FORWARD MODELLING FOR LIQUID WATER CLOUD AND LAND SURFACE EMISSIVITY

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Summary: A parameterisation for emissivity over land based on emissivities derived from SSM/I is being developed and some initial analysis is presented. A model for cloud liquid water emission has been developed and incorporated within RTTOV. This has been used to compare cloud liquid water diagnosed from a numerical weather prediction model with the effects of cloud liquid water on AMSU observations. The results show that there is still a need for quality control. Issues relating to ice scattering detection for AMSU-B are also briefly discussed.

1. INTRODUCTION

Radiance observations measured by ATOVS, and AMSU in particular, have been shown to deliver a significant improvement in global NWP by providing information on deep layer averages of temperature and humidity. This has been achieved despite the commonly adopted approach of rejecting, through rigorous quality control, any observations significantly affected by cloud or by errors in the specification of surface emissivity. This means that little more than half the microwave observations can be used for the channels which sense the lower troposphere due to effects of liquid water emission, and the data remains largely unused over land except in the stratosphere. There is nothing wrong with the unused observations; they are merely affected by radiative processes that are difficult to model. The next challenge is to improve the range of capability of the forward model and to reduce the number of observations (and hence amount of useful information) needlessly wasted. This is not trivial. Despite over twenty years experience of using infra-red sounder data the emphasis is still on improving the detection of, rather than modelling and retrieval of, cloud (English *et al.* 1999a).

2. RADIATIVE TRANSFER MODEL IMPROVEMENTS

2.1 Land surface microwave emissivity model

Many physical processes that determine land surface microwave emissivity are complex. However when viewed from a satellite perspective horizontal inhomogeneity tends to remove many features that would be observed on a fine scale (e.g. diffraction effects) and for many surfaces the emissivity is rather constant in time. Prigent *et al.* (1997) showed that emissivities derived from SSM/I on a fixed mercator grid have a standard deviation of less than 0.02 during the period of a month and, with the exception of regions which experience winter snowfall, have very little annual cycle. Coefficients have been produced for a simple multi-surface emissivity model based closely on work by Wang and Choudhury (1981) and Bauer and Grody (1995) using a least squares fit to the monthly emissivity maps of Prigent *et al.* (1997). This model is defined in terms of three Deybe parameters (P_0, P_∞, ν_t), and two roughness terms, h and Q. Note that Q can be parameterised in terms of large scale roughness length and $h=(4\pi\nu\sigma/c)^2$ where σ is the small scale roughness length. Thus we can compute the emissivities for vertical and horizontal polarisation (E^V and E^H) as follows,

$$P = P_0 + \frac{P_\infty - P_0}{1 + i\nu/\nu_t}$$

$$R_f^V = \left| \frac{-P\cos(\theta) + \sqrt{P\sin^2\theta}}{P\cos(\theta) + \sqrt{P\sin^2\theta}} \right|^2 \text{ and } R_f^H = \left| \frac{-\cos(\theta) + \sqrt{P\sin^2\theta}}{\cos(\theta) + \sqrt{P\sin^2\theta}} \right|^2$$

$$E^H = 1.0 - QR_f^V \exp(h\cos^2\theta) - (1-Q)R_f^V \exp(h\cos^2\theta)$$

$$E^V = 1.0 - (1-Q)R_f^V \exp(h\cos^2\theta) - QR_f^V \exp(h\cos^2\theta).$$

The permittivity, P, has been computed using Debye theory and the specular reflectivities $R^V{}_f$ and $R^H{}_f$ for vertical and horizontal emissivity are then given by the Fresnel equations. Emissivity is then computed following the reduction of the reflectivities by a coherent scattering term for Bragg scattering, $\exp(h^2\cos^2\theta)$, and a simple term, Q, allowing linear mixing of the two orthogonal polarisations. English and Hewison (1998) present the model in more detail. The values of the five model parameters which give the best fit to the emissivity atlases of Prigent are compared for January 1992 and July 1992 in Figure 1. Large-scale roughness and static permittivity are almost unchanged from summer to winter. Small-scale roughness and permittivity at infinite frequency are more variable. The implication is that to define the complete spectral emissivity curves for most surfaces requires the retrieval of two or three pieces of information from the six window channels (and four sounding channels which are partially sensitive to the surface) of AMSU. This gives reason for optimism that a background estimate of emissivity can be modelled from past data to within 1-2% in snow-free areas. English (1999) showed that if such accuracy can be achieved then useful temperature information is available over land, even in the presence of cloud.

