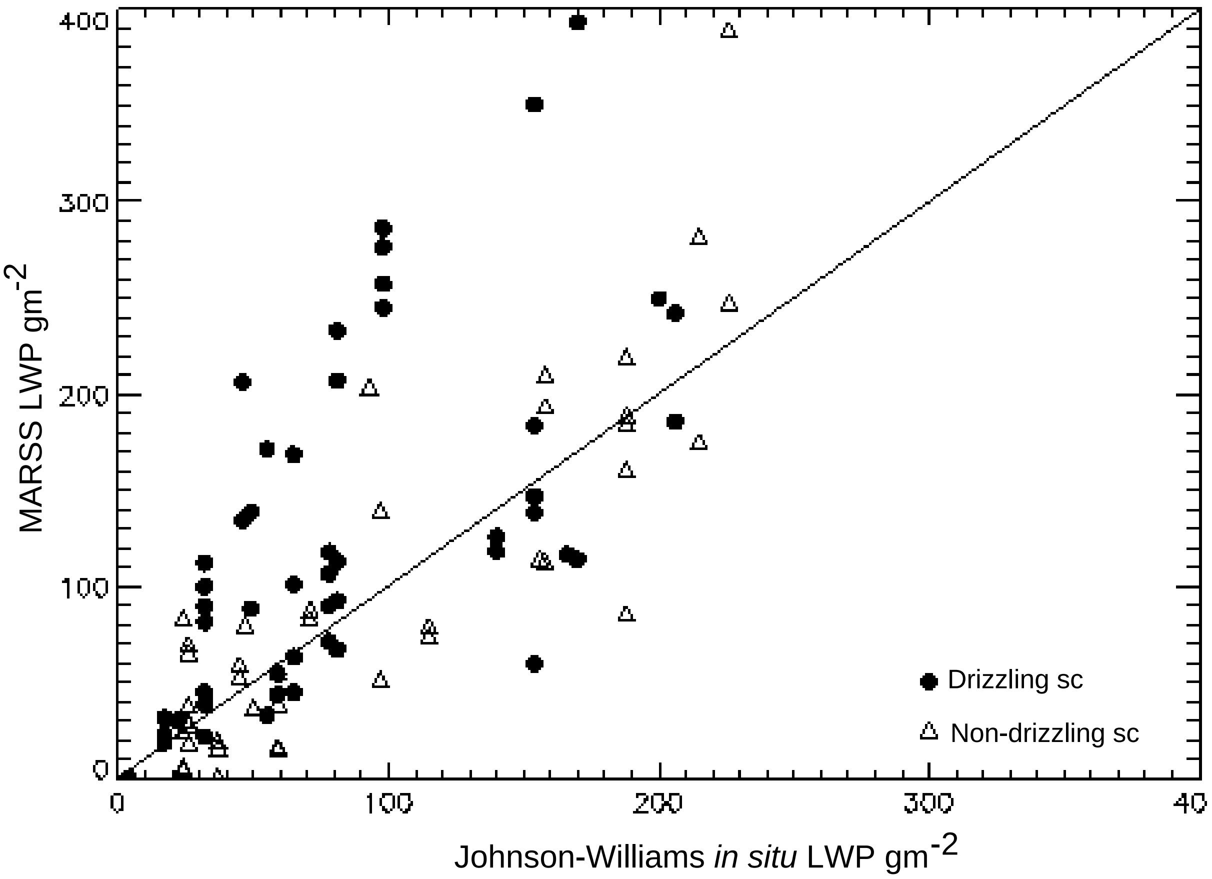

Figure 3: LWP derived from MARSS brightness temperatures against LWP intregrated using Johnson-Williams (JW) measurements. The agreement for non-drizzling sc (as observed by the cloud microphysics equipment and visual observations) is very good, giving an overall rms difference of 43gm^{-2}. For drizzling sc the LWP derived from MARSS tends to exceed that from the JW. This is believed to be largely due to undersampling of the drizzling cu by the aircraft (which often increase LWP by an order of magnitude over a few hundred metres).

Comparison can of course be made in brightness temperature space, but statistics can be dominated by cases of thin cloud where large model errors give small brightness temperature differences. Therefore there is a case for comparing LWP retrievals rather than brightness temperatures.

