Cloud detection by using cloud cost for the Advanced Infrared Radiometer Sounder (Part I)
- A simulation study -

August 19, 2002

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This documentation was developed within the context of the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF), under the Cooperation Agreement dated 25 November 1998, between EUMETSAT and the Met Office, UK, by one or more partners within the NWP SAF. The partners in the NWP SAF are the Met Office, ECMWF, KNMI and Météo France.

Change record			
Version	Date	Author / changed by	Remarks
1.0	19.8.02	Y.Takeuchi	Version for distribution

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Abstract

This report describes a simulation study to obtain an optimum cloud detection channels and the threshold for Atmospheric Infrared Sounder onboard Aqua earth observation satellite with a sampled profile database based on the European Centre for Medium-Range Weather Forecasts 40-year re-analysis. The RTTOV-7 code and IASI-1DVar code is used to simulate AIRS brightness temperatures for cloudy profiles and to calculate the cloud cost as a measure of cloudiness based on a Bayesian cloud detection scheme. The result shows combined channels with long IR window and short IR window can detect thin ice clouds efficiently. It is also shown that additional use of microwave window channels of AMSU-A onboard Aqua improves cloud detection for low-level water cloud.

1. Introduction

1.1 The importance of cloud detection for NWP

Cloud detection is essential to retrieve accurate atmospheric parameter such as temperature and water vapour from satellite data for Numerical Weather Prediction without considering cloud parameter such as cloud liquid water and cloud ice water in the retrievals because cloud affects observed radiance at the top of atmosphere through strong absorption, emission, and reflection particularly in infrared spectral region.

1.2 Contribution of AIRS data to cloud detection

The Atmospheric Infrared Sounder (AIRS) is an instrument onboard NASA’s Aqua earth observation satellite launched on 4 May 2002. The AIRS has 2378 channels and measures air temperature, humidity, clouds and surface temperature. MetOffice has ingested near real-time AIRS brightness temperature (BT) data at 281 selected channels distributed by the National Environmental Satellite, Data, and Information Service (NESDIS) and plans to use the data for meteorological applications. The original channel number and the wave number for each selected channel is listed in Table 1. An advantage of AIRS data over existing other instruments in view of cloud detection is availability of many window channels free from line absorption of gas with its very high spectral resolution. Another advantage of AIRS over Infrared Atmospheric Sounding Interferometer (IASI), an operational instrument on the Europe's Meteorological Satellite Organisation (EUMETSAT) Polar Systems - Meteorological Operational Satellite (EPS-Metop) series of satellites, the first launch of which is planned for 2005, is high signal/noise ratio measurement with smaller noise than the IASI due to the different architecture between grating spectrometer and interferometer as described section 2.2.

1.3 Purpose

Purpose of this report is to find out the optimum cloud detection channels for variational (Bayesian) cloud detection scheme introduced by English et al. (1999) and to determine the threshold of the cloud cost as a measure of cloudiness. To get reliable and practical results, we use a huge dataset of atmospheric profiles including cloud liquid and ice water profiles. Methodology is described in section 2, data set used in this study is described in section 3, and results are given in section 4. In this study the scheme is applied only to single-FOV observation. It means that we do not treat spatial variation of the observation that is used frequently to detect cloud because we are focussing on the advantage of high-spectral resolution radiometers.

2. Methodology

Fig. 1 shows the general flow of this study consists of three steps. The first step is radiation simulation with a fast radiative model for cloudy atmospheric profiles from the ECMWF sampled profile database explained in detail in section 3. The second step is a cloud cost calculation with IASI-1Dvar code based on the radiative model for a clear profile. The third step is to determine the threshold for cloud detection and validation of cloud detection performance with "true" total cloud liquid and ice water.

2.1 Cloudy radiation simulation

The Radiative Transfer for Tiros Operational Vertical Sounder fast radiative transfer model (RTTOV-7: Saunders et. al, 2002) is used to simulate the brightness temperature (BT) at each channel for cloudy atmosphere profiles in the ECMWF sampled database. Radiative transfer calculation is carried out by using temperature, water vapour and ozone volume mixing ratio profiles at 43 pressure levels and surface properties such as surface temperature, surface water vapour, and skin temperature and surface emissivity as input parameters.

The standard RTTOV model is not suitable for this simulation study because in this model clouds are assumed to be at one level, have unit emissivity and a top at a fixed cloud top pressure with a fractional coverage for each input profile. Therefore, we used RTTOVCLD routine which takes a profile of temperature, cloud cover, cloud liquid water and cloud ice water on user defined model pressure levels and computes infrared and/or microwave cloudy radiances for multilevel and multiphase cloud fields. In the RTTOVCLD code, cloud is assumed to be random-overlapped.

The simulation is carried out for 281 sampled AIRS channels, the Advanced Microwave Sounding Unit – A (AMSU-A) 15 channels, and AMSU-B 5 channels. Radiation simulation for the two microwave instruments is to investigate a combined use of microwave instrument data with AIRS data. RTTOV-7 coefficients for NOAA-16 AMSU-A are used instead of AMSU on Aqua and the coefficients for NOAA-16 AMSU-B are used instead of the Humidity Sounder for Brazil (HSB) on Aqua.

In this report, the satellite zenith angle is fixed at 0.0 deg (i.e. nadir view) assuming the channel selection and threshold value are insensitive to satellite zenith angle. Surface emissivity of IR channels is assumed as 0.98 for land, 0.99 for sea-ice, and ISEM (Sherlock, 1999) for sea. Surface emissivity of MW channels is assumed to be the nominal value of RTTOV-7 for land and sea-ice and the FASTEM-1 (English and Hawison, 1998) value for sea. At cloudy BT simulation step, observation noise is not considered.