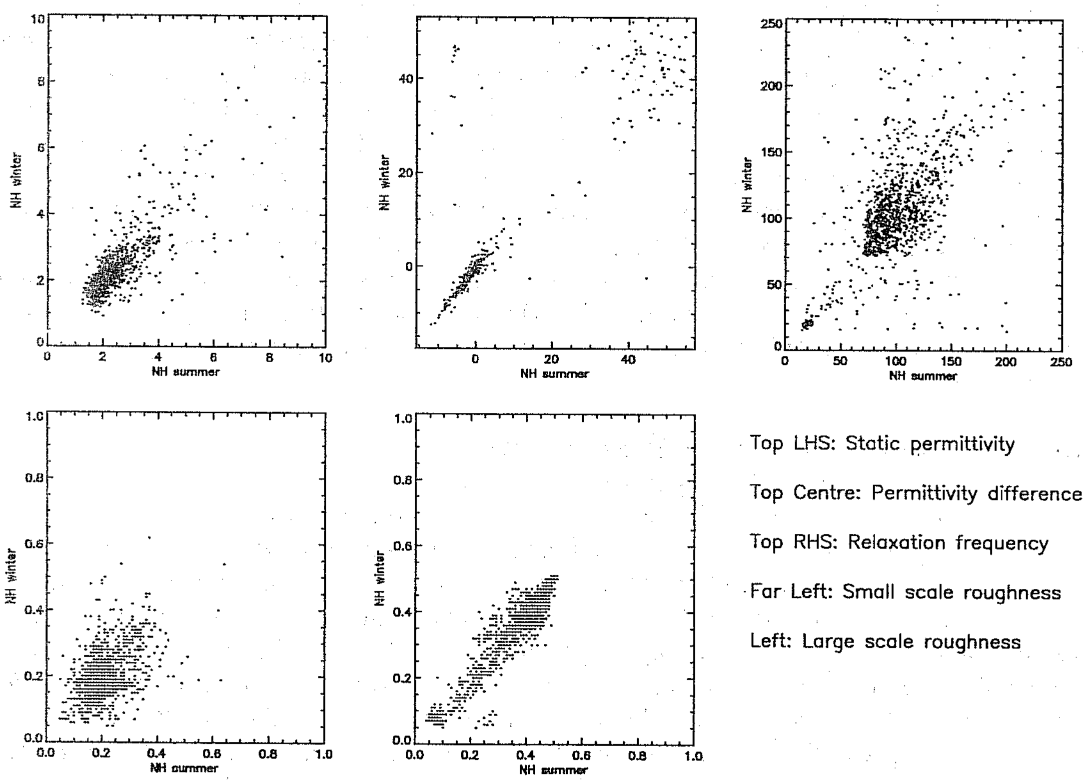

Fig. 1: Comparison of values of the five coefficients for the "land FASTEM" model for global data for January and June derived from a least squares fit to the emissivity atlas of Prigent *et al.* (1997).

