Observations of water vapour absorption using airborne microwave radiometers at 89 and 157 GHz.

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***Abstract*—In 1996 a new five channel humidity sounder, the Advanced Microwave Sounding Unit-B, will be be launched on the NOAA-K polar orbiting satellite. In support of the data interpretation from this instrument, including the retrieval of water vapour profile information, an airborne millimetre wave radiometer has been developed to validate the gaseous absorption model. In particular the so called water vapour continuum absorption has been measured and compared with predictions from models based on laboratory data. The two channel scanning microwave radiometer (MARSS) with channels at 89 and 157 GHz has been operating on the C-130 aircraft of the UK Meteorological Office for five years. The MARSS results have been compared with algorithms specific to microwave and millimetre wavelengths [1]–[4] based on independent laboratory measurements and also general purpose line by line models (GENLN2 [5] and FASCOD3 [6]). At 89 and 157 GHz the results using [1],[5]–[6] are broadly similar and all show good agreement except for very dry and very moist atmospheres. Averaging over all the aircraft data these three models give biases of less than 1K for both channels and RMS errors of under 3.5K at 89 GHz and 7.0K at 157 GHz. Best agreement was found in middle latitudes with a model overestimate for arctic atmospheres and a model underestimate for tropical atmospheres. The Liebe MPM-89 model was generally the best, particularly for the middle latitude dataset.**

I. Introduction

The Microwave Airborne Radiometer Scanning System (MARSS) is described in [7]–[8]. This airborne radiometer has been collecting data since 1990 comparing upward and downward looking views at 89 and 157 GHz with model predictions using the United Kingdom Meteorological Office (UKMO) C-130's meteorological sensors. The C-130 can fly straight and level runs at any altitude from 30m to 9km, over the sea, and also profile from 14m to 9km to measure atmospheric water vapour and temperature profiles. The radiative transfer throughout the troposphere is measured in this way. A subset of clear air data has been assembled where water vapour is believed to be homogeneous on the scale of the aircraft operations (60km runs and usually six hour flights). This dataset comprises flights from FATE (First ATSR Tropical Experiment) in tropical air near the equator, MASTEX (Mediterranean Aircraft and Ship Transmission Experiment), near Crete in middle latitude conditions and SAAMEX (Surface and Aircraft Microwave Experiment) in Finland, giving winter arctic conditions. The MARSS clear air dataset therefore covers a wide range of global conditions. In this paper we present comparisons of this dataset (33 individual runs) with a range of models which are derived from varying assumptions and laboratory measurements.

II. Transmission algorithms and models

Six separate and independent models [1]–[6] have been compared with the MARSS data. Hereafter [1] is referred to as MPM–89, [2] as MPM–93, [3] as the Ulaby model, [4] as the Barrett model, [5] as GENLN2 (as modified for the microwave by Peter Rayer, [personal communication]) and [6] as FASCOD3. Results from three of these, MPM–89, Ulaby and Barrett were presented in [8] with one profile from GENLN2. In this paper this work is extended to compare the same dataset with FASCOD3, MPM–93 and with a full run of GENLN2. The gaseous transmission at 157 GHz is solely due to water vapour absorption and is therefore determined by the parameterisation of the so called anomalous water vapour continuum. At 89 GHz there is a significant contribution from the oxygen model. MPM-89, Ulaby, Barrett and GENLN2 all use [9]; MPM–93 uses [10]; FASCOD3 uses [11]. For water vapour absorption both the choice of continuum and line dataset varies widely. The empirical continuum are as follows: Ulaby uses [12]; Barrett uses [13]; GENLN2 and FASCOD3 use [14]; MPM–89 uses its own dataset; MPM–93 uses the MPM–89 dataset with additional measurements. MPM–89, MPM–93, Ulaby and Barrett just predict transmission and the radiative transfer is calculated using a simple model described in [8]. Both GENLN2 and FASCOD3 perform the whole radiative transfer calculation.

