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# *Numerical* Weather Prediction



Forecasting Research  
Technical Report No. 261

## **The Effect of Undetected Cloud on IASI Retrievals**

by

**A.D. Collard**

**March 1999**



**The Met.Office**

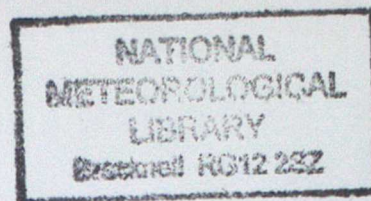
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# The Effect of Undetected Cloud on IASI Retrievals.

by A.D. Collard.

## Abstract.

In Technical Report 256 ("Notes on IASI Performance"), the performance of temperature and humidity retrievals using IASI observations in the clear sky case was investigated. It was shown that, for optimal estimation with a forecast *a priori* measurement, the measurement accuracy in the troposphere for temperature was around 0.6K and around 15% for absolute humidity, with averaging kernel widths of 2-3km and 1-2km for temperature and humidity respectively. These are all major improvements on the present generation of satellite sounding instruments.

In order to achieve these performances, one must be able to determine whether cloud is present in the field of view in order to reject the cloud-contaminated scenes or to somehow allow for the clouds' effect on the observed radiances. In both cases one should consider the effect of residual cloud in an assumed clear-sky or "cloud-cleared" observation. The retrieval error covariance may be affected not only by direct propagation of the increased observational error, but also by the difference between the assumed and actual observational error covariance matrix resulting in a non-optimal retrieval. Both of these effects are investigated in this report.

Given a reasonable estimate of the error covariance for the undetected cloud, the effect on the retrieval error covariance is small. However, large errors can arise when the undetected cloud error becomes significantly larger than the other observational errors and this error is not properly represented in the assumed observational error covariance matrix.



# The Effect of Undetected Cloud on IASI Retrievals.

A.D. Collard.

## Introduction.

This report investigates the effect of undetected cloud in the field of view of the IASI instrument on the retrieval of temperature and humidity fields. It is assumed that cloud detection algorithms will be in place that will be able to detect the majority of cloudy cases. Here we investigate the effect of those cases which are missed. It is anticipated that these will mostly be where high, thin ("sub-visual") cirrus or low, warm stratus is present.

The best estimate,  $\hat{\mathbf{x}}$ , of the atmospheric state,  $\mathbf{x}$ , given some observations,  $\mathbf{y}$ , and *a priori* measurements,  $\mathbf{x}_0$ , is in general found by minimising the cost function,  $J(\mathbf{x})$ , where

$$J(\mathbf{x}) = (\mathbf{x} - \mathbf{x}_0)\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}_0)^T + (\mathbf{y} - \mathbf{y}(\mathbf{x}))\mathbf{O}^{-1}(\mathbf{y} - \mathbf{y}(\mathbf{x}))^T \quad (1)$$

where the observations have error covariances  $\mathbf{O}$ ,  $\mathbf{B}$  is the error covariance matrix of the *a priori* measurements  $\mathbf{x}_0$ , and  $\mathbf{y}(\mathbf{x})$  is the observed radiance that would result for a given atmospheric state  $\mathbf{x}$ .

For weakly non-linear problems, the approximate solution and associated error covariance is given by the optimal estimation method of retrieval (Rodgers, 1976) where

$$\hat{\mathbf{x}} = (\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{O}^{-1}\mathbf{H})^{-1}(\mathbf{B}^{-1}\mathbf{x}_0 + \mathbf{H}^T\mathbf{O}^{-1}\mathbf{y}) \quad (2a)$$

and

$$\begin{aligned} \mathbf{A} &= (\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{O}^{-1}\mathbf{H})^{-1} \\ &= \mathbf{B} - \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{O})^{-1}\mathbf{H}\mathbf{B}. \end{aligned} \quad (2b)$$

Here,  $\mathbf{H} = \nabla_{\mathbf{x}}\mathbf{y}(\mathbf{x})$  is the matrix of instrument weighting functions.

The error covariance matrix  $\mathbf{O}$  (often expressed as  $\mathbf{O} + \mathbf{F}$ ) contains contributions due to instrument noise and forward model calculation error. In the latter one may include the error due to the presence of cloud in the field of view.

A complication in the investigation of IASI retrievals is that the  $\mathbf{O}$  matrix is 8461 elements square and thus has a total of 71,588,521 elements. This makes its manipulation unwieldy in many cases. If one can assume that the  $\mathbf{O}$  matrix is diagonal, however, the problems associated with inverting large matrices disappear.

In reality the  $\mathbf{O}$  matrix is not diagonal. The forward model errors are certainly correlated to some degree from channel to channel, while for an interferometer there will always be some channel-to-channel error correlations. However, the error term due to cloud contamination is investigated here since (as will be seen) it produces an extremely correlated error structure.

In this report we will investigate the effect on the retrievals of the inclusion of undetected cloud and the effect of assuming that the highly correlated cloud error covariance is diagonal. We will also investigate the additional errors in the retrievals that arise from assuming the wrong observational error covariance matrix. The theoretical basis for these latter calculations are outlined in the next section.



## Retrieval Errors Arising from the Wrong Choice of Error Covariance Matrix.

Watts and McNally (1988) showed that if a minimal variance retrieval is attempted where the true error covariances,  $\mathbf{O}'$  and  $\mathbf{B}'$ , are approximated by  $\mathbf{O}$  and  $\mathbf{B}$  respectively, the analysis error covariance can be derived as follows:

The linear minimum variance solution to the retrieval problem (Eqn. 2a) may be re-written as

$$\hat{\mathbf{x}} = \mathbf{x}_0 + \mathbf{W}(\mathbf{y} - \mathbf{y}_0) \quad (3a)$$

where

$$\mathbf{W} = \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{O})^{-1} \quad (3b)$$

and  $\mathbf{y}_0$  is the observation vector corresponding to the *a priori* state  $\mathbf{x}_0$ .

Here,  $\mathbf{H}$  is the Jacobian being assumed by the retrieval scheme. If the true Jacobian is  $\mathbf{H}'$  then  $\mathbf{y} - \mathbf{y}_0 = \mathbf{H}'(\mathbf{x}_T - \mathbf{x}_0)^*$  and

$$\hat{\mathbf{x}} - \mathbf{x}_0 = \mathbf{W}\mathbf{H}'(\mathbf{x}_T - \mathbf{x}_0) + \mathbf{W}\epsilon_y \quad (4)$$

where  $\epsilon_y$  is the measurement and forward model error.

From this it can be seen that the resolution matrix or averaging kernel,  $\mathbf{W}\mathbf{H}'$ , (Rodgers, 1976; Menke, 1984; Collard, 1998) depends on the *assumed* observational and background error covariances rather than the true values. The changes in the characteristics of the retrieval on using the wrong input error covariances therefore only manifest themselves in the noise levels and bias, not the resolution.

Rearranging Eqn. 4 gives

$$\hat{\mathbf{x}} - \mathbf{x}_T = (\mathbf{I} - \mathbf{W}\mathbf{H}')(\mathbf{x}_0 - \mathbf{x}_T) + \mathbf{W}\epsilon_y \quad (5)$$

As the true analysis error covariance matrix,  $\mathbf{A}' = E[(\hat{\mathbf{x}} - \mathbf{x}_T)(\hat{\mathbf{x}} - \mathbf{x}_T)^T]$ ,  $\mathbf{O}' = E[\epsilon_y\epsilon_y^T]$ , and  $\mathbf{B}' = E[(\mathbf{x}_0 - \mathbf{x}_T)(\mathbf{x}_0 - \mathbf{x}_T)^T]$ , and assuming background and observational errors are uncorrelated,

$$\begin{aligned} \mathbf{A}' &= (\mathbf{I} - \mathbf{W}\mathbf{H}')\mathbf{B}'(\mathbf{I} - \mathbf{W}\mathbf{H}')^T + \mathbf{W}\mathbf{O}'\mathbf{W}^T \\ &= \mathbf{B}' - \mathbf{W}\mathbf{H}'\mathbf{B}' - \mathbf{B}'(\mathbf{W}\mathbf{H}')^T + \mathbf{W}\mathbf{H}'\mathbf{B}'(\mathbf{W}\mathbf{H}')^T + \mathbf{W}\mathbf{O}'\mathbf{W}^T \\ &= \mathbf{B}' - \mathbf{W}\mathbf{H}'\mathbf{B}' - (\mathbf{W}\mathbf{H}'\mathbf{B}')^T + \mathbf{W}(\mathbf{H}'\mathbf{B}'\mathbf{H}'^T + \mathbf{O}')\mathbf{W}^T \end{aligned} \quad (6)$$

When  $\mathbf{O}' = \mathbf{O}$ ,  $\mathbf{B}' = \mathbf{B}$  and  $\mathbf{H}' = \mathbf{H}$  this reduces to Eqn. 2b.

In this work, only the effect of using the incorrect observational error covariance is being explored, therefore Eqn. 6 becomes.

$$\begin{aligned} \mathbf{A}' &= \mathbf{B} - \mathbf{W}\mathbf{H}\mathbf{B} - (\mathbf{W}\mathbf{H}\mathbf{B})^T + \mathbf{W}(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{O}')\mathbf{W}^T \\ &= \mathbf{B} - \mathbf{W}\mathbf{H}\mathbf{B} - (\mathbf{W}\mathbf{H}\mathbf{B})^T + \mathbf{W}(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{O})\mathbf{W}^T - \mathbf{W}\mathbf{O}\mathbf{W}^T + \mathbf{W}\mathbf{O}'\mathbf{W}^T \\ &= \mathbf{A} + \mathbf{W}(\mathbf{O}' - \mathbf{O})\mathbf{W}^T \end{aligned} \quad (7)$$

\* In fact  $\mathbf{y} - \mathbf{y}_0 = \mathbf{H}'\mathbf{x}_T - \mathbf{H}\mathbf{x}_0 = \mathbf{H}'(\mathbf{x}_T - \mathbf{x}_0) + (\mathbf{H}' - \mathbf{H})\mathbf{x}_0$ . In the purely linear case, the extra term will produce only a bias in  $\hat{\mathbf{x}}$  but when the problem is non-linear this will result in extra terms in the covariance of  $\hat{\mathbf{x}}$  also. This should be allowed for as part of the forward model error covariance matrix.



Eqn. 7 is used in the discussions to follow.

Rodgers (1990) pointed out that the analysis error covariance,  $\mathbf{A}$ , can be thought of as the sum of two error covariances,  $\mathbf{A}_N$  and  $\mathbf{A}_M$  corresponding to the contributions from the null-space and measurement errors respectively ( $\mathbf{A}_M$  is hereinafter referred to as the "propagated measurement error") and are given by

$$\mathbf{A}_N = (\mathbf{W}\mathbf{H} - \mathbf{I})\mathbf{B}(\mathbf{W}\mathbf{H} - \mathbf{I})^T \quad (8a)$$

and

$$\mathbf{A}_M = \mathbf{W}\mathbf{O}\mathbf{W}^T. \quad (8b)$$

Thus the effect of choosing the wrong  $\mathbf{O}$  matrix on the retrieval accuracy is seen (from Eqns. 8) through the propagated measurement error while the null-space error is unchanged.