2.2 Cloud liquid water absorption model

At microwave frequencies scattering by liquid water is negligible (except for larger precipitation sized drops; 0.1mm is a useful threshold) but absorption (and re-emission) is not. The window channels of AMSU will see liquid water effects well in excess of 10 K, rising to over 20 K for the 31 GHz channel. If precipitation is occurring the impact could be even larger. Ice cloud has a single scattering albedo of 0.98 at 31 GHz (i.e. absorption is negligible) but ice cloud scattering becomes increasingly important at shorter wavelengths. Ice cloud scattering is a very significant process for AMSU-B. The ATOVS and AVHRR Processing Package (AAPP) has tests, described by English *et al.* (1997), which attempt to identify which observations are significantly affected by cloud liquid water emission and which see significant ice scattering. Indeed the problem of detecting liquid water emission and/or ice scattering at 50 GHz over the sea using channels at 23.8, 31, 50.3 and 89 GHz is a trivial problem and can be regarded as solved (English *et al.* 1999b). However radiative transfer modelling of cloud liquid water emission is also not difficult in the absence of significant scattering by ice cloud or raindrops (ignoring for the moment the problem of specifying the cloud profile). Simple cloud emission models have validated well against *in situ* measurements in intensive field campaigns for warm clouds i.e. no supercooled water (English 1995). The major difficulty is the permittivity of supercooled water, which is not well known. A model has been devised which in the low temperature limit fits loosely the values reported by Liebe *et al.* (1991) and in the high temperature limit fits very precisely the values reported by Lamkaouchi *et al.* (1997). This model is compared with other options (Ray 1971, Kummerow and Weinman 1988, Grody 1993, Obligis [pers. comm.]) in Figure 2. There is a considerable spread in the predicted absorption coefficient for supercooled water whereas for warm water the models show good consistency, especially at low frequency. In all these calculations Rayleigh absorption is assumed (i.e. the model is not applicable for drops with radii greater than 0.1mm) and ice scattering is neglected. The new merged model has been added to the fast radiative transfer model (RTTOV-5) described by Saunders *et al.*, (1999).

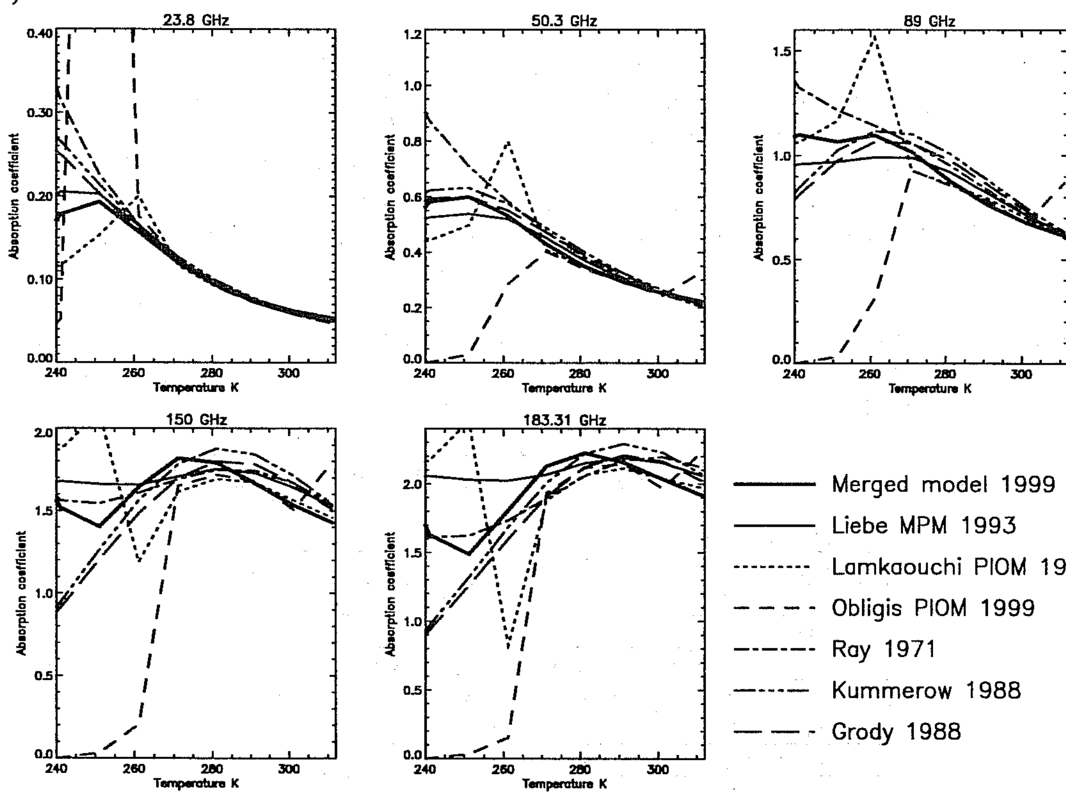

Fig. 2 Comparison of different model functions for calculation of the absorption coefficient for liquid water at 23.8, 50.3, 89, 150 and 183.31 GHz as a function of absorber temperature.