To select some candidates for cloud detection channels, we examine not only cloudy BT itself but also sensitivities to a water vapour increment and a surface temperature increment.

2.1.1 Limitation of RTTOV-7

Two major limitations should be noted associated with cloud detection. The first limitation is that RTTOV-7 does not take into consideration any reflected solar component. For the short wave infrared spectrum lower than 4 microns the solar reflection term is not negligible in daytime. Cloud detection performance will be much improved for a low reflectance surface where the contrast between surface and cloud is large and it will be degraded for a high reflectance surface. The second limitation is that RTTOV-7 does not consider scattering effects. For the short wave infrared spectrum region, the size of cloud water particles has the same order as the wavelength and the emissivity of the cloud is less than unity, so the scattering by cloud water particles is not negligible.

2.2 Cloud cost calculation

The cloud cost J_C that is a measure of cloudiness is calculated from the difference between the observed and background BT over the given channels as follows;

$$J_C = (\Delta y)^T \left\{ H(x_b) B H(x_b)^T + R \right\}^{-1} (\Delta y) \tag{1}$$

where $\Delta y = y_o - y(x_b)$, y_o is the observation and $y(x_b)$ is the estimated observation vector calculated from the background profile x_b by a forward model, $H(x_b) = \nabla_x y(x_b)$ is the matrix containing the partial derivatives of the simulated observations with respect to the elements of x_b. *B* is the error covariance matrix of a priori measurements x_b, *R=(E+F)* is the total observation error covariance matrix consists of the instrumental error covariance matrix *E* and the forward model error covariance that is given by the matrix *F*.

The cloud cost in this study is calculated by IASI_1DVAR code version 2.3 (Collard, 2002). The IASI_1DVAR code is a program developed at the Met Office as part of the Numerical Weather Prediction Satelllite Application Facility (NWP SAF) to retrieve atmospheric properties such as temperature and humidity by using 1DVar scheme. The code was originally developed for the IASI instrument but it can be used with many different sounding instruments such as AIRS and AMSU. By changing the channel selection for cloud detection, cloud cost for any channel combination can be calculated. One of great benefits of IASI_1DVAR code is capability to treat multi-sensor data such as AIRS and AMSU simultaneously.

The input data of IASI_1DVAR code are background profiles at 43 pressure levels, observation BTs of the instruments, the background error covariance matrix, and observation and forward model error covariance matrices. Radiative transfer model for AIRS and AMSU in IASI_1DVAR is based on RTTOV7 except that it does not include the cloudy radiation simulation function.

Equivalence between RTTOV7 code used for cloudy BT simulation and RTTOV7 code in IASI_1DVAR code are verified using clear profiles. To process a large profile dataset, the code is modified so that the background profiles are given one at a time, rather than all together. In addition, a kind of profile modification as a pre-processing of IASI_1DVar is removed from the code to avoid producing an unexpected cloud cost because the modification is implemented to get better retrieval results. In this step, we add the background perturbation and observation noise in a random manner as described later.

2.2.1 Background data

Background data are given by the ECMWF sampled profile database with a background perturbations. The background perturbations are consistent with the error covariances expressed in the background error covariance matrix, *B*. As described in Collard and Healy (2002), this is done by decomposing the B-matrix,

$$B = X \Lambda X^T \tag{1}$$

And then calculating true-minus-background perturbation through

$$x_T - x_b = \sum_{i=1}^{N} a_i \sqrt{\lambda_i}\, x_i \tag{2}$$

Where the *N* eigenvalues, are the diagonal values of , x_i are the associated eigenvectors (and columns of *X*), and a_i is from a set of normally distributed random numbers with unit variance and zero average. The background error covariance matrix used is the same as that used in IASI_1DVAR code.

2.2.2 Observation data

The observation data is given by simulating BTs based on the ECMWF sampled profile database in the prior step and then adding random noise that is consistent with the *R* matrix being assumed for AIRS, AMSU-A, and AMSU-B.

2.2.3 Background error covariance matrix

The background error covariance is related to the expected error in a 6hr NWP forecast. A background error covariance matrix calculated for Mid-Latitude Winter is applied to cloud cost calculation. The constant matrix is given both for ocean and land and all latitudes and seasons.

2.2.4 Total observation error covariance matrix

The total observation error covariance matrix consists of the instrumental error covariance matrix and the forward model error covariance. The instrumental error covariance matrix for AIRS Flight Model is provided by JPL. The forward model error is given by Collard (2002). Fig. 2 shows the square root of diagonal elements of R-matrix for AIRS and IASI. Instrumental noise of AIRS is less than those of IASI except for sounding channels sensitive to upper atmosphere at long wave spectral region. In particular, the observation noise values for the short wave channels of AIRS are about half of those of IASI.

2.3 Validation and threshold determination

In this simulation study, we know "true" total cloud liquid water and total cloud ice water by calculating directly from the ECMWF sampled profile database, therefore we can investigate the relationships between cloud cost and total cloud liquid/ ice water. From these relationships, we can determine optimum channel selection and threshold for cloud detection and can verify the performance of cloud detection.

3. Dataset

3.1 ECMWF sampled profile database

The ECMWF sampled profile database (Chevallier, 2001) is a key source of information for this work. It consists of 13495 atmospheric profiles sampled, i.e. geographically, temporally, and weather conditions, from the ECMWF 40-year re-analysis (ERA-40) data. The ECMWF sampled profile database also includes cloud properties, i.e. cloud liquid water, and cloud ice water, cloud cover, at ECMWF 60 model levels. The dataset characterises a regular distribution of physically consistent atmospheric temperature, water vapour and ozone profiles. Since these profiles are equally sampled in temperature, humidity, and ozone, the dataset is very useful, for example, in making a kind of regression coefficient for some retrievals and in this study. Atmospheric properties such as temperature, water vapour mixing ratio, ozone-mixing ratio are given at 60 model levels. This data set is used as an input to calculate cloudy Brightness Temperatures (BTs) of AIRS, AMSU-A, and AMSU-B by RTTOV-7 as described in section 2.1. To match the interface, temperature, water vapour mixing ratio, ozone mixing ratio is interpolated onto 43 pressure level pre-determined in RTTOV-7.