### Constructing the Cloud Error Covariance Matrix.

For this study one needs to construct a reasonable cloud error covariance matrix. To do this a set of brightness temperature spectra are produced for various cloudy scenarios using a doubling model (Wiscombe 1976a,b) with clear sky radiances supplied by the IASI fastmodel being developed by Marco Matricardi at ECMWF. This doubling model has been used in previous investigations of cloud radiative properties with the University of Wisconsin's High Spectral Resolution Interferometer Sounder (HIS) (Collard *et al.*, 1995).

Calculations were made for two types of cloud — a high cirrus at 10km altitude and a low stratus at 200m altitude. In both cases the radiative properties of the cloud cloud particles are modelled with Mie theory (Mie, 1908) and the clouds were assumed to be thin and homogeneous. The cirrus cloud particles are assumed to be ice spheres with an effective radius of either 15 $\mu\text{m}$  or 50 $\mu\text{m}$  while the stratus cloud is made up of liquid water spheres with an effective radius of 5 $\mu\text{m}$  or 50 $\mu\text{m}$ .

A set of spectra are calculated for the two different cloud heights, the four cloud sizes and for a range of ice water paths. The ice water paths (IWP) that are used range from 0.001 to 100 $\text{gm}^{-3}$  with two calculations per decade of IWP. Only clouds that result in a maximum brightness temperature difference of less than 1K relative to the clear sky case are included in the next step. This is because it is expected that clouds with relatively high radiometric signals are likely to be detected and allowed for in the retrieval process (either by ignoring the observation all together, attempting some form of cloud-clearing or simultaneously retrieving temperature, humidity and those cloud properties that would affect the retrieval of the clear sky parameters) and only the clouds with relatively small signals will directly affect the clear-sky retrieval statistics.

The error covariance matrix for undetected cloud is then calculated via the relation

$$\mathbf{S}_{\text{cloud}} = \frac{1}{n} \sum (\mathbf{I}_i - \bar{\mathbf{I}})(\mathbf{I}_i - \bar{\mathbf{I}})^T \quad (9)$$

where  $\mathbf{I}_i$  is the array of brightness temperatures for the  $i^{\text{th}}$  spectrum and  $\bar{\mathbf{I}}$  is the mean brightness temperature spectrum for all  $n$  spectra considered. The deviation of the mean cloudy brightness temperature spectrum,  $\bar{\mathbf{I}}$ , from the clear sky case would in practice manifest itself as an extra term in the bias correction.

The cloud error covariance matrix produced contains many approximations, the most important ones being:



- The cloud scenarios chosen are somewhat arbitrary. A much more detailed study involving examination of the frequency of different cloud types that are not detected by the — as yet undefined — IASI cloud detection algorithms would be required to get this entirely correct.
- Mie scattering is applicable to spherical particles only and hence is only an approximation when dealing with cirrus clouds composed of ice crystals.
- The distribution of calculated spectra is not Gaussian (as cloud normally reduces the observed radiance).

However, to investigate the gross properties of the effect of the off-diagonal elements of the observation error covariance matrix, the cloud error covariance described above is deemed adequate.

The resulting cloud error covariance matrix and its associated correlation matrix are shown in Figures 1 and 2. Figure 3a shows the diagonal of this cloud observational error covariance matrix compared to the other IASI noise sources and Figure 3b shows how the diagonals of this matrix change when only high cirrus and only low stratus clouds are considered.

### Exploration of Retrieval Properties.

In this study we shall explore the errors on the retrieved profiles via the parameters identified in Collard (1998). These are:

- 1) The diagonals of the analysis error covariance matrix,  $\mathbf{A}$ .
- 2) The vertical resolution derived from the resolution matrix,  $\mathbf{R} = \mathbf{I} - \mathbf{AB}^{-1}$ , using the Purser and Huang (1993) definition where the vertical resolution is  $dz(i)/\mathbf{R}(i,i)$  with  $dz(i)$  being the height interval at level  $i$ .
- 3) The number of degrees of freedom for signal (DFS) in the retrieval which is given by the trace of the resolution matrix and is hence closely related to the resolution.
- 4) The information content of the retrievals  $\mathbf{S}$  given by  $-0.5 \ln |\mathbf{AB}^{-1}|$ .\*

As with the previous study, the calculations are done for a mid-latitude winter scenario. The Jacobians are calculated using the IASI fastmodel being developed by Marco Matricardi at ECMWF and the ECWMF 40-level forecast error covariance matrix is used for  $\mathbf{B}$  after interpolation to the 43 levels used by the fastmodel.

The total instrument noise is made up of diagonal terms due to the “Cannes” specification instrument noise and the forward model error of 0.2K plus the cloud error covariance matrix calculated above.

In order to simplify these comparisons we shall look at a subset of the total number of instrument channels so that the inversion of the  $\mathbf{O}$  matrix can be achieved without the need for special inversion routines. To this end, 2000 of the 8461 channels (every fourth channel between  $645\text{cm}^{-1}$  and  $2645\text{cm}^{-1}$ ) have been picked out for this study. The rationale for this is that, as the spectral resolution of the instrument is not changed but only the sampling rate, the behaviour of the retrieval error covariances will be unchanged apart from a small reduction in the absolute value of the retrieval accuracy due to the reduced number

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\* This was not used in Collard (1998). It is discussed in Rodgers (1976).



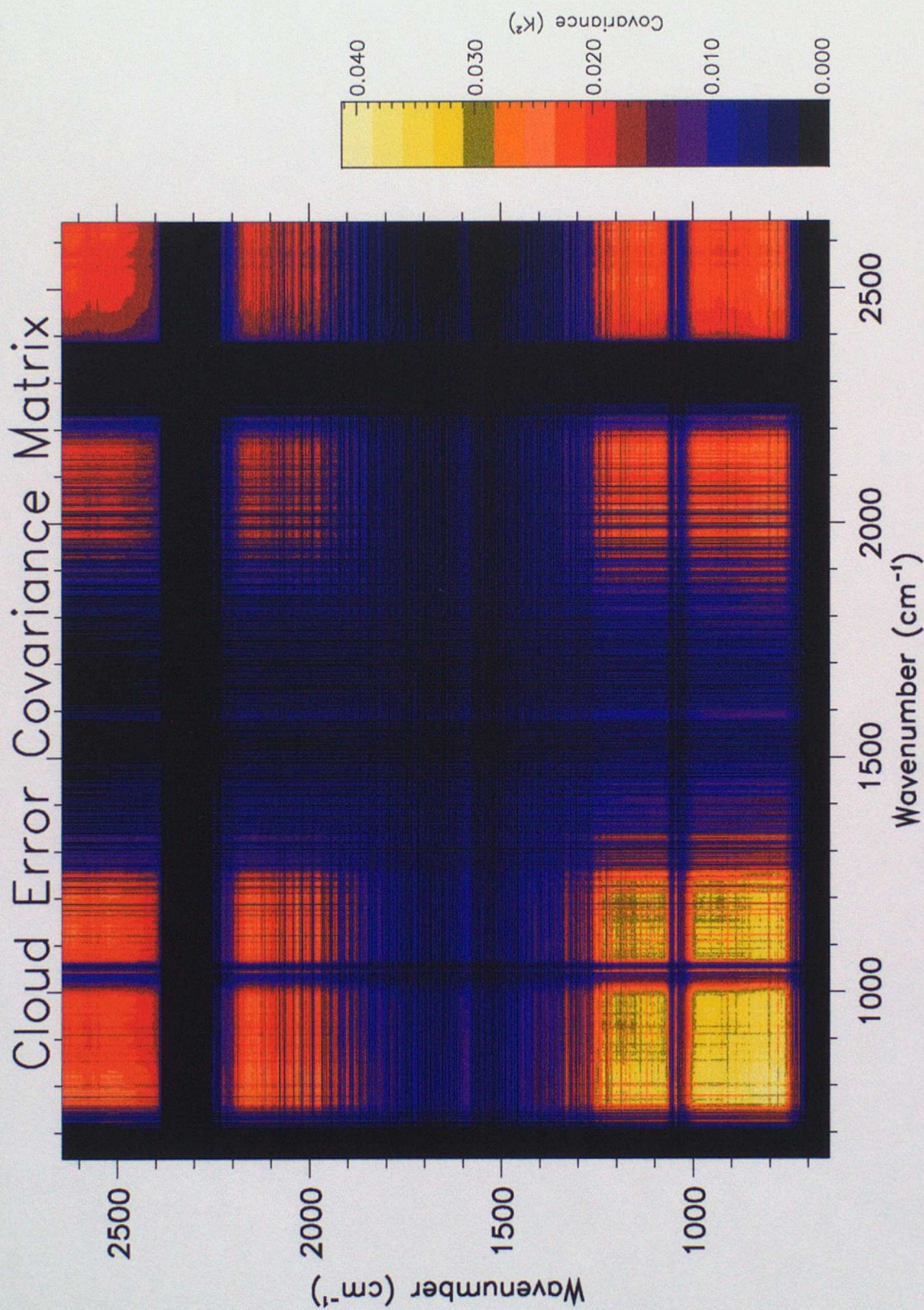


Fig. 1. A simulated observational error covariance matrix due to the presence of undetected cloud. The relatively high error covariances in the window regions and the low covariances in the absorption bands due to  $\text{CO}_2$ ,  $\text{H}_2\text{O}$  and  $\text{O}_3$  can be seen clearly.