3. COMPARISON WITH AMSU OBSERVATIONS

3.1 Cloud model

The diagnosed liquid water profiles have been used along side temperature and humidity profiles to calculate brightness temperatures for comparison with AMSU brightness temperatures for two separate six hour assimilation periods in mid-October 1999. Unlike clear air brightness temperatures, which usually show broadly the same features as the NWP model, the cloudy radiances can at times show features completely absent, or in different positions, compared to the model background. Therefore it is not immediately clear whether modelling the cloudy radiances using the background liquid water fields will give a better or worse fit to the observations compared to radiances calculated ignoring model cloud. In practise it is found that the fit of the calculated brightness temperatures to the observations is degraded in terms of standard deviation. An example of impact on observation minus background differences for 18 October 1999 is shown in Table 1. The observations in Table 1 have been categorised according to the value of the microwave cloud cost described by English et al. (1997). This cost is defined as $J=(y-y^m)^T C^{-1}(y-y^m)$ where y is the vector of observations, y^m is the mean vector of calculated observations for clear air and C is the expected covariance of the observations in the absence of cloud. This method assumes $y-y^m$ has zero mean in clear air and has a normal distribution. AMSU channels 1, 2 and 3 are used to calculate J. For clear observations the model often has significant cloud liquid water and therefore the fit is degraded both in terms of standard deviation and root mean square (RMS). For cloudy observations the root mean square error is significantly reduced if cloud is modelled because the bias is reduced. However the random component of the difference rises. Furthermore the improvement in bias for cloudy FOVs is small (around 25% of total bias); the mean bias of 8.9 K for all cloudy FOVs is reduced to just 6.7 K for AMSU channel 2 at 31.4 GHz. This is because a significant number of cloudy FOVs have no cloud in the model profile. Considering all observations globally the bias is reduced by 1.6 K, from 3.9 to 2.3 K. Ignoring other sources of bias this suggests that the global mean liquid water amount may be only half that observed by AMSU. The increased random differences can be attributed to mislocation of liquid water in the horizontal but does not answer whether the vertical distribution of liquid water from the model is realistic. The impact of cloud on the lower AMSU sounding channels is significant; the global bias for AMSU channel 4 is reduced from 0.6 K to 0.4 K when cloud is modelled whereas the bias for clear FOVs only is changed from 0.00 K to –0.27 K.

For areas identified as clear these results suggest it is prudent to use clear air radiative transfer (i.e. ignore model liquid water) although care will then be needed in interpretation of global mean bias. The NWP model may be providing a reasonable representation of mean liquid water over large areas, to within a factor of two, but it is not currently adequate in the detail. Phalippou (1995) successfully used model liquid water for modelling Special Sensor Microwave Imager (SSM/I) observations but only to specify the location of cloud; no weight was given to the actual amount of liquid water predicted by the model. It is possible that the model generates cloud at the correct height but with an incorrect horizontal distribution of liquid water. It is very difficult to test this aspect with this type of observation because of the insensitivity to cloud height in the window channels. Therefore the method of Phalippou is adequate for an imaging microwave radiometer like the SSM/I but is not yet tested for a sounding instrument like AMSU. Cloud height is important for the sounding channels of AMSU.

Liquid water emission model not used			
	RMS	St. Dev.	Bias
Clear J < 5.5	5.1	4.5	2.4
Cloud J > 5.5	9.7	5.3	8.9
Cloud J > 10	11.2	5.7	9.7
Cloud J > 20	16.1	6.8	14.5
Liquid water emission model used			
	RMS	St. Dev.	Bias
Clear J < 5.5	5.6	5.6	0.3
Cloud J > 5.5	8.9	5.8	6.7
Cloud J > 10	10.3	6.2	8.2
Cloud J > 20	15.1	7.4	13.1

Table 1: Root mean square, standard deviation and bias of fit of observed AMSU channel 2 (31 GHz) brightness temperatures to the model background with and without the use of model liquid water path in the forward model calculation for four different cloud categories based on the cloud cost index, J. The background fields are for 18 October 1999.