Fig. 3 shows accumulated probability of total cloud liquid water (TCLW) and total cloud ice water (TCIW). Usually, TCLW takes the range from 1.0 (g/m^2) to 1000 (g/m^2), and TCIW takes the range from 0.5 (g/m^2) to 300 (g/m^2).

4. Results and Discussion

4.1 Definition of cloud categories

At the beginning, we define the cloud categories in this work. Total cloud water content in ECMWF sampled profile database ranges from near zero to very large values continuously. So to our convenience, we define three cloud categories namely 'clear', 'thin cloudy', and 'thick cloudy'. Each category is defined by total cloud liquid water and total cloud ice water as shown in Fig.4. The threshold between clear and thin cloudy is very small because the infrared broadband emissivity is about 0.1 even for water cloud (Stephens,1984). Emissivity of ice cloud at the threshold between clear and thin cloudy is less than 0.01 (Kinne and Liou, 1989). The number of samples in each category is 8954 (66.3%) for 'thick cloudy', 3356 (24.9%) for 'thin cloudy', and 1185 (8.8%) for 'clear', respectively. The 'clear' category consists of 797 completely clear, i.e. TCLW=0 and TCIW=0, profiles and 388 profiles with very thin cloud. Because the change in BT for these very thin cloud profiles is bias of 0.13K and standard deviation of 0.21K for ch.843, which is the most sensitive channel to cloud, and these values are much smaller than total observation error, these profiles can be regarded as clear profiles.

4.2 Strategy for channel selection

For cloud detection, the clouds to be considered are thin ice clouds and lower level clouds, the top temperature of which are close to surface temperature. Sufficiently thick cloud or much colder cloud than surface temperature are easy to detect by any simple algorithm. Channels to be selected should have, 1) large BT sensitivity to cloud, 2) small BT sensitivity to variable gas (e.g. water vapour, ozone) absorption, and 3) small BT sensitivity to surface properties (e.g. skin temperature).

4.2.1 Sensitivity to cloud water

The first condition is that the channels have high sensitivity to cloud liquid and ice water. Fig. 5 shows BT sensitivities to cloud for AIRS, AMSU-A, and AMSU-B. The red coloured channels are used in the cloud cost calculation described later. In general, BTs in cloudy areas are colder than those in clear areas at infrared wavelengths because the cloud top temperature is lower than the surface temperature. Occasionally, very low-level cloud such as stratus or fog seems warmer than the surface. In AIRS channels, three significant bands sensitive to cloud exist around 10.5 microns (selected ch.120-130), 8.9 microns (selected ch.155-160), and 3.8 microns (selected ch.260-280). These three window bands are suitable for cloud detection. Other bands are affected by very strong CO_2, O_3, and H_2O gas absorption. In these bands radiation at the top of the atmosphere comes from the atmosphere above the clouds, therefore no information about clouds are included in such channels.

For AMSU-A and AMSU-B to represent AMSU-A and HSB on Aqua, BT sensitivities to cloud are shown in Figs. 5 b) and c). Ch.1-3, and 15 of AMSU-A have large sensitivity to cloud but other channels are less sensitive because of the strong oxygen absorption band located at 60GHz. In the microwave spectral region, the cloudy BT over ocean is larger than the clear BT, i.e. a negative value of BT decrease, and the cloudy BT over land is smaller than the clear BT, i.e. a positive value of BT decrease. This contrast between ocean and land makes cloud detection with microwave observation very difficult over coast region. Since AMSU-A ch.1 is affected by the water vapour absorption line centred at 22.235GHz, AMSU-A ch.2, 3, and 15 are expected to be the channels best suited for cloud detection. AMSU-B ch.2 (150GHz), the frequency of which is the same as HSB ch.1 has small sensitivity to cloud but the average and standard deviation is too small to use for cloud detection. We should pay attention that this small sensitivity of AMSU-B partly comes from that RTTOV-7 does not consider the scattering by cloud.

Unfortunately, AMSU-A channels are less sensitive to ice cloud so those microwave channels are not good for ice cloud detection. Due to this disadvantage, the cloud cost with AMSU-A should be implemented carefully. It also should be noted that the BTs of the AMSU-A window channels are affected by surface emission over land and sea ice and ocean which also varies with surface wind speed. This means the background error is larger for AMSU-A channels and cloud cost tends to have a smaller value and it might be difficult to distinguish cloud signal from background perturbation.

4.2.2 Sensitivity to water vapour amount

The second condition is that the channels had to be insensitive to water vapour absorption because the variability of water vapour amount is an error source for the radiative transfer calculation. Even for weak water vapour channels, we have not much prior information on humidity, it is better to avoid water vapour channels.

Fig. 6 shows the BT sensitivities to a water vapour increment of 5% without changing water vapour profile. For almost all spectral regions, water vapour affects the observed BT. Large sensitivity can be seen at the 6.3 micron water vapour absorption band (selected ch.180-210) and at wavelengths longer than 11 micron (selected ch.100-120). At lower troposphere channels, water vapour’s effect is large. However for shorter wavelength channels the effect of water vapour is small. The three window channels picked up in section 4.2.1 have rather smaller sensitivities. In particular, some channels in the 3.8 micron bands are almost free from water vapour perturbation.