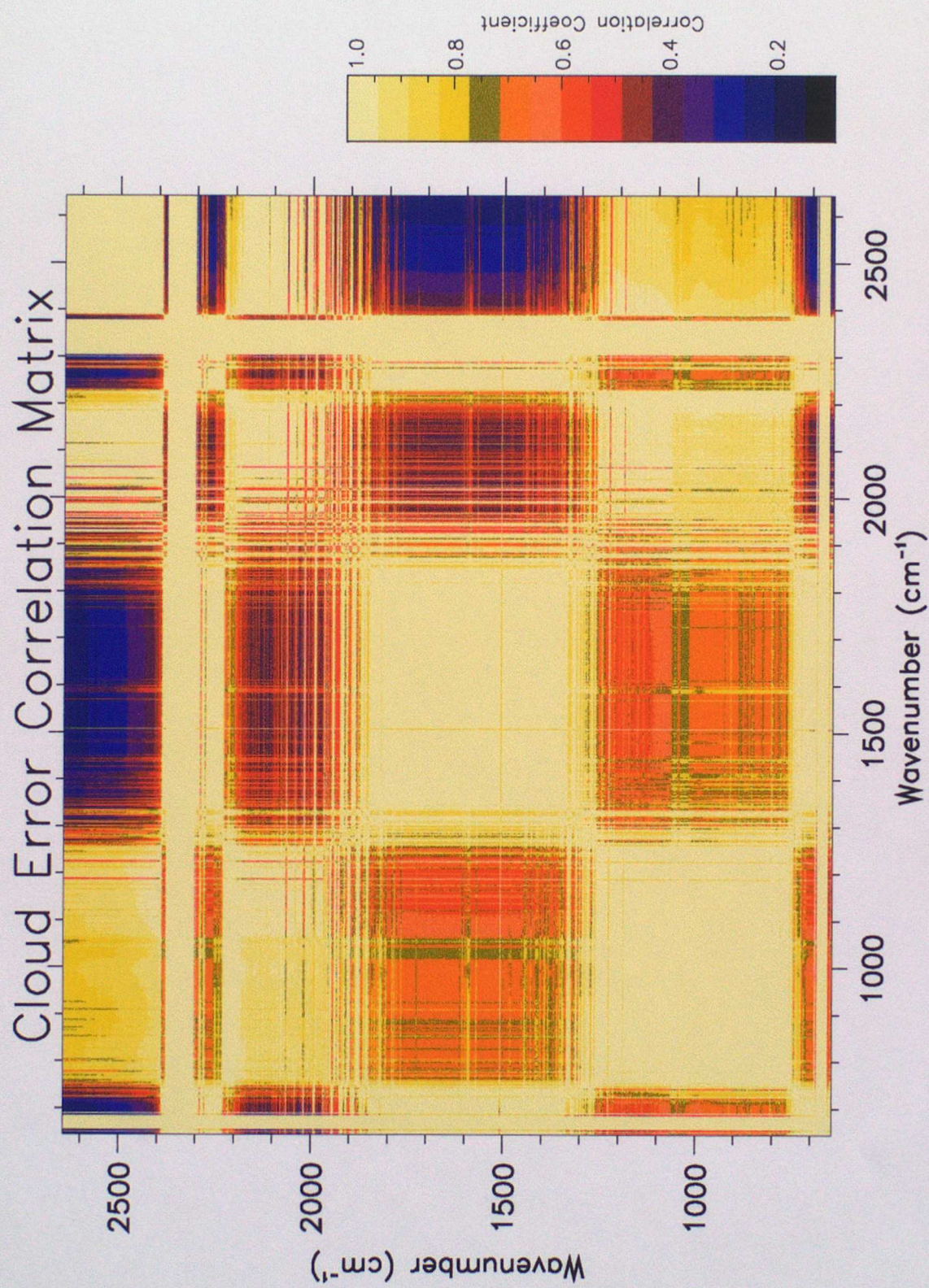


Fig. 2. The correlation matrix corresponding to the error covariance matrix shown in Fig. 1.



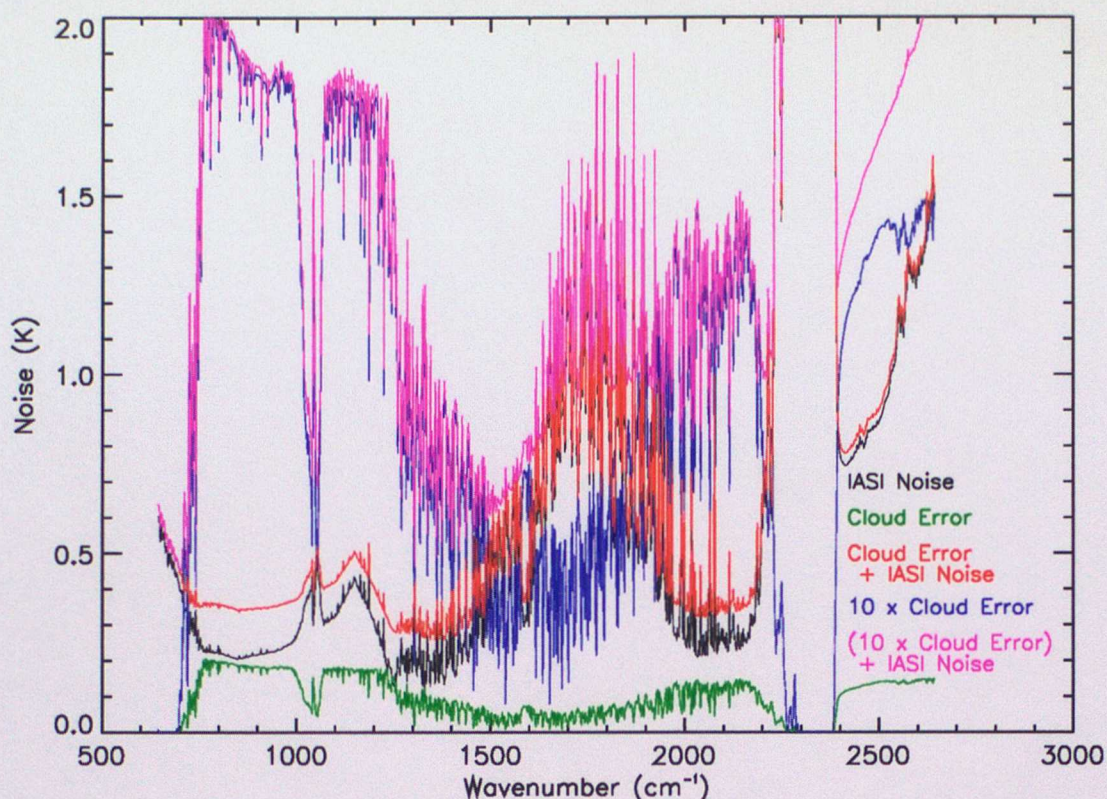


Fig. 3a. The diagonal elements of the cloud error covariance of Figure 1 and the non-cloud forward model error. Examples with no cloud, the default cloud error covariance and the default cloud error covariance multiplied by 100 (standard deviation times 10) added to the forward model are shown illustrating the situations being explored in this report.

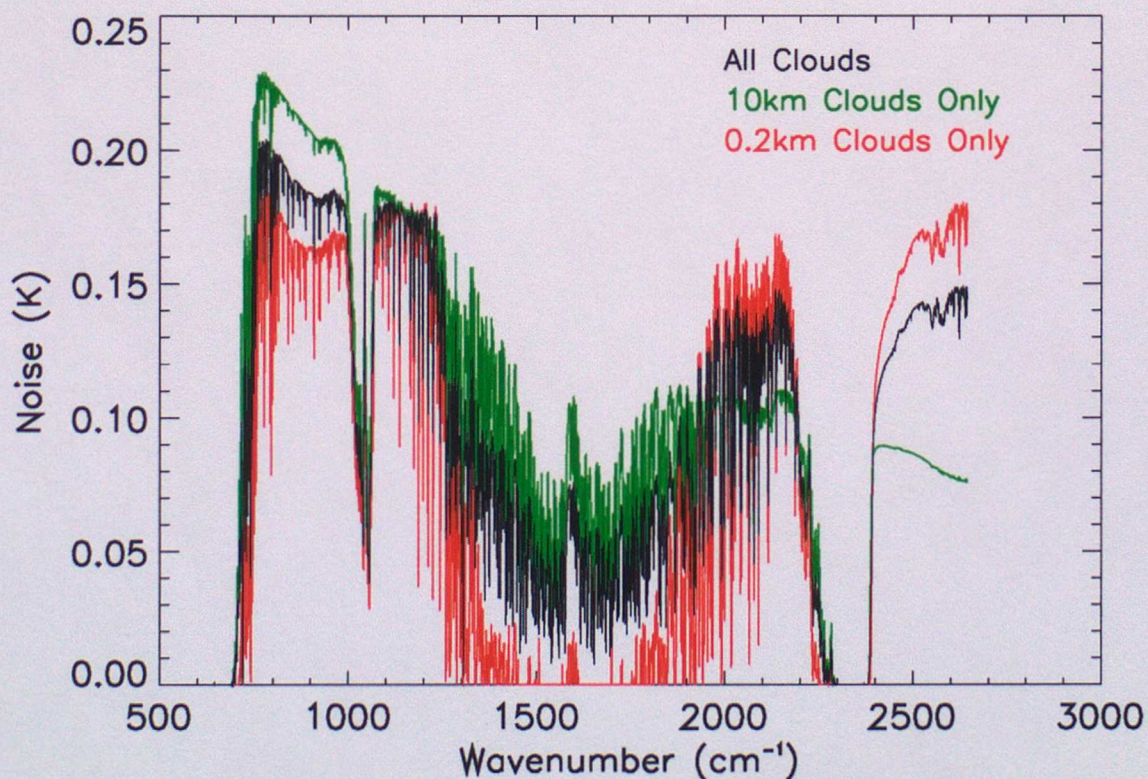
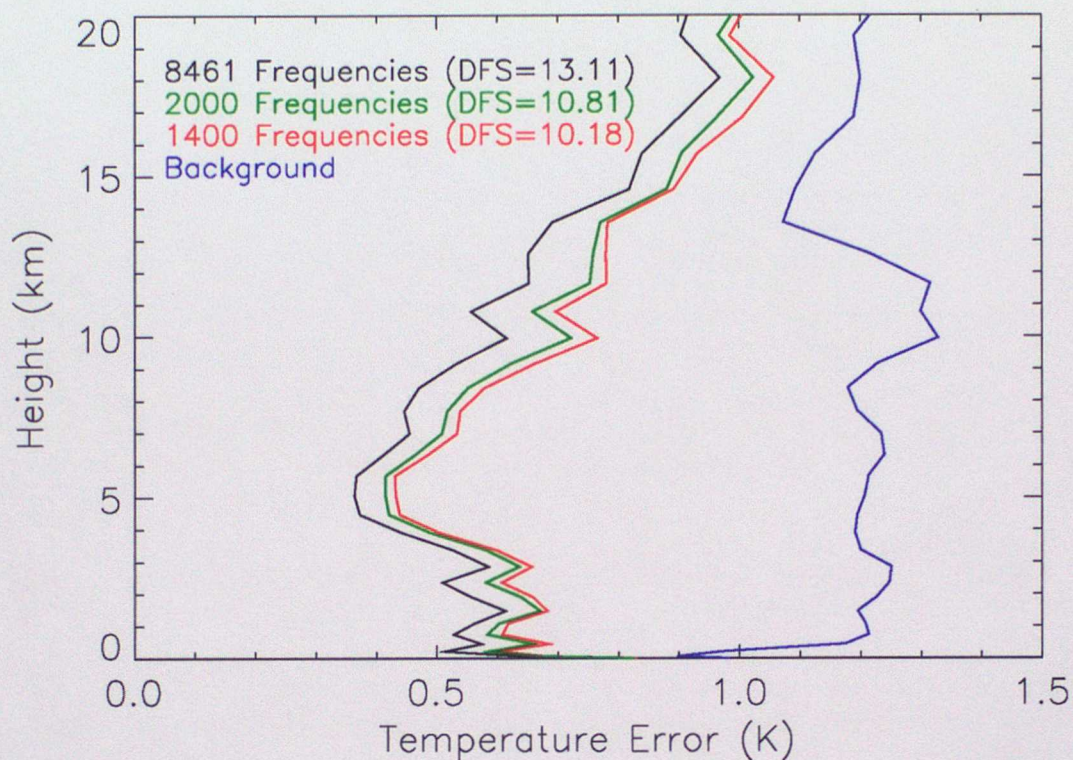


Fig. 3b. The diagonal elements of the cloud error covariance of Figure 1 compared to the diagonal elements of similar matrices where only cirrus clouds at 10km altitude and only stratus clouds at 0.2km altitude are considered.



of channels. Hence we will be looking at the relative impact of the cloud error covariance rather than absolute values.