Comparisons are restricted to ice-free stratocumulus clouds. Cases are mostly from the ASTEX experiment in 1992 and flights around the United Kindgom and Ascension Island. Some of these clouds were drizzling. The dataset was divided into drizzling and non-drizzling cases. For non-drizzling stratocumulus a rms error of only 43gm^{-2} was found with a mean bias of -7gm^{-2} (retrieval -

observation). Information content theory, using the known errors of the instrument and 0.4K for the forward model, predicts an optimal retrieval accuracy of 30-50gm^{-2}, depending on atmospheric conditions. For drizzling stratocumulus the rms was 81gm^{-2} with a mean bias of 40gm^{-2}. This bias and higher rms were thought to arise from a combination of marginally enhanced emission from large drizzle drops, poor collection efficiency of large drops by the cloud water probe and the inhomogeneity of drizzling clouds (where the aircraft tends to undersample the deeper embedded cumulus in the stratocumulus). An alternative explanation is that the one-dimensional cloud model is inappropriate for inhomogeneous clouds. *Liu, Simmer and Ruprecht (1996*) showed that three dimensional model predictions depart significantly from one dimensional models both in bias and rms.

Figure 3 shows the validation of LWPs derived from MARSS against the Johnson-Williams probe. The large retrieval-observation bias for drizzling cases from ASTEX are clearly visible, as is the exceptionally good agreement for most of the non-drizzling UK and FATE (Ascension Island) flights. Figure 3 is based on comparing retrievals averaged along a ten to twenty minute run with the aircraft profile through the cloud on that run. A complete description of the results is given by *English (1995).*

3.4 Ocean surface emissivity

At microwave wavelengths the emissivity of natural surfaces varies from 0.2 to 1.0, and from 0.2 to 0.9 for the sea surface alone. This is equivalent to over 200K for the window channels, but sounding channels which see the surface are also very sensitive to emissivity. For many surfaces the relationship between known physical variables (e.g windspeed) and the emissivity is known. Of these the most important, and easiest to model, is the ocean surface.

If a water surface is flat then its emissivity can be calculated easily from the Fresnel equations based on laboratory measurements of the dielectric properties of saline water. However as soon as the surface becomes rough the calculation becomes more difficult. For large scale ocean swell we can assume the surface scattering is in the geometric limit, and sum the contributions from all ocean facets. At high frequencies (above 30 GHz) we assume all ocean scales are long. For this we need a model of ocean slope variance as a function of windspeed. Several are available but the predicted variance at a given windspeed can vary by a factor of two. Also above 10 GHz measurements of the dielectric properties of saline water are sparse. The numerous combinations of different roughness models and dielectric treatments, not to mention foam which becomes important above 10ms^{-1}, make it impossible to give a full account here. Full details are given in the paper by *Guillou et al. (1996)*, where a trend of difference against SST was found (Figure 4) when using the single Debye model of *Klein and Swift (1977)*. The optimum configuration of the geometric optics model, following *Wilheit (1977)*, of the ocean surface gave rms errors of 2K at 89 and 157 GHz. The large trend with SST was significantly reduced, especially at 157 GHz (Figure 4b), when a double Debye formula (*Liebe 1991*) was introduced, suggesting the presence of a second relaxation process at high frequency (*Guillou 1997*).