It should be noted that the neighbour channel of ch.271 (2611.84cm^{-1}) and ch.272 (2617.16cm^{-1}) have very different sensitivities to water vapour. The sensitivities of ch.270 (2608.66cm^{-1}) and ch.273 (2623.57cm^{-1}) are over ten times as those of ch.271 and ch.272. Since the half-power bandwidths of HIRS ch.18 (2515.6cm^{-1}) and ch.19 (2663.4cm^{-1}) are 35cm^{-1} and 100cm^{-1}, respectively (Kidwell, 1998), the HIRS instruments can not distinguish this kind of large spectral variation. This means that observation with high spectral resolution is essential for cloud detection and/or retrieval particularly in the short wave region. Similar feature can also be seen in the long wave region around 10.5 micron and 8.9 micron bands we considered.

4.2.3 Sensitivity to skin temperature

Fig. 7 shows the BT sensitivities to a skin temperature increment of 1K. Large sensitivity can be seen in the window bands. Small variation of the sensitivity arises from differences in water vapour absorption. For the 3.8 micron window channel free from water vapour, the sensitivity is near to unity for all profiles. Since channels sensitive to cloud are also sensitive to skin temperature, the third condition, i.e. small BT sensitivity to skin temperature, can not be used as a measure for channel selection.

4.2.4 Channels selection

Fig. 8 shows the mean sensitivities to water vapour amount and cloud water for the AIRS 281channel set. The 3.5-4.2 micron channels are almost free from water vapour absorption but the sensitivities to cloud are lower than the 10-13 micron and 8-9 micron channels. The 3.8 micron (2610 cm^{-1}) channels located around the minimum of the water vapour continuum (Kneizys et al.,1980) is a secondary candidate for cloud detection. It is noted that 8.9 micron are also a candidate because these channels are less sensitive to water vapour than the 10.5 micron channels though both channels have almost same sensitivity to cloud.

From these results, we nominate five channel selection sets as shown Table 2. S914 and S2333 are single channel sets in long IR window and short IR window respectively. DBL is combination of S914 and S2333 channels. MIX is a combination of seven channels selected from 10.5micron (ch.787, ch.843, and ch.914), 8.9micron (ch.1221 and ch.1237), and 3.8 micron (ch.2328 and ch.2333) bands. Ch.1221 and ch.1237 in 8.9 micron band have almost the same sensitivities to cloud and water vapour and ch.2328 and ch.2333 in 3.8 micron band have also the same sensitivities to cloud and water vapour. MIX with AMSU is a simultaneous use with seven IR channels and three MW channels (AMSU ch.2,3, and 15). These selected channel sets have large sensitivities to cloud and small or medium sensitivity to water vapour.

4.2.5 Number of channels to be applied

In IASI-1DVar, the cloud cost is normalised by dividing by the number of used channels. If these channels are independent of each other, the cloud cost value is independent of number of channels used. However, the BT difference of these channels generally have some correlation. Therefore, the more channels we used, the lower the cloud cost that is calculated. So a key point is to find channels as much as possible provide independent information. The comparison between DBL channels and MIX channels will give insight on the efficiency or redundancy of selected cloud channels.

4.3 Cloud cost

For these selected channel sets, cloud costs are calculated by IASI_1DVAR code (Collard, 2002). This code can treat reduced channel observation data and multi-instrumental observations. This function enables us to perform this study saving computer memory and calculation time. Background data is produced by adding background noise consistent to background error covariance, which is used in the cloud cost calculation. Simulated observation data is also modified by adding observation error consistent to observation error covariance given as a R-matrix.

4.3.1 Sensitivity of cloud cost to cloud liquid and ice water

Fig. 9 shows sensitivities of cloud cost to a) total cloud liquid water, and b) total cloud ice water for each of the channel sets. The sensitivities are calculated near clear profile cases, namely TCLW less than 100 (g/m^2) and TCIW less than 4 (g/m^2). One of significant features is that the single channel cloud cost (S914 and S2333) has large sensitivity to water cloud and less sensitivity to ice cloud. On the other hand, multiple IR channel cost (DBL and MIX) have larger sensitivity to ice cloud and less sensitivity to water cloud. In the case of adding AMSU-A channels (MIX + AMSU), the cloud cost has a little larger sensitivity to water cloud than MIX channels. However MIX with AMSU-A channels have less sensitivity to ice cloud than MIX channels. These results suggest that, 1) single IR channel can not detect low emissivity ice cloud well, 2) multiple IR channels can detect such ice cloud due to the difference of spectral sensitivity to ice cloud, 3) AMSU-A channel has some sensitivity to water cloud and can detect a kind of water cloud.

4.3.2 Combination of short wave IR channels and long wave IR channels

To confirm the advantage of cloud cost calculation consisting of short wave IR channels and long wave IR channels over single channel cloud cost, MIX cloud cost and S914 cloud cost for each profile is plotted in Fig.10. The abscissa denotes single channel (S914) cloud cost and ordinate the difference between MIX cloud cost and S914 cloud cost. Green dots mean 'thick cloudy' and liquid water dominant (TCIW<TCLW) profiles, blue dots mean 'thick cloudy' and ice water dominant (TCIW>TCLW) profiles, and red dots means ‘clear’ profiles. Small black dots mean ‘thin cloudy’ profiles. The dense green belt distributed towards the bottom right in Fig. 10 a) corresponds to thick water cloud and scattered blue dots in the upper right is the area corresponds to ice-dominated cloud. It means that ice abundant cloud has rather large MIX cloud cost and water abundant cloud has rather small MIX cloud cost.