Figure 4 shows how the retrieval accuracies are degraded by this sub-sampling.



*Fig. 4. IASI temperature retrieval accuracies using all channels and reduced sampling. In all cases the instrument spectral response function width remains at  $0.5\text{cm}^{-1}$ .*



## Effect of Cloud on Retrieval Accuracy.

Figure 5 shows the relative retrieval accuracies expected on doing a retrieval in the presence of uncleared cloud and Figure 6 shows the associated vertical resolution. In this case it is assumed that we have specified the cloud contribution to the observational error correctly in the **O** matrix. Results are shown for no cloud error, the cloud error covariance calculated above, and the same cloud error covariance multiplied by a factor of one hundred (i.e., standard deviation multiplied by ten). Also, for the cloudy cases, calculations using the full cloud error covariance matrix and just the diagonal elements are presented.

The effect of adding the default cloud error covariance contribution is relatively small, especially if the covariance matrix is assumed to be diagonal. The main difference between the results from the diagonal and full matrices is in the retrieval accuracy of the surface temperature. When it is assumed that there are no channel-to-channel correlations in the observational error, the large number of observations in the window channels result in the predicted error in surface temperature being very low (in this case approximately 0.02K). When the full cloud error covariance matrix is assumed, the inter-channel correlations are such that the number of independent observations of the surface temperature is greatly decreased and the error in the retrieved surface temperature is increased six-fold. As when the full covariance matrix is used, the optimal retrieval is weighted less towards retrieval of surface temperature, there is a small improvement in the accuracy of both temperature and humidity retrievals in the lowest few layers of the atmosphere in this case.

When the higher cloud error covariance is assumed, the situation is similar but more extreme. If the cloud error covariance is truly diagonal, the effect on the retrieval accuracy and resolution is seen to be significant ( $\sim 0.1K$  in lower tropospheric temperature). When the full error covariance is used, once again the surface temperature retrieval accuracy is predicted to be much worse, but the errors associated with the lower atmospheric levels are much closer to the cloud-free case (although the vertical resolution of humidity retrievals in the lowest 1km of the atmosphere are still degraded by 1km to 3km).

Inspection of the information content and DFS figures for these retrievals emphasise the conclusions drawn above. The information content is, of course, degraded relative to the cloud-free case when the extra cloud error term is introduced. For the default cloud error covariance matrix, the overly optimistic surface temperature retrieval for the diagonal matrix results in both the information content and degrees of freedom for signal being higher than for the retrieval using the full matrix. When the cloud error covariance matrices are increased one-hundredfold, however, the unrealistic weighting given to the surface temperature retrieval detrimentally affects the rest of the retrieval to the extent that both the information content and DFS are degraded for the diagonal relative to the full matrix.

Figures 7 and 8 are similar to Figure 5 except the expected retrieval accuracies shown are for the cases when the undetected cloud is purely high (10km) cirrus or purely low (0.2km) stratus. The results are not dissimilar to those in Figure 5. It can be seen, however, that the retrieval errors arising from undetected cirrus are spread out over a larger range of altitudes than those from undetected stratus which tend to be confined to the lowest few kilometres.

Of course, in reality the cloud error covariance will never be uncorrelated between IASI channels. If the retrieval is truly optimal these results indicate that the effect of undetected cloud on retrieval accuracy may be minor. However, correctly specifying the observational and forward model error covariances so that the retrieval is optimal may be problematic or even undesirable (due to the problems of inverting the full 71,588,521 element **O** matrix).



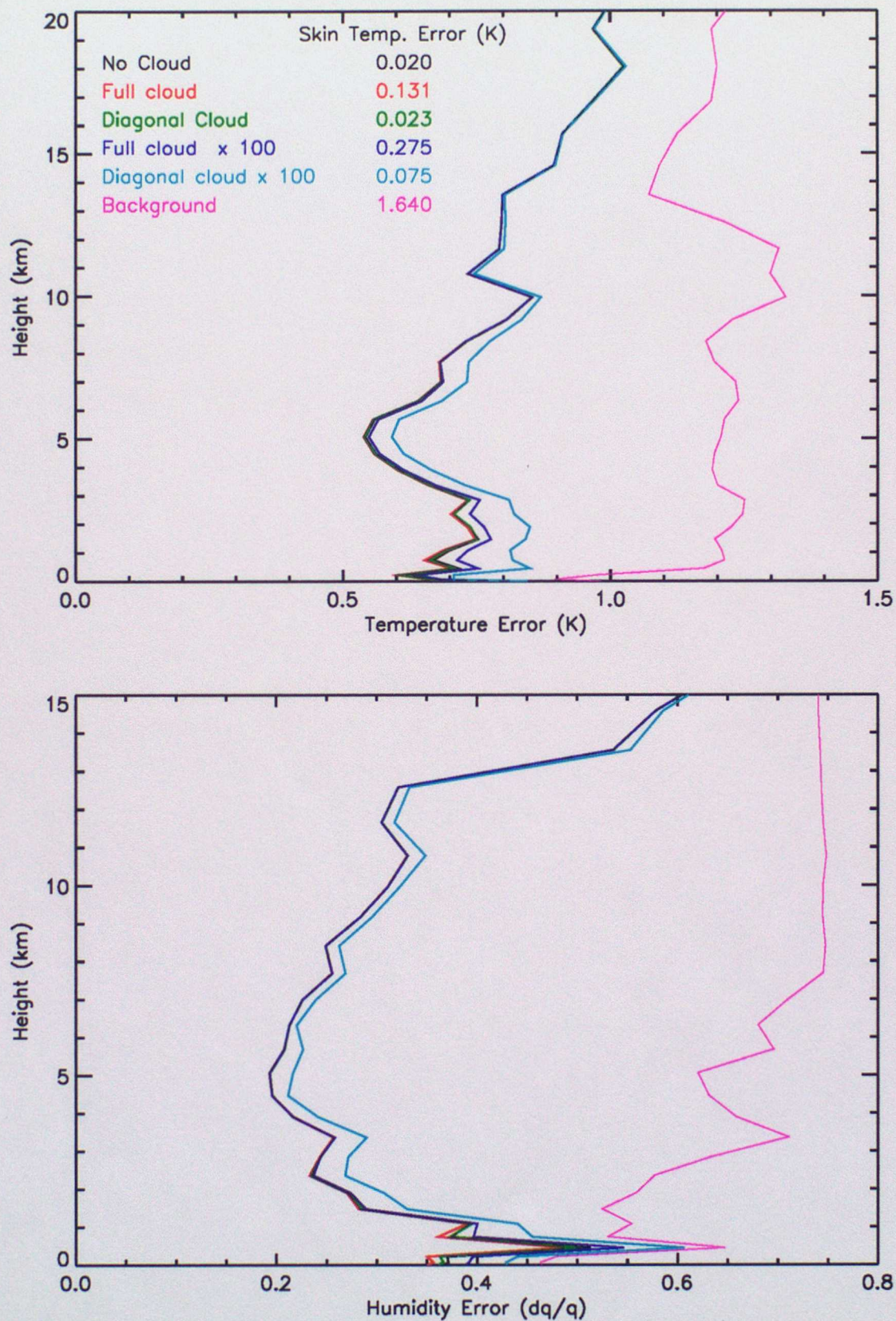


Fig. 5. IASI retrieval accuracies using 2000 channels and various assumed cloud error covariances. See text for details.



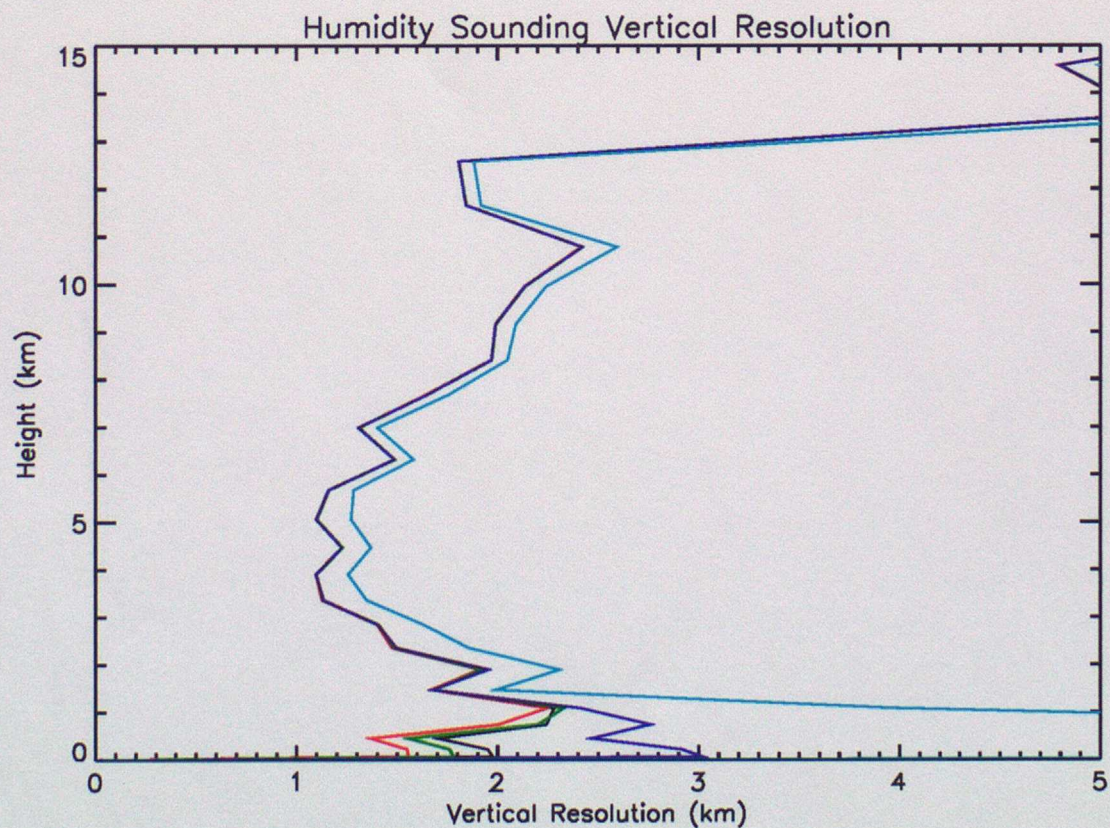
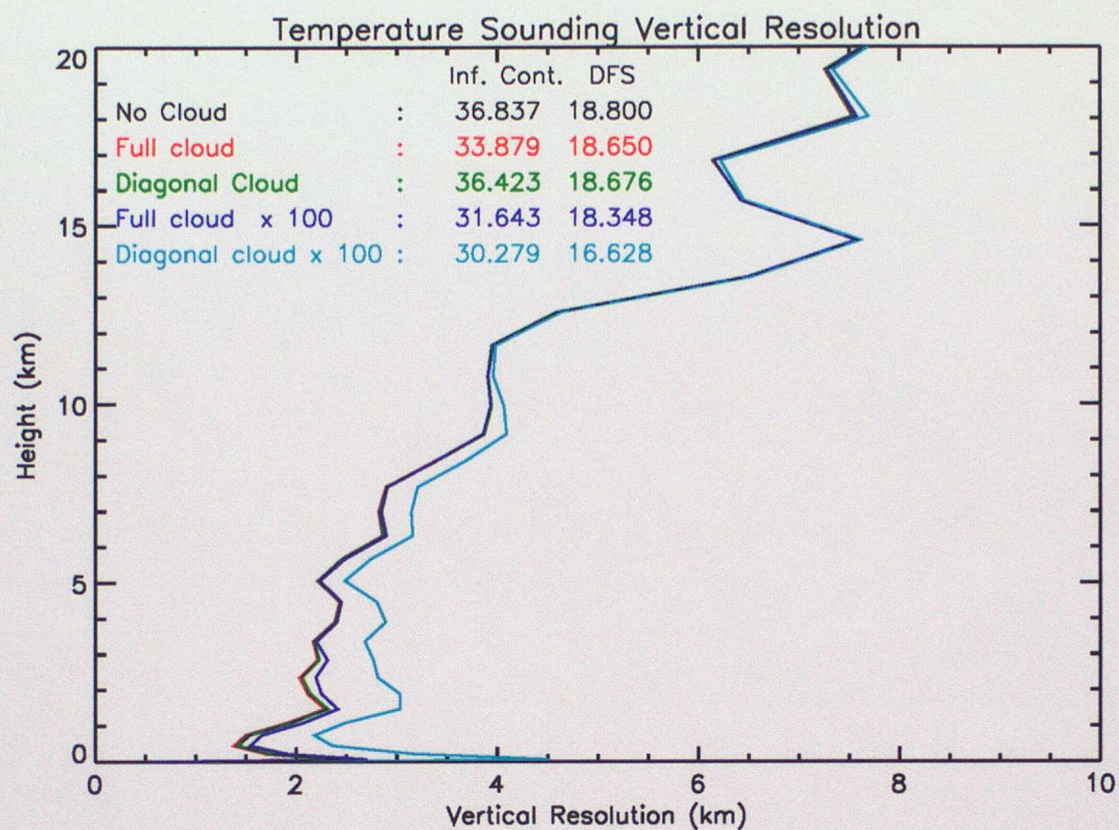


