THE AAPP MODULE FOR IDENTIFYING PRECIPITATION, ICE CLOUD, LIQUID WATER AND SURFACE TYPE ON THE AMSU-A GRID.

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1. INTRODUCTION
The ATOVS and AVHRR Processing Package (AAPP) is a EUMETSAT-led initiative to produce portable software for the processing of ATOVS and AVHRR data from locally received satellite data (Klaes 1997). The package adopts the structure of the International TOVS Processing Package (ITPP) and is coded to UK Met. Office standard in Fortran-77. The package contains modules for the ingest of raw HRPT datastreams, the calibration and navigation of these data and the application of quality control checks on the Advanced Microwave Sounding Unit observations to identify cloud, rain and surface type. This information is used in making intelligent decisions when mapping from the AMSU-A grid to the HIRS grid (e.g. not mixing different surface types or clear and rain-affected data). Flexibility exists to make similar decisions before mapping from the AMSU-B grid to the AMSU-A grid. In this implementation a simple bi-linear interpolation is used and we flag the mapped data if the total variance of the AMSU-B data within an AMSU-A field of view exceeds a threshold. The philosophy of AAPP is to provide information to the user through these tests, but not to attempt to correct the radiances for emissivity or cloud effects. The user can then decide whether to process all channels in the retrieval/assimilation stage, for which AAPP will provide a number of options, or whether to reject flagged data as contaminated (e.g. by rain). This paper describes what we are attempting to flag and the science behind the science tests in AAPP.

2. THE ATOVS AND AVHRR PROCESSING PACKAGE (AAPP)
The AAPP has a modular design. Figure 1 provides a high level block diagram of these modules. The preprocessing is performed in a module known as ATOVPP. The objective of ATOVPP is to prepare the radiances for the retrieval stage. This involves mapping to a single grid (the current configuration maps to the HIRS grid, although other grids could be chosen e.g. AMSU-B). ATOVPP provides information about cloud, rain and surface type from the microwave observations, but at present does not have an infra-red cloud detection module, although this could be added.

3. GENERATION OF SIMULATED AMSU LEVEL 1C DATA
A complete test of ATOVPP required the generation of simulated AMSU radiances including all the "contamination" the science tests are designed to detect. This is difficult for two reasons. Firstly the radiative transfer is complicated and significant assumptions need to be made about the ice and mixed phase layers of clouds and their dropsize distributions. Secondly meteorological fields are required and NWP model fields represent the cloud and rainfall features poorly. To overcome this problem it is necessary to use data from a high resolution limited area model. The UK Met. Office runs a mesoscale model at 12km resolution. This is ideal for studies at 50km resolution and adequate at 17km. The radiative transfer model of Kummerow and Giglio (1994) is used to generate brightness temperature images from the mesoscale model data. Figures 2a-2c give distributions of rainfall, ice water path and liquid water path corresponding to the simulated AMSU brightness temperature images in Figure 3.
Figure 1: Schematic diagram of the main stages of the AAPP for processing TOVS or ATOVS data. The purpose of ATOVPP is to process calibrated and navigated but raw data (level 1C) to produce mapped data with quality control flags (level 1D data) which are suitable to interface directly to the retrieval or assimilation stage.
ENGLISH S.J. et al. THE AAPP MODULE FOR IDENTIFYING PRECIPITATION....

Figure 2a: Rainfall rate for the 4 August 1996 case study. Cross reference to Figure 3 for coast line. There was a broken region of rain to the SW of the model domain, with a thin line of rain in the east and north.

AMSU channel 1 (Figure 3a) follows closely the cloud liquid water changes seen in Figure 2b. Similarly AMSU channel 16 (Figure 3b) follows the ice water path closely (which itself corresponds closely to surface rainfall, Figures 2a,2c). Where there is significant liquid water but no ice cloud or rain the channel 16 brightness temperatures show a similar behaviour to channel 1, following the liquid water path changes. The AMSU sounding channels show little sensitivity to cloud liquid water except for AMSU-4, 5 and 20 but are sensitive to the ice scattering in the tops of high cumulus or frontal cloud. This contamination produces sharp falls in brightness temperature in the 183 GHz channels. Therefore it is important to provide separate masks for liquid cloud and rain/ice cloud. A different selection of channels for processing in the retrieval or radiance assimilation stage will be appropriate depending on the type of contamination and the skill of the radiative transfer model used.