Fig. 10 b) is an enlarged part of Fig. 10 a) showing the small cloud cost area. The black vertical line is the threshold for the single channel (S914) cloud cost and the sloped line is the threshold for the MIX channels cloud cost. How to determine the threshold values is described section 4.4. Cloud cost with MIX channels can have large values even if single channel (S914) cloud cost is less than the threshold and these large MIX cloud costs correspond to profiles with ice-dominated cloud which can not be detected by S914 cloud cost. This suggests that the sensitivities of each of these channels are different for background perturbation and for cloud contamination. Also we can see that many ‘clear’ profiles have larger S914 cloud cost than its threshold but MIX cloud cost can determine these ‘clear’ profiles as ‘clear’. It should be noted that this large advantage can be obtained by combining of short wave infrared channels and long wave infrared channels. Single channel cloud cost only with long wave IR channel or only with short wave IR channel can not detect the ice abundant cloud definitely.

However, MIX cloud costs for some profiles with water abundant cloud is less than its threshold, therefore, such cloud is overlooked by MIX cloud cost. Radiative properties of lower-level water cloud in infrared region is similar to that of ground surface, so cloud cost with many channels which have similar sensitivities to cloud and ground surface give ambiguous results.

4.3.3 Simultaneous use of IR channels and MW channels

In this part, we describe the simultaneous use of microwave channels for cloud detection. The microwave is a promising spectral region to detect some cloud because most microwave channels are almost free from water vapour absorption and are sensitive to water cloud as shown in Fig. 5. Though the sensitivity of cloud in the microwave spectral region is smaller than that at infrared spectrum, BTs of microwave channels give independent information about cloud because the surface emissivity is less than unity and cloud emissivity is lower than that in the infrared region. Therefore, microwave channels can detect low-level cloud even if the temperature of cloud surface and ground surface are almost the same.

MIX with AMSU channel cloud cost and S914 channel cloud cost is plotted for all profiles in Fig.11. ‘Thick cloudy’ and liquid water dominant profiles and ‘thick cloudy’ and ice water dominant profiles do not distribute separately but liquid water dominant profiles have larger MIX with AMSU cloud cost. This difference results from the microwave channels considered here having little sensitivity to ice cloud. In small cloud cost cases, many ‘thick cloudy’ and liquid water dominant profiles are detected by MIX with AMSU cloud cost as well as some ‘thick cloudy’ and ice water dominant profiles even when the MIX cloud costs for the profiles are smaller than the threshold of MIX cloud cost. Some ‘thick cloudy’ and ice water dominant profiles are overlooked by using MIX with AMSU cloud cost.

4.4 Threshold determination

Figs. 12 a)-e) are used to determine thresholds for the five channel sets to be considered. The abscissa is the cloud cost and ordinate shows probabilities of each cloud category defined at section 4.1. In these figures, raw probabilities (thin lines) and accumulated probabilities (thick lines) are shown. Raw probabilities are smoothed by cloud cost and normalised by its maximum value. Accumulated probability for the ‘clear’ category denoted by a thick red line is plotted and it becomes unity at a cloud cost of zero. For the ‘thin cloudy’ category denoted by a thick green line and ‘thick cloudy’ category denoted by a thick blue line, the accumulated probabilities are plotted as they become zero at cloud cost of zero.

Raw probabilities of each category have a maximum at zero for single channel (S914 and S2333) cloud cost. When many channels are used in a cloud cost the maximum of raw probability is at a larger cloud cost for all cloud categories.

English et al. (1999) show that a threshold around five is proper for cloud detection. But their threshold is determined for limited synoptic conditions. Cloud cost takes continuous values for globally and seasonally equal-sampled profiles so we can not get the threshold to be able to divide cloud area and clear area perfectly. Raw probabilities for the ‘clear’ category and raw probabilities for the ‘thin cloudy’ and/or ‘thick cloudy’ categories overlap as shown in Fig. 12.

In this study, we define the threshold for cloud detection so that the accumulated 'clear' profiles detection rate equals the accumulated 'thick cloudy' profiles detection rate at that threshold. The crossing point of the red thick line and the blue thick line in Fig.12 corresponds to the cloud cost threshold for each channel set.

Table 3 summarises the determined thresholds. The thresholds are 1.36 for S914 cloud cost, 1.23 for S2333 cloud cost, 1.31 for DBL cloud cost, 0.97 for MIX cloud cost, and 0.93 for MIX with AMSU cloud cost. For channel sets with many channels, thresholds near unit are obtained.

Table 3 also shows the hit ratio for cloud detection by each channel set for each cloud category. These hit ratio are 90.4% for S914 cloud cost, 88.3% for S2333 cloud cost, 92.6% for DBL cloud cost, 92.9% for MIX cloud cost, and 95.1% for MIX with AMSU cloud cost. With these optimum thresholds, about 31% of thin cloud can be detected by single channel cloud costs. The value rises to about 33% for DBL and MIX cloud cost and reaches 38% for MIX with AMSU cloud costs. It is interesting that the performance of S2333 cloud cost is worse than that of S914 even though the sensitivity of BT at 3.8 micron to water vapour is much smaller than that at 10.5 micron. It means that the sensitivity to cloud is essential for cloud detection with single channel cloud cost.

Combined use of long wave infrared channels and short wave infrared channels gives remarkable improvement to cloud detection. The proportion of overlooked 'thick cloudy' cases is decreased from 10% for single channels to 7% for combined channels and more than 3% 'thin cloudy' can be detected by the combined channels. We can also note that the difference of the hit ratio between DBL and MIX is very small. Addition of AMSU also results in large improvement to cloud detection. The proportion of overlooked 'thick cloudy' cases is decreased to 5% and more 'clear' profiles can be found.

When it is necessary to obtain purer clear cases, we can apply a smaller threshold. However, some clear profiles with high cost value caused by background perturbations are rejected as cloudy profiles.