Fig. 6. IASI retrieval vertical resolution using 2000 channels and various assumed cloud error covariances. See text for details.



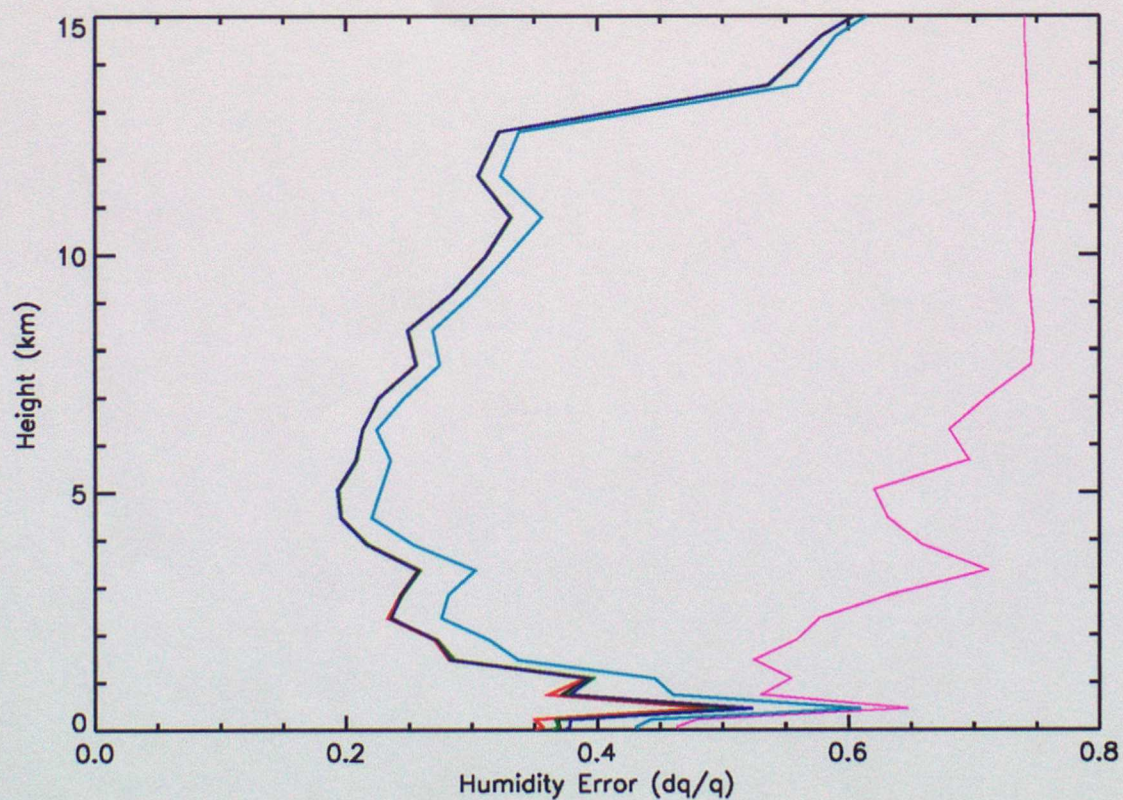
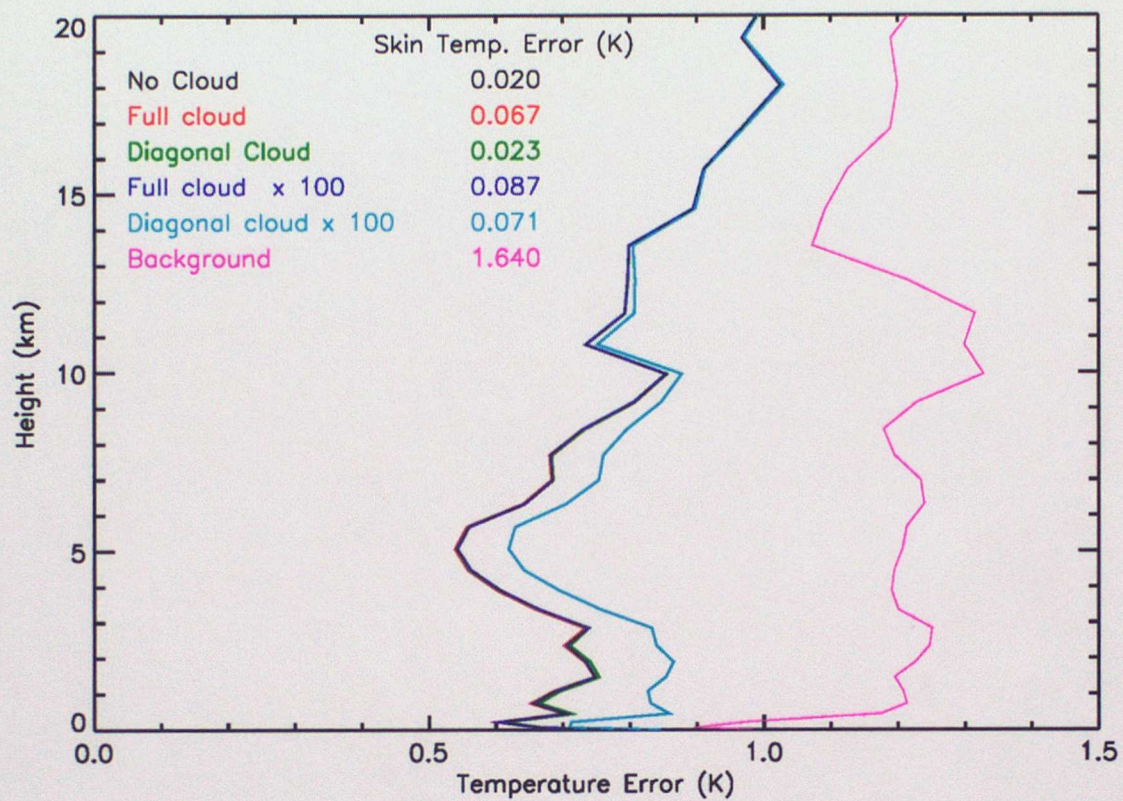


Fig. 7. As Figure 5 except only the effect of high cirrus is considered.