The other important aspect of processing AMSU data is the surface emissivity. The ocean has a high refractive index at microwave wavelengths and reflects downwelling radiation strongly. The reflection is greatest when the electric field vector is perpendicular to the plane of observation. By contrast most other surfaces have a low refractive index and reflect less than 10% of downwelling radiation back to space (between 20 and 200 GHz). As a result the ocean appears cold compared to most other surfaces and to atmospheric emission. Typically the ocean apparent brightness varies from around 100K at 20 GHz, when the electric field vector is perpendicular to the plane of observation, to around 270K at 200 GHz, when the electric field vector is parallel to the plane of observation.
Figure 2b: Liquid water path in the model domain for 4 August 1996. The cloud covers a more extensive region than the rain, but shows broadly the same pattern.

Figure 2c: Ice water path in the model domain for 4 August 1996. The ice cloud corresponds closely to the surface rainfall pattern. Note that there are some areas with high LWP but with no LWP or surface rainfall.
The increase in surface emissivity when passing from sea to land changes the sensitivity to atmospheric parameters. Liquid water clouds which would be clearly visible over the sea are undetectable over the land. Conversely precipitation and ice cloud cause a very rapid fall of brightness temperatures over the land. In the mesoscale model domain there is no sea ice. The change in emissivity from sea to sea ice is as large as the change from sea to land, except for grease ice, thin nilas and unconsolidated ice. For this reason the preprocessor is designed to retrieve the surface type corresponding to each AMSU-A field of view before mapping to HIRS. Only fields of view with the same surface type are mapped. If necessary this means that the nearest neighbour is used rather than a bilinear interpolation.

3. THE BACKGROUND TO THE SCIENCE TESTS IN ATOVPP

3.1. Radiative impact of cloud in microwave observations

The Microwave Sounding Unit (MSU) on TOVS has only four channels with surface resolution around 150km. Most retrieval schemes ignore the effect of cloud and rain on MSU radiances, but in fact their contribution at 50.3 GHz (MSU channel 1) is often in excess of 10K. For MSU channel 2 the largest impact of cloud is around 0.5K and for MSU channels 3 and 4 cloud has no effect on the measured radiances. This is because clouds at high altitude are usually composed of ice and the total
amount of liquid water is insignificant. Ice clouds are almost transparent at 50 GHz, except when associated with deep convective or rapidly developing frontal regions, whereas liquid water clouds absorb very strongly. The reason is that the dielectric properties of ice hydrometeors are very different from those of water drops. At 50 GHz both absorption and scattering by ice cloud are usually negligible but increase rapidly between 50 GHz and 183 GHz. However absorption by liquid cloud is non-negligible at all frequencies above 20 GHz and also increases with increasing frequency. Cloud absorption and scattering will therefore be greater for the Advanced Microwave Sounding Unit (AMSU) than for the MSU. The reason for this lies not only with the range of observation frequencies but also the horizontal resolution. The typical spatial scales of clouds are small compared to MSU and AMSU channel footprints. For this reason the variance of cloud rises as the field of view gets smaller. At MSU resolution the maximum cloud liquid water path we expect to see is under 400gm⁻². For AMSU-A1 and A2, at 50km resolution this is doubled to 800gm⁻² and for AMSU-B at just 17km resolution will have risen as high as 1500gm⁻². For AMSU channels 4 and 5 the cloud contribution to the measured radiance can’t be ignored. Of course there will be an increased number of fields of view
where there is less cloud liquid water than is experienced with MSU. Therefore it is desirable to flag those fields of view which are significantly contaminated. For AMSU "significantly contaminated" means liquid water path in excess of 100gm$^{-2}$. If the liquid water path is less than this the contribution to the measured radiances will be small, even if there is a complete cover of cloud. It is important to recognise that flagging cloud in microwave radiances does not mean we will not use them in cloudy areas. The purpose is to flag cloud which will have a larger impact on the radiances than the perturbations of temperature or humidity we are trying to measure.

Whilst AAPP does not prescribe which channels to use in the retrieval based on any of the tests - it is up to the user and the retrieval method used - the use of AMSU channels 4 and 5 is not recommended for cloudy (>100gm$^{-2}$) radiances unless liquid water cloud is treated in the retrieval stage. Although AMSU channel 5 is equivalent to MSU channel 2 this does not represent a degradation on TOVS performance as the number of uncloudy microwave radiances will increase. We are just excluding more efficiently those data which we can't handle in the retrieval stage, and thereby improving the quality of the final product.

For the two completely new instruments on ATOVS - AMSU-A1 and AMSU-B - the impact of cloud is very important. AMSU-A1, with channels at 23.8 and 31 GHz, is affected similarly to AMSU channel 3, i.e. maximum liquid cloud effect well in excess of 10K. For AMSU-B a combination of a larger absorption coefficient and the small field of view combine to give very large contamination. Again it is in excess of 10K for the window channels, and significant for the humidity sounding channels, especially channel 20.