4.5 Geographical characteristics of cloud detection result

Fig. 13 shows geographical distribution of all profiles. Fig.13a) is the result for the S914 cost and Fig.13b) is the result for the MIX cost, respectively. Green dots and blue dots in Fig.13a) and Fig.13b) mean profiles assigned correct categories, i.e. 'cloudy' and 'clear', respectively, by the cloud detection. Where the threshold between clear and cloudy is given at TCLW of 10(g/m^2) and TCIW of 1(g/m^2). Purple and red coloured dots are mis-assigned profiles. In particular, red dots mean undesirable cases, which have small cost though it is cloudy. For S914 cost, mis-assigned profiles are seen over Siberia, Canada, and the edge of the Antarctic continent. Fig.13c) shows the improvement and degradation of cloud detection performance. Blue dots are profiles, which are correctly assigned by MIX cost but mis-assigned by S914 cost. Red dots are vice versa. Cloud detection with MIX cost is improved over most land areas and the Southern Ocean. On the other hand, the cloud detection with MIX cost is degraded over ocean at mid- and low-latitudes. By these two categories validation, the hit ratio of cloud detection is improved from 80.6% for S914 to 83.1% for MIX. Cloudy but cloud cost less than the threshold ratio is reduced from 17.8% for S914 to 15.7% for MIX.

Fig.14 shows the result for MIX with AMSU cost. Fig.14b) shows improvement and degradation of cloud detection performance of MIX with AMSU cost against S914 cost and Fig.14c) is those of MIX with AMSU cost against MIX cost. MIX with AMSU cloud detection improves its performance over ocean then addition of AMSU channels partly compensates the disadvantage of MIX cloud cost to S914 cloud cost. On the other hand, the effects of AMSU channels are generally neutral over land or little negative particularly over high-latitude land such as Antarctica and Greenland. Total performance of MIX with AMSU cost is better than MIX cloud cost because hit ratio of cloud detection is improved from 83.1% for MIX to 85.4%. Cloudy but cloud cost less than the threshold ratio is reduced from 15.7% for MIX to 13.3% for MIX with AMSU.

5. Conclusions and Summary

5.1 Optimum selection of cloud detection channels

A simulation study to obtain an optimum set of cloud detection channel selection and the threshold for AIRS was performed with a sampled profile database based on the ECMWF 40-year re-analysis. The RTTOV-7 code and IASI-1DVar code is used to simulate AIRS, AMSU-A, and AMSU-B brightness temperatures for cloudy profiles and to calculate the cloud cost as a measure of cloudiness based on a Bayesian cloud detection scheme. Sensitivity of the brightness temperatures to cloud and water vapour are calculated and five candidates for channel set for cloud detection are obtained. Thresholds for each channel set is determined and cloud detection performance is verified with the true total cloud liquid and ice water.

The conclusions of this study are,

- Cloud cost with single window channel tends to overlook ice cloud and lower-level warm cloud.
- The 3.8 micron window single channel shows worse performance than the 10.5 micron single channel.
- By using long wave infrared window channels (10.5 micron and 8.9 micron) and short wave infrared window channels (3.8 micron) of AIRS simultaneously, clear profiles of 93%, thick cloudy profiles of 93% and thin cloudy profiles of 33% can be detected. Combined use of long wave and short wave infrared window channels is essential to ice cloud detection.
- Very little improvement is obtained by using 7 AIRS channels cloud cost over 2 AIRS channels cloud cost.
- Simultaneous use with AMSU-A gives much better performance by detecting low-level water cloud. Combined use of infrared and microwave channels is essential to low-level water cloud detection, therefore, an additional use of AMSU-A onboard Aqua will improve cloud detection.
- If more channels are included in the cloud costs, smaller cloud cost is calculated and the cloud detection performance is degraded. To avoid this, a kind of virtual channels, which consist of linear combination of real channels, is to be investigated.

5.2 Some remarks on limitation of the investigation with RTTOV_CLD and IASI_1DVar codes

The characteristics of water cloud at 3.8 micron are, 1) weaker absorption (smaller emissivity) than that at 10.5 micron, and 2) larger reflection than that at 10.5 micron. Larger reflection by cloud causes larger BT differences between cloudy area and clear areas. However, RTTOV_CLD does not consider cloud reflection, and so can not simulate such a kind of BT difference. If we include the cloud reflection effect into RTTOV_CLD, we will be able to find out that some short infrared channels are sensitive to low-level water cloud without microwave channels.

When scattering effect by ice cloud in microwave is considered in RTTOV_CLD, the sensitivities of HSB channels to ice cloud and efficiency of these channels for cloud detection can be estimated.

In this study, a constant background error covariance matrix was applied. It is possible that use of detailed covariance matrices categorised by surface type, latitude, and seasons would give better results.

5.3 Toward the use of AIRS near real-time data

Near real-time AIRS data will be available in fall 2002 at Met Office. Some investigations with near real-time AIRS data will be used to verify the result of this study. In addition, AIRS observed BT at short wave, for lower water cloud particularly in daytime will tell us if these channels are more effective than we found in this study.

Future subjects to be studied are, 1) to apply ECMWF cloud detection scheme (Watts, 2002) to AIRS simulation data produced in this study, 2) to apply Bayesian scheme and the ECMWF scheme to AIRS near real-time data, 3) to develop a scheme to detect channels uncontaminated by cloud, and 4) to test some assimilation tests of AIRS clear and/or cloudy data.

As can be seen in Fig. 13 and Fig.14, the cloudy case is predominant in actual profiles, then cloud clearing or extracting unaffected cloud channels is essential for assimilation of AIRS data. When we use AIRS data and AMSU data simultaneously, it should be noted that accurate coincidence of Field of View (FOV) of both instruments is required. We also pay attention to whether AMSU data is contaminated by small islands, lakes, or coast line in a FOV.