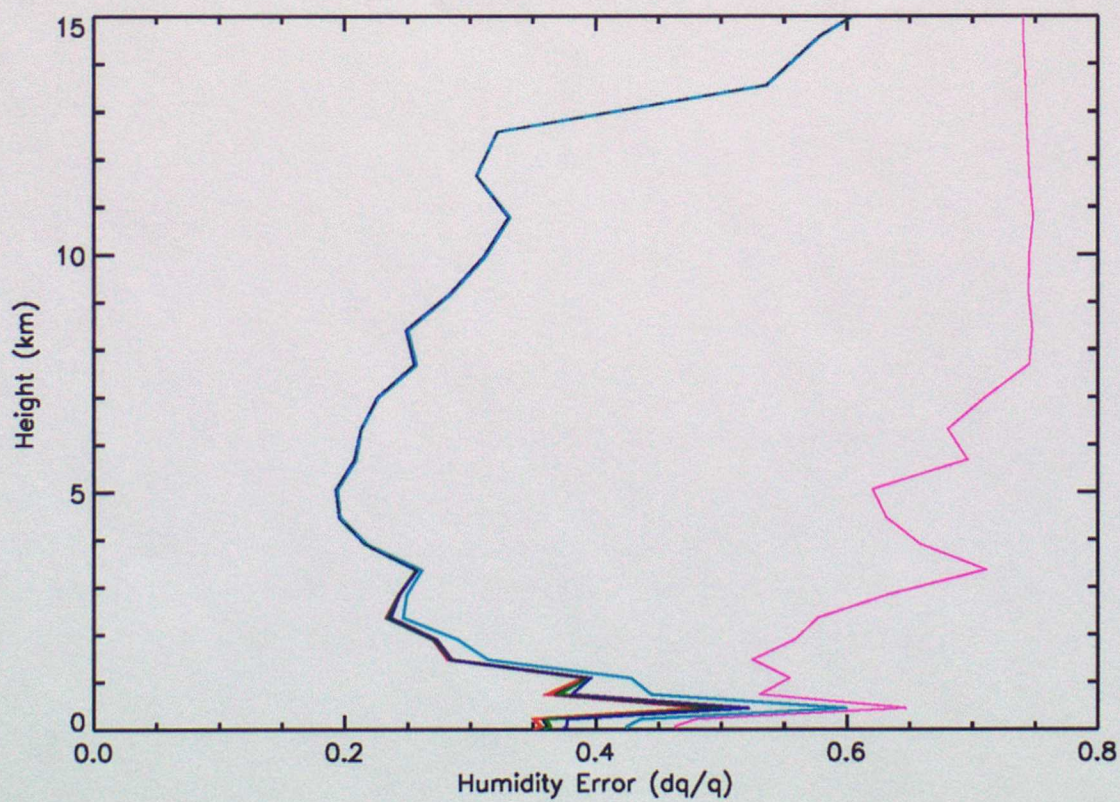
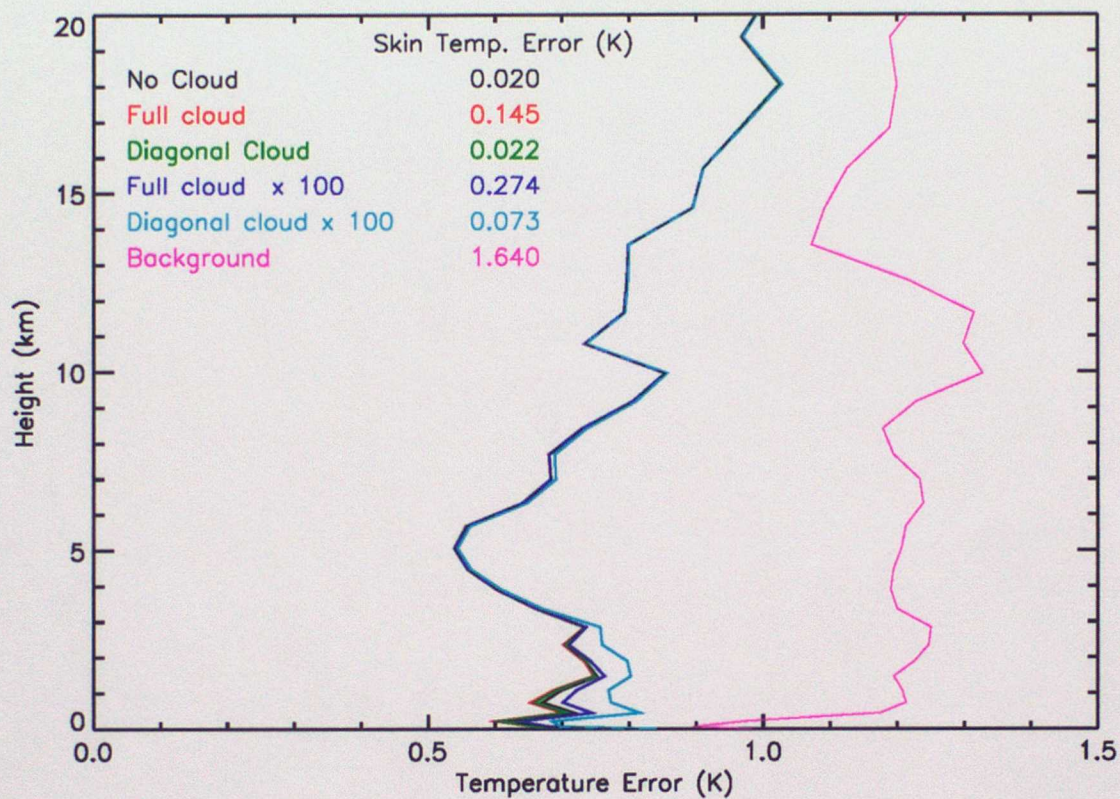


Fig. 8. As Figure 5 except only the effect of low stratus is considered.



Therefore in the next section the issue of retrievals using an incorrect error covariance matrix is explored.

### **Effect of Assuming an Incorrect Observational Error Covariance on Retrieval Accuracy.**

In Figures 9a and 9b the effect of assuming the incorrect cloud error covariance in the retrieval process as given by Eqn. 7 are shown. As stated above, the resolution matrix for the retrieval is a function of the *assumed* error covariance matrices only and so are not considered in this section.

Figure 9a shows the case where the true observations' error characteristics include the "default" cloud error covariance of Figure 1. The true analysis error covariances are shown for cases where the assumed cloud error covariance is either the same as reality; just the diagonals of the true error covariance; and where no account is taken of the cloud error covariance.

The results are quite encouraging. Except for humidity retrievals in the lowest kilometre, the retrieval accuracy is largely unaffected by the assumption of a diagonal cloud error covariance matrix and the impact of ignoring this error source altogether is only about 0.05K for temperature retrievals.

However, when the effect of cloud is multiplied tenfold (covariance times 100) as in Figure 9b the situation is much less encouraging. The errors introduced due to using an inappropriate observational error covariance can be very large and even exceed the original background errors at some levels. Even specifying the true observational error covariance as a diagonal matrix introduces these large additional errors. Clearly if retrievals are to be attempted in the presence of cloud, the error characteristics of the cloud detection algorithm must be explored in order to ensure an optimal retrieval.

Figures 10a/b and 11a/b are similar to Figures 9a/b except the cloud error covariances being considered are for high cirrus and low stratus cloud respectively. It can be seen that uncertainty in the radiative effects of both high and low cloud affects the final analysis error covariance matrix.

Finally, Figures 12a/b show the situations displayed in Figures 8a/b decomposed into the contributions from propagated measurement and null-space error. It can be seen that in the case where the assumed measurement error covariance accurately describes the real situation, the null-space error (i.e., the effect of structures that the instrument cannot see) is the major contributing factor to the analysis error covariance matrix. However, when the assumed  $\mathbf{O}$  matrix (and hence  $\mathbf{W}$ ) is not appropriate, its effect is seen in a large amplification of the measurement noise. This is a manifestation of the contribution function,  $\mathbf{W}$ , amplifying noisy components of the observations as the assumed  $\mathbf{O}$  matrix erroneously indicated that these components contained useful information.



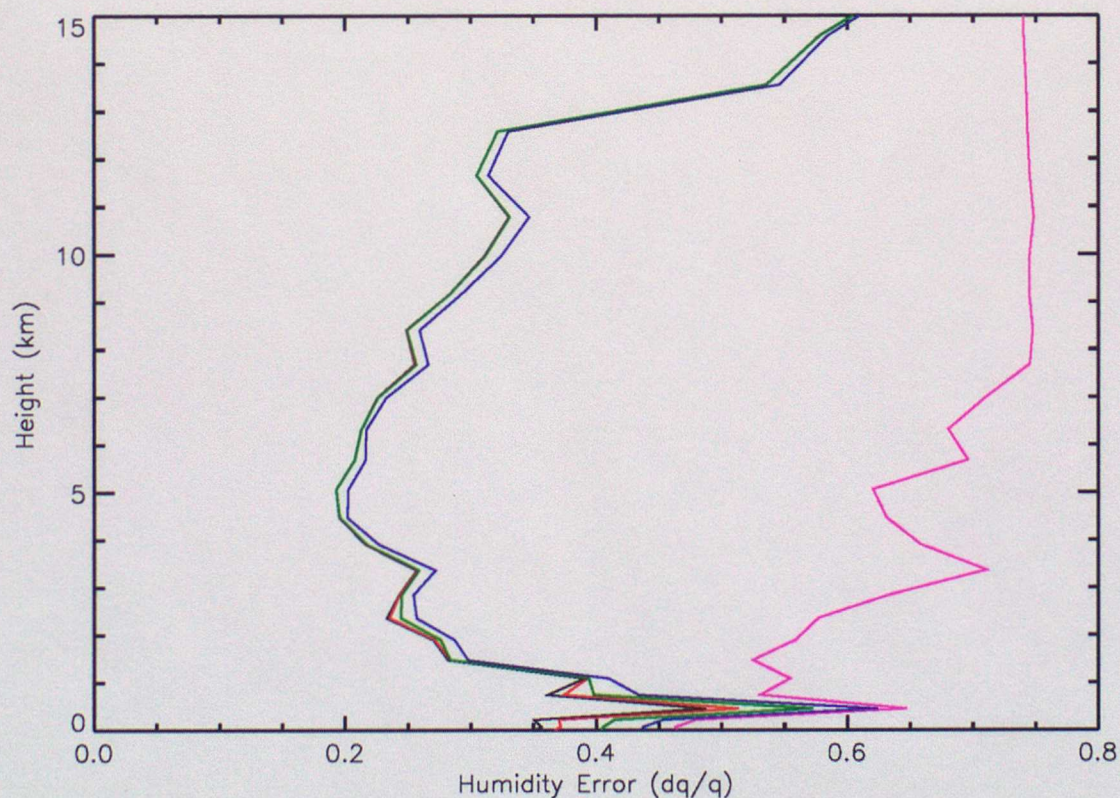
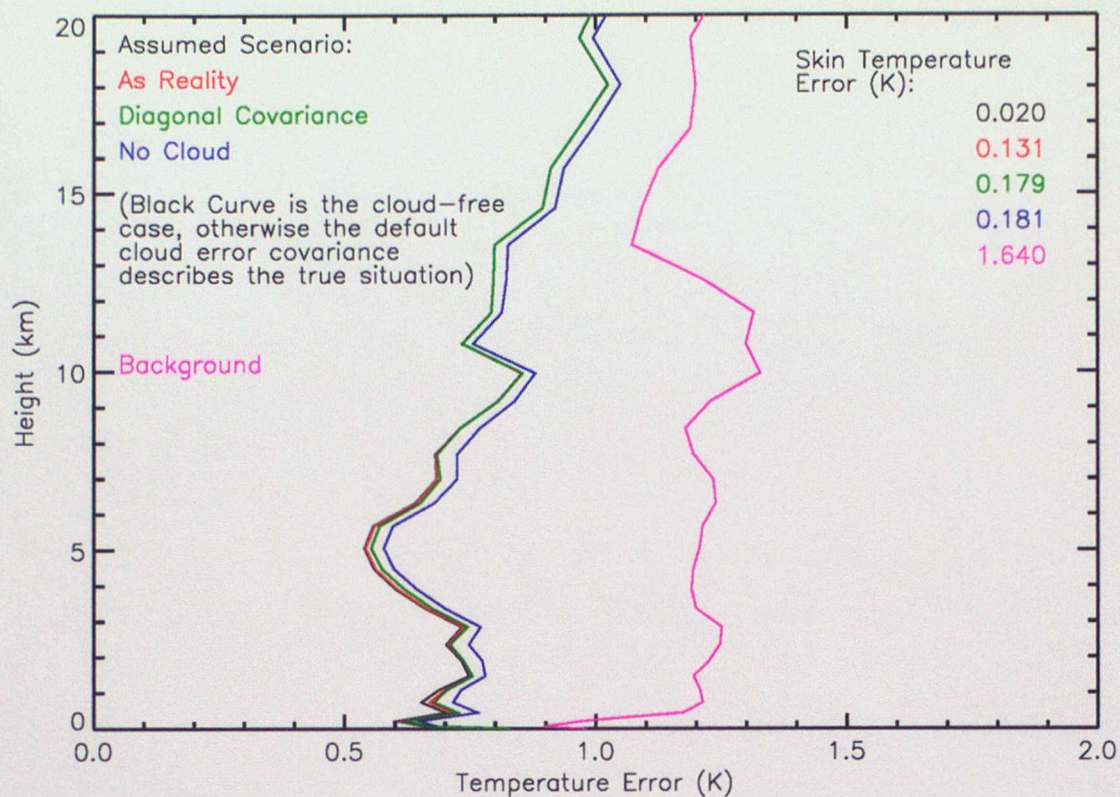


Fig. 9a. IASI retrieval accuracies using 2000 channels where the true observational error covariance is described by the full error covariance matrix shown in Figure 1. Retrieval accuracies when the assumed observational error covariance is the same as the truth, is just the diagonal elements of the truth and omits the errors due to cloud entirely are shown.