3.2 Radiative impact of rain in microwave observations
Rain, and associated deep ice cloud, has a very large impact on measured microwave radiances. Bennartz (1997) and others propose to use AMSU data to retrieve rainfall rate. At low frequency the ice cloud will be transparent and the rainfall itself will be measured, which usually gives strong emission, appearing warm against a cold sea background or cold against a land background. At high frequency scattering by ice cloud and the rainfall itself reflects cold space into the radiometer field of view, reducing the measured radiances. The situation is further complicated by both enhanced scattering and emission from melting snow and from the wide range of scattering behaviour of different ice crystal types (graupel, snow etc.). Few radiative transfer models attempt to model precisely the complex radiative transfer in these situations and it is hard to foresee a time when it will be worth processing these data to extract sounding products. However the data are far from useless - the precipitation information will be useful both qualitatively in the form of images and quantitatively in the form of rainfall retrievals as attempted by Kummerow and Giglio (1994) and Bennartz (1997). From the perspective of AAPP we only require to flag those radiances affected by rain.

3.3 Radiative impact of surface type on microwave observations
The surface type is very important for microwave radiative transfer. Unlike infra-red observations, where emissivity usually falls no lower than 0.95 (exceptionally as low as 0.80) and is usually treated as 1.0 in radiative transfer models, microwave emissivity can fall as low as 0.2. The lowest emissivities are usually found for open water, although desert, snow and glacial ice can also give very low emissivities. Most surfaces behave either as a smooth (specular) dielectric slab, or a rough
(lambertian) dielectric slab, or display anisotropic volume or surface scattering. However some surfaces, especially snow on thin ice and wet rough surfaces behave differently at different observation frequencies. Dielectric surfaces show a monotonic change of emissivity with frequency, which for most natural surfaces takes the form of increasing emissivity with increasing frequency (between 20 and 200 GHz). Surfaces displaying a strong scattering behaviour usually show the opposite effect - a monotonic decrease of emissivity as the observation frequency rises and the wavelengths become shorter. Some surfaces appear dielectric at low frequency but at high frequency scatter strongly, leading to a non-monotonic change of emissivity with frequency. However the greatest source of complex spectral behaviour of emissivity is from mixed surfaces in the field of view (e.g. coastline, ice edge). It is undesirable in mapping from the AMSU-A grid to the HIRS grid to make this problem worse by mapping data with different surface types. Therefore it is important to identify surface type before mapping and only map data with the same surface in a single interpolation.

4. DETAILS OF THE SCIENCE TESTS IN ATOVPP

4.1. The AAPP test for liquid cloud

As discussed in the introduction we are attempting to flag those radiances contaminated by more than 100gm⁻² cloud liquid water path. When the cloud liquid water path exceeds 500gm⁻² precipitation usually occurs. Therefore this test needs to work effectively in the range 100 to 500 gm⁻². The test used is very simple. The mean and covariance of brightness temperatures in the AMSU-A window channels is calculated using a radiative transfer model with no liquid water cloud. In simple terms AMSU-A channel 1 is sensitive to total water vapour, AMSU-A channel 2 cloud liquid water and AMSU-A channel 3 absorber temperature. A cost, J, is calculated for the departure of the observed brightness temperatures, x, from the mean, m, of a set of brightness temperatures with covariance, C, calculated from a representative set of profiles.

\[ J = (x-m)^T C^{-1} (x-m) \]  

(1)

Because the covariance due to water vapour and temperature variations is large in channels 1 and 3, changes in the atmospheric profile have little impact on the cost, J. However the introduction of liquid water, which increases channel 2 out of proportion, leads to a very rapid rise of cost. This test is sensitive enough to the presence cloud liquid water to detect cloud amounts below 100gm⁻². Figure 4 shows the behaviour of the cloud test. The cost, J, is contoured as a function of channel 1 and 2. The data points plotted are from a simulation of AMSU level 1C data from August 1996 over the UK (Figures 2 and 3). Although very warm and moist air had reached the UK on this day, it is still rather unrealistic that the UK points should lie near the tropical mean. This is because the atmospheric profile dataset has a dry bias. The colour denotes liquid water path. The cost function shows a long narrow minimum into which all clear air points fall. As liquid water increases the cost rises very rapidly. In addition mean figures for an arctic, middle latitude and tropical profile are shown. The clear air point for all three always lies near the minimum and the cloudy point always at a high cost. This test is intended to work globally without regional tuning, and the evidence using simulated AMSU data is that this aim is achievable.
4.2 The AAPP test for surface type

The test for surface type is similar to that for cloud liquid water. A mean and covariance is calculated for a number of surface types. There are eight classes: Sea ice (with/without snow), land (dry, wet, dry snow, wet snow, forest) and open water. In addition dry land should be divided into agricultural and desert. The cost, $J$, of each surface is calculated and the surface with the lowest value of $J$ is accepted. A similar scheme was used by English (1991) to identify surface type from SSM/I. The skill of the scheme depends on how accurately surface emissivity is treated in the original calculation of the mean and covariance (or the accuracy of a ground truth dataset if real data are used).