III. Results

Fig. 1 shows brightness temperature profiles for three flights, one arctic case (H990); one middle latitude case (A012); and one tropical case (A143) for the 89 GHz channel. In each case observations for the nominal MARSS zenith view (actually at 12° to the local vertical - see

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[8] for a description of the view geometry) are plotted against pressure (as a vertical coordinate). The observations, denoted by circles, are plotted with error bars (see [7]) which are typically 2–3K. Results from MPM–89, MPM–93, GENLN2 and FASCOD3 are plotted using different linestyles. As the FASCOD3 and GENLN2 lines are indistinguishable in Fig. 1 only one line is plotted, but note there is a difference at 157 GHz (see Tables 1 and 2). The Ulaby and Barrett results are not plotted as these were shown to give inferior agreement in [8] and Tables 1 and 2. All the models overestimated for the arctic flight, H990, which had a water column of only about 8mm. The worst agreement for the 89 GHz channel occurs for altitudes above 900mb where oxygen absorption dominates. MPM–93 captures the shape of the curve better than the other models. However at 157 GHz (not shown) MPM–93 overestimates by over 10K and good agreement is given by MPM–89, GENLN2 and FASCOD3. For A012, the middle latitude case, MPM–89 gives excellent agreement with an RMS well within the error bars. The other models give agreement mostly within the error bars, except MPM–93 which again overestimates, especially at 157 GHz. The tropical case, A143, with a water vapour burden over 4cm, gives a contrasting result. All models except MPM–93 underestimate with respect to the observation.

The results from all the flights, including all altitudes from 30kPa to 100kPa, are summarised in Table 1 (RMS) and Table 2 (bias). The bias and RMS of all the models is given for four categories: all data, arctic only, middle latitude only and tropical only. These correspond to water vapour burdens of 0.8cm or less for arctic, 1.2 to 2.4cm for middle latitude and over 4cm for tropical. Overall the two general line by line models, GENLN2 and FASCOD3 give negligible bias at 89 GHz ($\leq$ 0.15K) and small bias at 157 GHz ($\leq$ 1.0K). The RMS is however rather high at nearly 4K at 89 GHz and around 7K at 157 GHz. The 'best fit' from [8] attempted to fit MPM–89 more closely to the form of the MARSS results by tuning the 'self' term in the empirical continuum algorithm whilst retaining the advantages of the MPM model. It does not lower the RMS from the value for MPM-89 but does reduce some of the worst errors. This 'best fit' and MPM–89 give the lowest overall RMS. The RMS for the Barrett model is much higher (5.80K and 8.15K) and Ulaby also gives a significantly higher RMS (5.78K and 8.82K).

The statistics for each zonal category follow the examples given in Fig. 1. For arctic atmospheres all models have a significant bias, which is lower at 89 GHz than at 157 GHz. Again MPM–89, FASCOD3 and GENLN2 give the lowest RMS and bias for both channels. Most models perform well for the middle latitude dataset. Only Barrett gives a bias over 1.3K at 89 GHz and MPM–89 gives bias of under 0.3K for both channels and RMS of 2.2K and 3.1K at 89 and 157 GHz respectively. For tropical atmospheres all models except MPM–93 have a negative bias. Here even MPM–89, GENLN2 and FASCOD3 all have large bias (about 10K in each) at 157 GHz. In this case the 'best fit' from [8] and MPM–93 give the best agreement.

IV . Conclusions

The model of MPM–89 gives the best overall agreement with this wide ranging observational dataset at 89 and 157 GHz. However this model does have a large negative bias in tropical atmospheres and a smaller positive bias in arctic atmospheres. The agreement using two independent general purpose line by line models (GENLN2 and FASCOD3) is only marginally inferior to MPM–89, indeed overall these models give a lower bias. The modification of MPM–89 to fit the MARSS results reduce the worse differences but makes little overall impact and worsens the agreement in middle latitude regions and also arctic regions. The updated MPM–93 did not give closer agreement. In particular the agreement at 157 GHz was much worse than using MPM–89 except for the tropical cases. MPM–93 did however eliminate the error for tropical atmospheres. However based on these results the use of MPM–93 can not be recommended at AMSU–B frequencies. It must also be noted that whilst these observations cover a range of extreme profiles, globally most profiles will be close to the middle latitude case. The relative success of MPM–93 and Barrett for the tropical case represents only a small sub–section of global profiles. This analysis implies that at millimetre wavelengths MPM–89 remains the best available transmission algorithm.