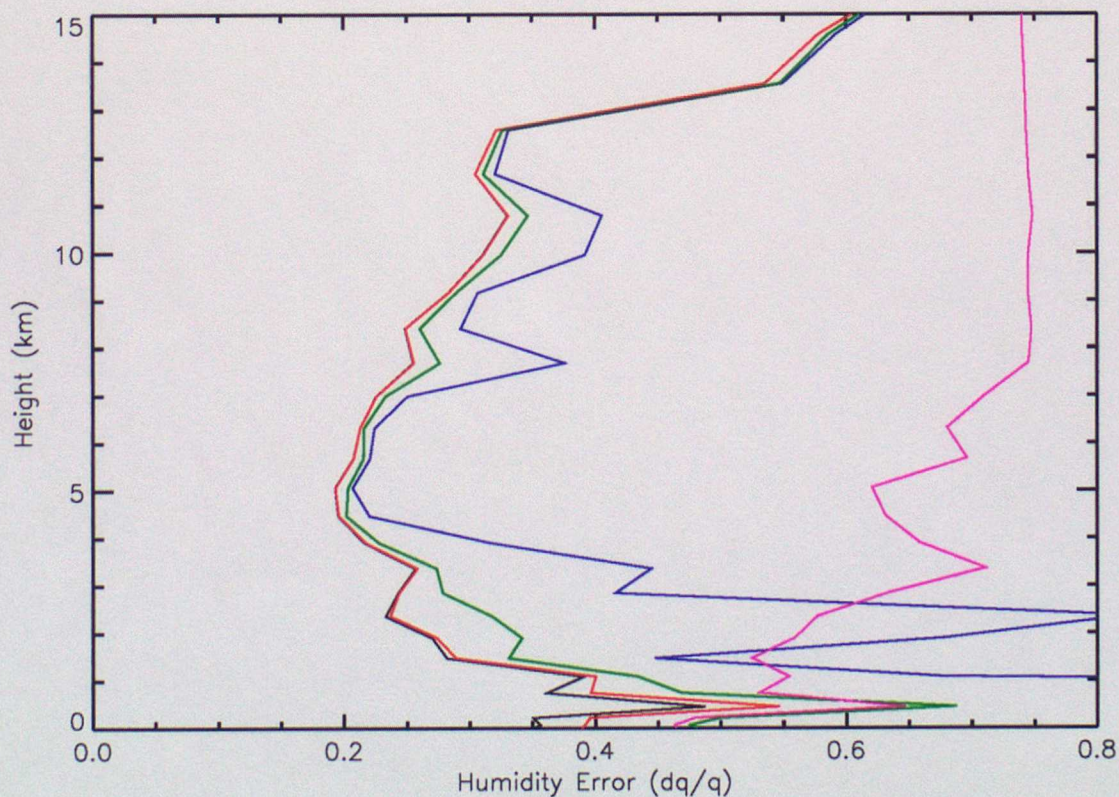
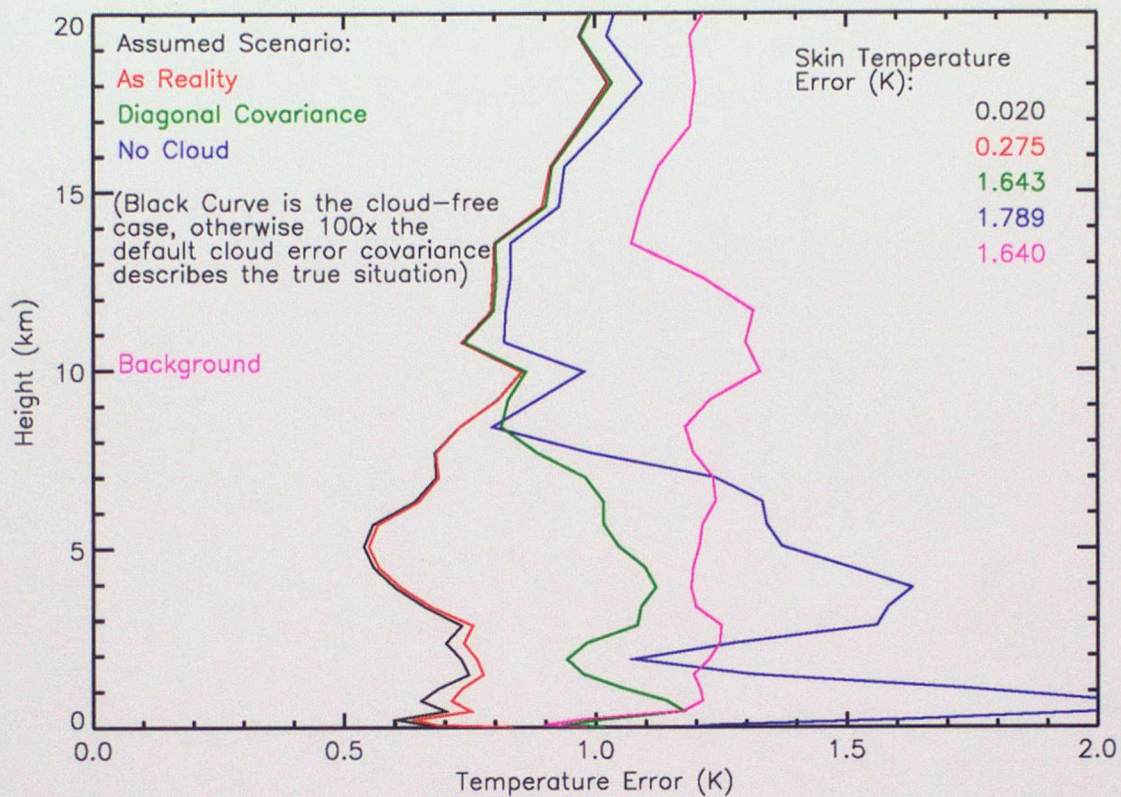


Fig. 9b. As figure 8a except the cloudy error covariance is multiplied by a factor of one hundred.



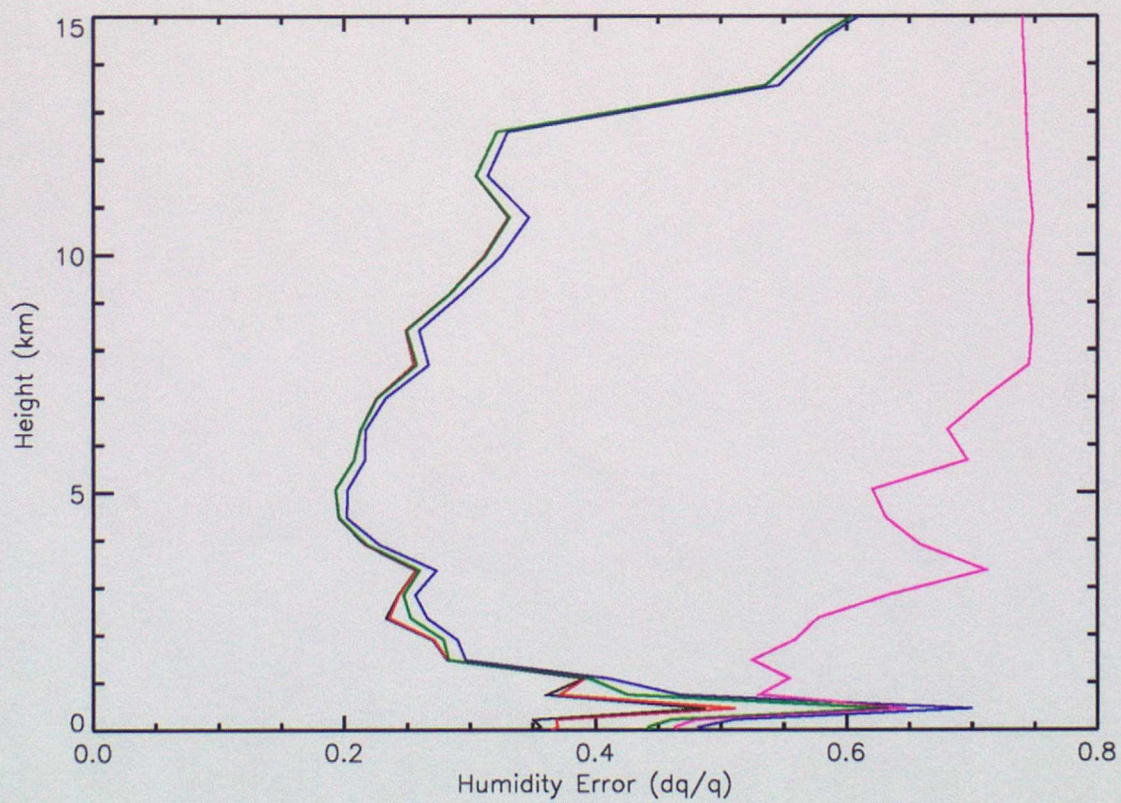
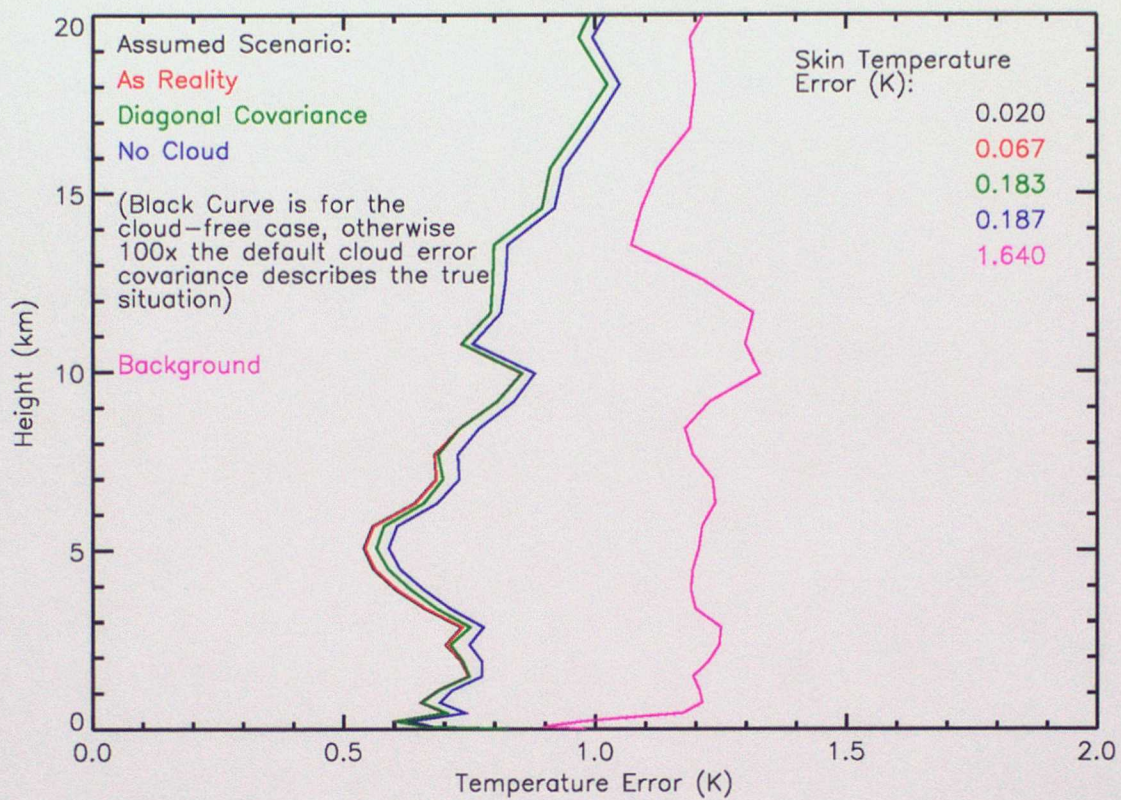


Fig. 10a. As Figure 9a except only high cirrus is considered.