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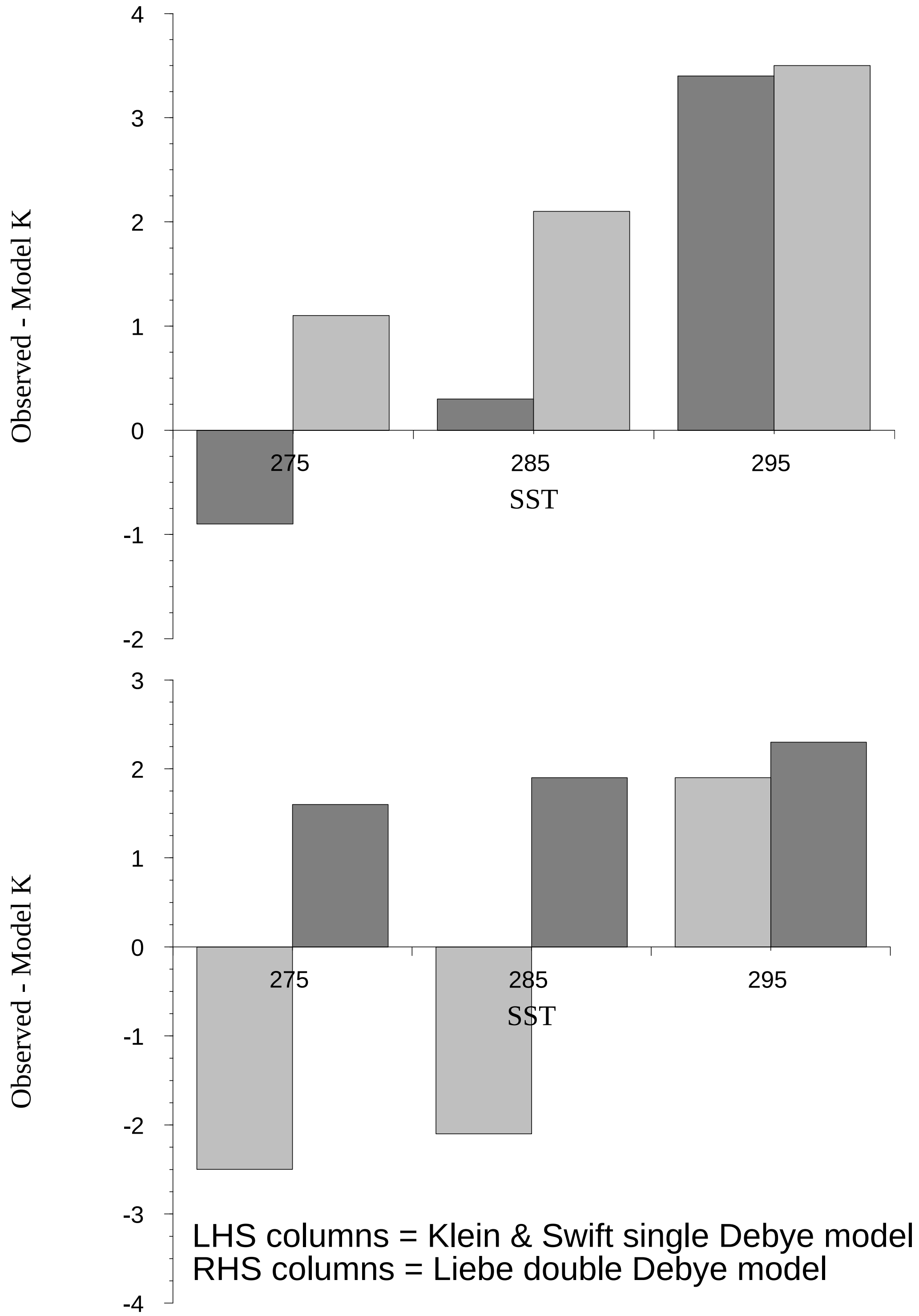

Figure 4: MARSS observations against geometric optics model predictions at 89 GHz (above) and 157 GHz (below). Note the trend against SST for the single Debye model is reduced for the double Deybe model.

At low frequency, below 30 GHz, the model complexity rises as small scale ripples do not scatter in the geometric limit, and we can no longer apply the Fresnel equations. This is treated by dividing ocean roughness into two scales, one geometric, the other modifying the Fresnel equations. Below 30 GHz calculated two-scale model brightness temperatures exceed those from the geometric optics model by 4K, even at low windspeed.

3.5 Ice and mixed phased cloud and precipitation

In addition to studies to validate the radiative transfer model for operational sounding, initial studies have also been undertaken of radiative transfer models for precipitation and ice cloud (*Jones 1995*). Data from the three dimensional radar at Chilbolton, UK, have been used to derive the ice water content of stratiform frontal clouds. A model of the ice-water ratio is then produced using the aircraft *in situ* measurements, in order to derive liquid water content from the radar ice water content. These are then used as inputs to the radiative transfer model for comparison with the observations. Sensitivity to changes in the treatment of ice aggregate and graupel in the cloud have been made. The comparison is very sensitive to the density and dielectric properties of the ice aggregates. For the stratiform cases sampled the ice cloud needs to be treated as a Maxwell-Garnett low density mixture of ice and air.

4. CONCLUSIONS

A wide-ranging and accurately calibrated dataset of microwave window channel observations at a range of heights has been assembled. This has been used to study the accuracy of the key components of a radiative transfer model able to predict observations in the AMSU window channels. In clear air the models predict the observations very accurately except in very dry and very moist atmospheres. The microwave transmission algorithm of *Liebe (1989)* gives the best overall agreement with the observations. The measurements of sea surface emissivity suggested an excellent agreement with the *Cox and Munk (1954)* sea slope variance model, using a geometric optics approach. It is important to note that at these high frequencies (above 89 GHz) small scale ripples have only a very small effect and most reflections are in the geometric limit. For a standard single Debye model a trend with SST was observed, which was reducedd when using a double Debye formula. Validation of cloudy observations through comparison of observed and retrieved liquid water paths has given very encouraging results, given the considerable difficulty involved in this task. Work continues to measure the emissivity of a wide range of natural surfaces, in order to derive a generally applicable surface emissivity model. Research into radiative transfer in stratiform precipitating systems is also being undertaken, with the major effort focusing on the ice and mixed phase layers.

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