V. Tables & Figures

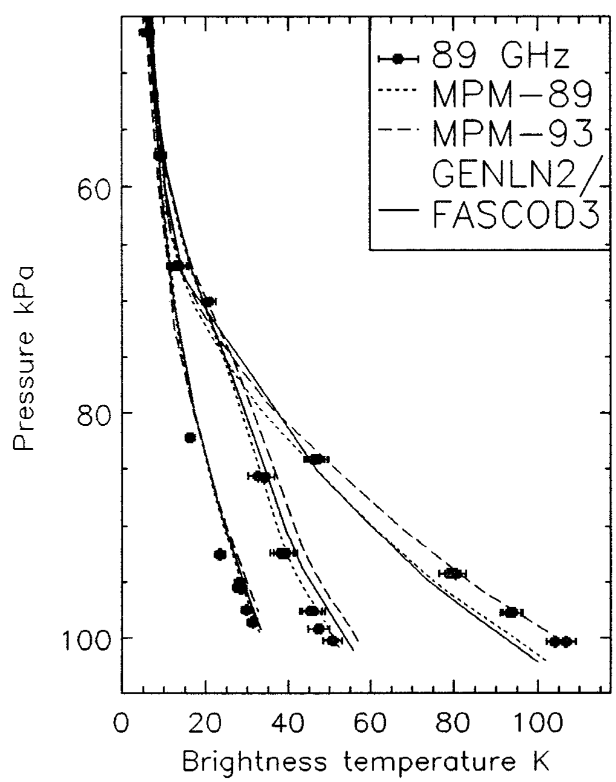

Fig. 1 Brightness temperature profiles for three flights A012, A143 and H990 for the 89 GHz channel of MARSS.

Table 1. Model RMS for four water vapour burden categories.

Model	All data	≤0.8 cm	1.2–2.4 cm	≥4.0 cm
	89 GHz RMS K			
FASCOD3	3.77	2.72	2.58	6.87
GENLN2	3.82	2.60	2.74	6.90
MPM-89	3.18	2.64	2.23	5.56
MPM-93	3.39	2.79	3.94	1.77
Barrett	5.81	3.49	6.02	7.12
Ulaby	5.78	5.02	2.54	11.53
'Best Fit'	3.16	4.64	2.44	3.05
	157 GHz RMS K			
FASCOD3	6.83	5.18	3.41	13.68
GENLN2	7.18	6.41	4.27	13.22
MPM-89	6.10	4.86	3.06	12.07
MPM-93	9.64	13.04	9.24	4.90
Barrett	8.15	7.06	7.30	10.79
Ulaby	8.82	12.93	4.27	13.13
'Best Fit'	6.11	9.25	3.48	7.81

Table 2. Model bias for four water vapour burden categories.

Model	All data	≤0.8 cm	1.2–2.4 cm	≥4.0 cm
	89 GHz bias K			
FASCOD3	-0.00	2.48	0.72	-5.29
GENLN2	-0.07	2.32	0.68	-5.39
MPM-89	-0.13	2.37	0.24	-4.26
MPM-93	1.46	2.48	1.21	1.04
Barrett	1.96	3.18	3.44	-4.42
Ulaby	0.12	4.49	0.60	-6.57
'Best Fit'	0.81	4.19	0.50	-2.12
	157 GHz bias K			
FASCOD3	-0.06	3.76	1.77	-10.63
GENLN2	0.84	5.03	2.67	-10.15
MPM-89	-0.92	2.82	0.30	-9.35
MPM-93	7.10	11.6	6.39	4.26
Barrett	2.70	5.73	4.14	-4.20
Ulaby	3.20	10.80	2.65	-3.84
'Best Fit'	1.36	7.91	1.17	-5.69

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