Though a nominal surface emissivity value of RTTOV-7 for land and sea-ice are given in this study, a simulation with a more realistic surface emissivity in particular over land should be required to verify the AIRS near real-time data.

Acknowledgements

The author thanks R.Saunders, A.Collard, and S.English (Met Office) for encouraging support of this work and giving valuable comments.

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Figure captions

Fig.1 General flow of this study.

Fig.2 Square root of diagonal elements of R-matrix (unit: K) for AIRS (red line) and IASI (blue line).

Fig.3 Accumulated probability of total cloud liquid water (red solid line) and total cloud ice water (green dotted line) for 13495 profiles in ECMWF 60L_SD data set.

Fig.4 Cloud categories definition in this study. Abscissa denotes total cloud liquid water and ordinate denotes total cloud ice water.

Fig.5 Sensitivity of simulated BT to cloud for a) AIRS, b) AMSU-A, and c) AMSU-B. Abscissa is channel number of each instrument. Average (diamond marks) and standard deviation (bars) for 13495 profiles are shown. Red coloured channel is used for cloud cost calculation.

Fig.6 Sensitivity of simulated BT to water vapour increment of 5% for AIRS. Average and standard deviation for 13495 profiles are shown.

Fig.7 Sensitivity of simulated BT to surface temperature increment of 1K for AIRS. Average and standard deviation for 13495 profiles are shown.

Fig.8 Mean sensitivity of simulated BT to water vapour and cloud for AIRS selected channels for 13495 profiles. Ordinate is BT difference for water vapour increment of 5% and abscissa is BT difference due to cloud. The BT difference is average of these for 13495 profiles in 60L_SD data set. The number assigned is channel number of AIRS 2378ch.

Fig.9 Sensitivities of cloud cost to a) total cloud liquid water, and b) total cloud ice water, for each of the channel set.

Fig.10 Multi-channel cloud cost against single-channel cloud cost. Abscissa is S914 cloud cost and ordinate denotes difference between MIX cloud cost and S914 cloud cost. Fig.10 a) is plots for wide cloud cost range and Fig.10 b) is for small cloud cost range.

Fig.11 MIX with AMSU cloud cost against MIX cloud cost. Abscissa is S914 cloud cost and ordinate denotes difference between MIX cloud cost and S914 cloud cost. Fig.10 a) is plots for wide cloud cost range and Fig.10 b) is for small cloud cost range.

Fig.12 Abscissa denotes cloud cost and ordinate denotes accumulated and raw probability of each cloud categories (clear, thin cloudy, and thick cloudy). The raw probability is normalized by its maximum value.

The vertical black line is the determined threshold for cloud detection. Fig. 12 a) is for S914, b) for S2333, c) for DBL, d) for MIX, and e) for MIX with AMSU.

Fig.13 Geographical distribution of each category assigned correctly and misassigned profiles. Blue colour shows clear, green colour cloudy, purple colour clear with large cloud cost, and red colour cloudy with small cloud cost. Red colour can be seen continental region. a) is for S914 and b) for MIX. c) is the upgraded profiles and degraded profile.

Fig.14 Geographical distribution of each category assigned correctly and misassigned profiles. Blue colour shows clear, green colour cloudy, purple colour clear with large cloud cost, and red colour cloudy with small cloud cost. Red colour can be seen continental region. a) is for MIX with AMSU. b) and c) is the upgraded profiles and degraded profile MIX with AMSU channels against S914 and MIX with AMSU channels against MIX channels, respectively.

Table 1 AIRS channels and the central wave numbers for 281ch selected channels (next page)