![Figure 4 Performance of AMSU-A liquid cloud test on simulated AMSU 1C data using the Kummerow-Eddington model (Kummerow 1994) for August 22 1996 over the UK and simulated data for mean middle latitude, arctic and tropical conditions.](image)

4.3 The AAPP tests for precipitation

In the introduction it was explained that the radiative transfer through precipitating clouds is complex and can result in a variety of different radiative signatures. Therefore we test both for emission at low frequency and scattering at high frequency. However it is anticipated that the major test will be for scattering by ice and rain. The idea used is an extension of the Grody and Ferraro (1992) scattering index from SSM/I to AMSU. This test has the advantage that it does not require the polarisation information available on SSM/I but not available on AMSU. It relies on scattering being negligible below 50 GHz but strong at 89 GHz. Therefore in the absence of scattering the low frequency
channels should be able to predict the high frequency channel to within 5K. However if ice cloud is reflecting cold space at 89 GHz the measurement will be colder than the predicted 89 GHz brightness temperature calculated from the low frequency channels. This difference is known as the scattering index. (Grody and Ferraro 1992). A simple threshold can be applied to the scattering index to determine the presence of scattering. For AAPP the test is designed to work only over the sea. However there is no reason why the test can’t be extended to land.

Fig 5 The change of scattering index with ice water path over sea (lower points) and land (upper points) with some mixed fields of view. SI rises slowly, then more rapidly before leveling off for very deep ice cloud (with associated very large crystals).

Figure 5 shows the scattering index plotted against model integrated ice water path. For thin cirrus with low integrated water path increasing ice water path makes little difference to the scattering index. This is because thin ice cloud usually contains small crystals which are transparent even at 89 GHz. However as the ice water path rises the probability of large crystals increases (because of the crystal size distribution assumed) and the scattering index rises. As the crystal size increases beyond a few centimetres the scattering passes from the Mie regime into the geometric optical limit and scattering efficiency no longer rises. Therefore the scattering index ceases to rise for very high ice water paths. There is also a degree of saturation as the weighting function peaks above the freezing level and all the
measured radiation originates from the ice layer. Finally, an emission threshold test is applied to the channel 1 and channel 2 observations. If they are warm over the sea, precipitation is assumed.

Figure 6 shows an example of an image of scattering index for the 4 August 1996 case study. In regions of ice cloud the index rises to 50-60K over the sea. In clear areas it usually falls in the range ±3K. A threshold of 5K is used to define contamination by ice cloud or rain. A different threshold would be required over land.

5. CONCLUSIONS
A number of science tests have been brought together to form part of a unique preprocessing package for ATOVS. None of the tests rely on modelling complex radiative transfer situations but rather on well tested clear air and liquid water cloud models. A more sophisticated radiative transfer model has been used to generate a number of case studies using meteorological data from the UK Met. Office mesoscale model. One such case study (4 August 1996) has been examined in detail in this paper. The results of this case study are similar to the others, but at present only summer cases from the UK have been simulated. The tests have been applied to the 4 August 1996 data and the cloud and rain/ice cloud mask shown in Figure 7 was obtained. The ice and rain scattering information (from the high frequency channels) gives a rain flag which corresponds closely to the model rain and deep ice cloud layers from Figure 2. The cloud flag corresponds to those areas with liquid water cloud only. The information for this arises from both high and low frequency channels. The tests using simulated data
give confidence that the methods proposed work. When ATOVS is launched in 1998 the scheme will be tested, and improved where necessary, using real data.

Figure 7: Cloud and rain flags from ATOVPP for the 4 August 1996 case study. Both ice and liquid cloud is well identified, leaving a smaller set of data with only thin liquid cloud or cirrus. This residual cloud does not significantly affect the microwave sounding channels. Both tests are easily tunable. The flags above are based on scattering index threshold=6K (over sea) and cost function threshold=50. The additional test for omission was redundant (flagging no additional data to either of the above). The surface identification correctly separated sea and land.

6. REFERENCES