3.2 Emissivity atlas

The emissivity atlas has only been compared qualitatively with AMSU. Many features are clearly common. High emissivity over forest, lower emissivity over regions with low vegetation cover and very low emissivity over desert. A more quantitative comparison is planned in the near future.

4. EFFECT OF CIRRUS ON AMSU-B

Ice scattering efficiency increases rapidly at frequencies above 150 GHz. The efficiency with which an ice crystal scatters incoming radiation is therefore larger at 183.31 GHz than 150 GHz. This poses severe problems for quality control, as the impact can be significant but comparable with other sources of difference between the observations and the calculated brightness temperatures (e.g. errors in the NWP 6 hour forecast of humidity) for the microwave humidity sounders utilising the 183.31 GHz water vapour line (e.g. AMSU-B or SSM/T2). For example, based on the values published by Evans *et al.* (1998) for cirrus with ice water path of 100 g m^{-2} and mean diameter of 200 μm, the observed brightness temperatures will be reduced by less than 1 K at 150 GHz (which may be undetectable) but by over 3 K at 220 GHz. Evans *et al.* did not publish a figure at 183.31 GHz. Thin cirrus is not a problem as ice clouds with mean crystal diameter of 50 μm have a sensitivity to ice water path of less than 0.003 K (g m^{-2})$^{-1}$ even at 220 GHz, although sea surface temperature may be lowered under such clouds (Wang *et al* 1998). Equally there will be no problem detecting deep ice layers associated with severe storms as these will lower the observed brightness temperatures dramatically, even at 150 GHz. The quality control problems will occur for situations with moderately thick layers (a few kilometres) containing large crystals (a few hundred μm). For these situations ice cloud scattering may be small but significant at 183.31 GHz but be difficult to detect at 150 GHz. Even if the brightness temperatures are lowered by a similar amount at 183.31 GHz and at 150 GHz it may still be difficult to use the window channel to provide quality control information.

Wang *et al.* (1998) published measurements at 89, 150, 183.31±3, 183.31±7, 220 and 325 GHz in the presence of cirrus. The effect of the cirrus cloud, which was reported to be 8-11km deep, was to lower the measured brightness temperatures by a comparable amount at 150 and 183.31±3 GHz but at 220 GHz the brightness temperature depression was three times that measured at 150 GHz, as would be expected from the calculations by Evans *et al.* (1998). The depression of the measured brightness temperatures at 183.31±7 GHz was smaller than at 220 GHz but larger than at 183.31±3 GHz. The maximum brightness temperature depressions due to cirrus in the data of Wang *et al.* were 35 K at 220 GHz and 13 K at 150 GHz. Racette and Wang (1998) found consistency between the observations taken by Wang *et al.* (1998) and the model of Gasiewski (1992) and qualitatively the comparison with the published values of Evans *et al.* also look consistent. These studies suggest that without a window channel observing at 220 GHz or above detection of cirrus contamination at 183.31±7 will be difficult and is an unsolved problem for an instrument like AMSU-B. More study of this effect is warranted such that an effective method of detection can be devised.

5. CONCLUSIONS

A new model for calculating emission and absorption by cloud liquid water has been devised and incorporated in RTTOV. Initial use of NWP model liquid water profiles for improved modelling of AMSU window and lower tropospheric channels has not been encouraging but this almost certainly reflects the inaccuracy of the background cloud profiles. At present continued rejection of all observations influenced by liquid water emission, which can be considered to be a solved problem for AMSU-A over sea, continues to be the safest option. Detection is much easier than forward modelling or retrieval. However work needs to continue to determine how to make better use of observations in cloudy areas if, as seems probable, the background cloud profiles from NWP models are not currently good enough for this application. Further study is also needed on the influence of scattering by ice clouds for the higher frequency channels of AMSU.

A semi-empirical model has been fitted to the emissivity atlases derived from SSM/I observations by Prigent *et al.* (1997). These look a promising way of utilising some basic global information on land surface emissivity. However this approach will not allow for the effect of variable snow emissivity and short-term response of emissivity to rainfall, and it leaves the provision of a sea ice emissivity unsolved.

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