selected ch. #	ch. #	wave number (1/cm)	selected ch. #	ch. #	wave number (1/cm)	selected ch. #	ch. #	wave number (1/cm)	selected ch. #	ch. #	wave number (1/cm)
1	1	649.786	72	168	697.915	143	1090	1040.490	214	1852	1605.580
2	6	650.981	73	169	698.192	144	1092	1041.420	215	1865	2182.160
3	7	651.221	74	170	698.470	145	1095	1042.810	216	1866	2183.060
4	10	651.940	75	172	699.027	146	1104	1056.450	217	1868	2184.880
5	11	652.181	76	173	699.305	147	1111	1059.790	218	1869	2185.780
6	15	653.144	77	174	699.584	148	1115	1061.710	219	1872	2188.510
7	16	653.385	78	175	699.863	149	1116	1062.190	220	1873	2189.430
8	17	653.626	79	177	700.422	150	1119	1063.640	221	1876	2192.170
9	20	654.352	80	179	700.982	151	1120	1064.120	222	1881	2196.740
10	21	654.594	81	180	701.262	152	1123	1065.570	223	1882	2197.660
11	22	654.836	82	182	701.823	153	1130	1068.960	224	1883	2198.580
12	24	655.321	83	185	702.666	154	1138	1072.870	225	1911	2224.620
13	27	656.051	84	186	702.948	155	1142	1074.840	226	1917	2230.280
14	28	656.294	85	190	704.076	156	1178	1092.820	227	1918	2231.230
15	30	656.782	86	192	704.642	157	1199	1103.580	228	1924	2236.920
16	36	658.249	87	198	706.345	158	1206	1107.210	229	1928	2240.730
17	39	658.985	88	201	707.199	159	1221	1115.060	230	1937	2249.350
18	40	659.231	89	204	708.056	160	1237	1123.550	231	1941	2253.200
19	42	659.724	90	207	708.915	161	1252	1131.620	232	2099	2379.130
20	51	661.948	91	210	709.776	162	1260	1135.970	233	2100	2380.100
21	52	662.196	92	215	711.215	163	1263	1217.340	234	2101	2381.070
22	54	662.693	93	216	711.504	164	1266	1218.870	235	2103	2383.020
23	55	662.942	94	221	712.950	165	1285	1228.600	236	2104	2383.990
24	56	663.191	95	226	714.403	166	1301	1236.920	237	2106	2385.940
25	59	663.939	96	227	714.694	167	1304	1238.490	238	2107	2386.910
26	62	664.689	97	232	716.154	168	1329	1251.750	239	2108	2387.890
27	63	664.939	98	252	722.055	169	1371	1285.890	240	2109	2388.870
28	68	666.194	99	253	722.353	170	1382	1292.120	241	2110	2389.840
29	69	666.446	100	256	723.247	171	1415	1311.190	242	2111	2390.820
30	71	666.950	101	257	723.546	172	1424	1316.490	243	2112	2391.800
31	72	667.202	102	261	724.742	173	1449	1331.420	244	2113	2392.780
32	73	667.454	103	262	725.042	174	1455	1335.050	245	2114	2393.760
33	74	667.707	104	267	726.545	175	1466	1340.060	246	2115	2394.750
34	75	667.959	105	272	728.055	176	1477	1345.690	247	2116	2395.730
35	76	668.212	106	295	734.375	177	1500	1357.620	248	2117	2396.710
36	77	668.466	107	299	735.607	178	1519	1367.640	249	2118	2397.700
37	78	668.719	108	300	735.915	179	1538	1377.820	250	2119	2398.680
38	79	668.972	109	305	737.462	180	1545	1381.610	251	2120	2399.670
39	80	669.226	110	310	739.016	181	1565	1392.560	252	2121	2400.660
40	82	669.734	111	321	742.456	182	1574	1397.540	253	2122	2401.640
41	83	669.989	112	325	743.715	183	1583	1402.560	254	2123	2402.630
42	84	670.243	113	333	746.246	184	1593	1408.190	255	2128	2407.590
43	86	670.753	114	338	747.836	185	1614	1420.150	256	2134	2413.560
44	92	672.287	115	355	753.293	186	1627	1427.650	257	2141	2420.570
45	93	672.544	116	362	755.562	187	1636	1432.900	258	2145	2446.940
46	98	673.829	117	375	759.813	188	1644	1437.590	259	2149	2451.050
47	99	674.087	118	453	793.431	189	1652	1442.320	260	2153	2455.170
48	101	674.603	119	475	801.365	190	1669	1469.280	261	2164	2466.560
49	104	675.378	120	484	804.654	191	1674	1472.360	262	2189	2492.850
50	105	675.637	121	497	809.451	192	1681	1476.700	263	2197	2501.380
51	108	676.415	122	528	821.112	193	1694	1484.830	264	2209	2514.280
52	110	676.935	123	587	844.206	194	1708	1493.680	265	2226	2532.780
53	111	677.195	124	672	871.524	195	1717	1499.430	266	2234	2541.570
54	113	677.716	125	787	917.569	196	1723	1503.280	267	2280	2561.870
55	116	678.499	126	791	919.010	197	1740	1514.310	268	2318	2601.270
56	117	678.760	127	843	938.183	198	1748	1519.550	269	2321	2604.430
57	123	680.333	128	870	948.465	199	1751	1521.530	270	2325	2608.660
58	124	680.596	129	914	965.722	200	1756	1524.830	271	2328	2611.840
59	128	681.650	130	950	979.428	201	1763	1542.940	272	2333	2617.160
60	129	681.914	131	1003	1001.700	202	1766	1544.980	273	2339	2623.570
61	138	689.689	132	1012	1005.580	203	1771	1548.380	274	2348	2633.250
62	139	689.960	133	1019	1008.620	204	1777	1552.480	275	2353	2638.660
63	144	691.318	134	1024	1010.800	205	1780	1554.540	276	2355	2640.830
64	145	691.590	135	1030	1013.430	206	1783	1556.600	277	2357	2643.010
65	150	692.955	136	1038	1016.960	207	1794	1564.220	278	2363	2649.550
66	151	693.229	137	1048	1021.400	208	1800	1568.400	279	2370	2657.230
67	156	694.600	138	1069	1030.860	209	1803	1570.500	280	2371	2658.320
68	157	694.875	139	1079	1035.420	210	1806	1572.600	281	2377	2664.950
69	159	695.426	140	1082	1036.800	211	1812	1576.830			
70	162	696.253	141	1083	1037.260	212	1826	1586.780			
71	165	697.083	142	1088	1039.560	213	1843	1599.020			

Table 2 Channel selection for each combinations

Channel set	Selected channels
S914	AIRS ch.914(965.722cm^{-1},10.35micron)
S2333	AIRS ch.2333(2617.16cm^{-1},3.82micron)
DBL	AIRS ch.914 and 2333
MIX	AIRS ch.787(917.569cm^{-1},10.90micron), 843(938.183cm^{-1},10.66 micron), 914,1221(1115.06cm^{-1},8.96micron), 1237(1123.55cm^{-1},8.90 micron), 2328 (2611.84cm^{-1},3.83micron), 2333
MIX + AMSU	MIX and AMSU ch.2(31.4GHz),3(50.3GHz),15(89.0GHz)

Table 3 Cloud detection results

Channel set	Threshold	Hit ratio (%)		
		Clear	Thin cloudy	Thick cloudy
S914	1.36	90.4	31.3	90.4
S2333	1.23	88.3	30.9	88.3
DBL	1.31	92.6	33.7	92.6
MIX	0.97	92.9	33.3	92.9
MIX + AMSU	0.93	95.1	37.8	95.1