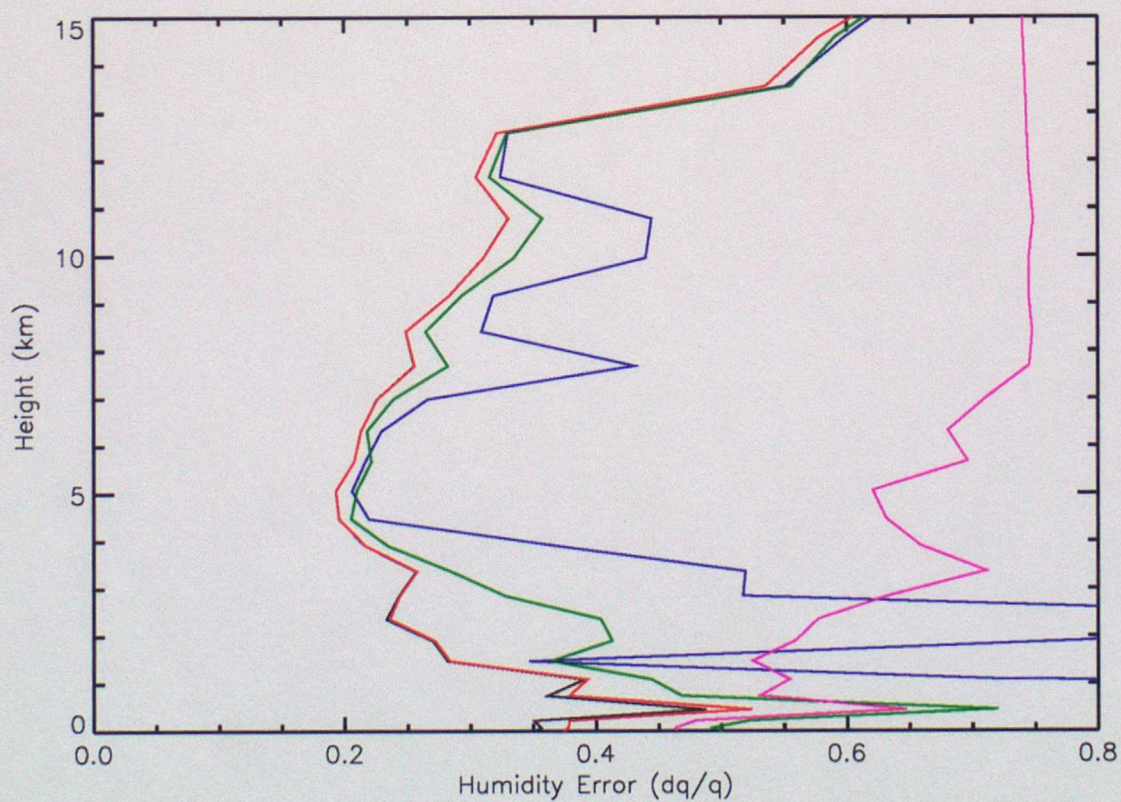
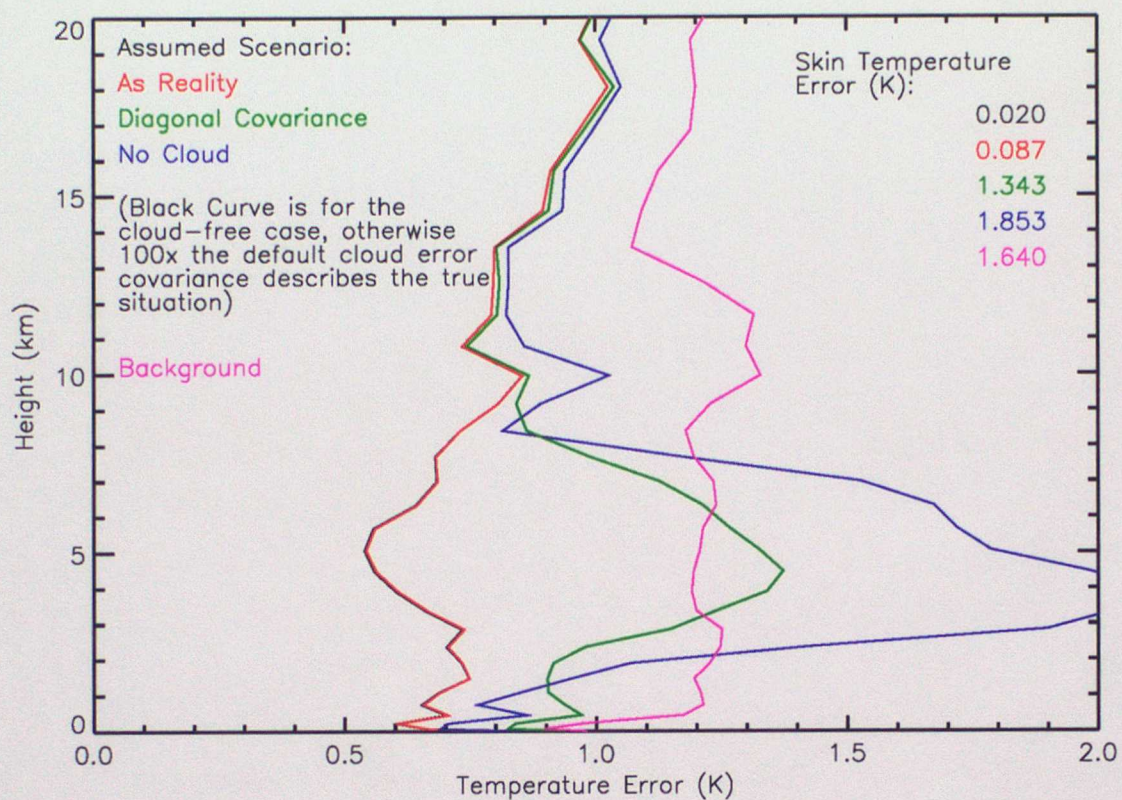


Fig. 10b. As Figure 9b except only high cirrus is considered.



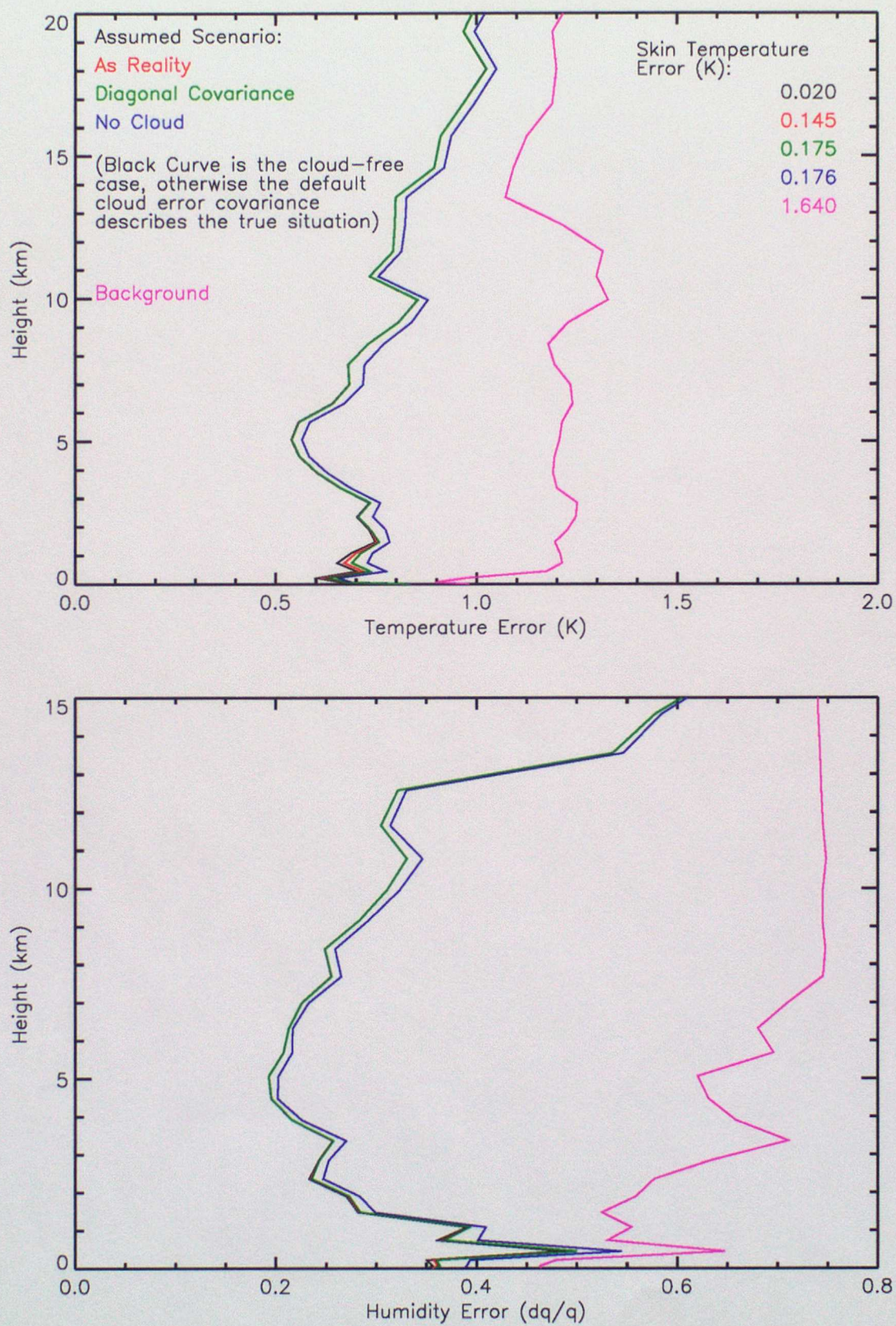


Fig. 11a. As Figure 9a except only low stratus is considered.



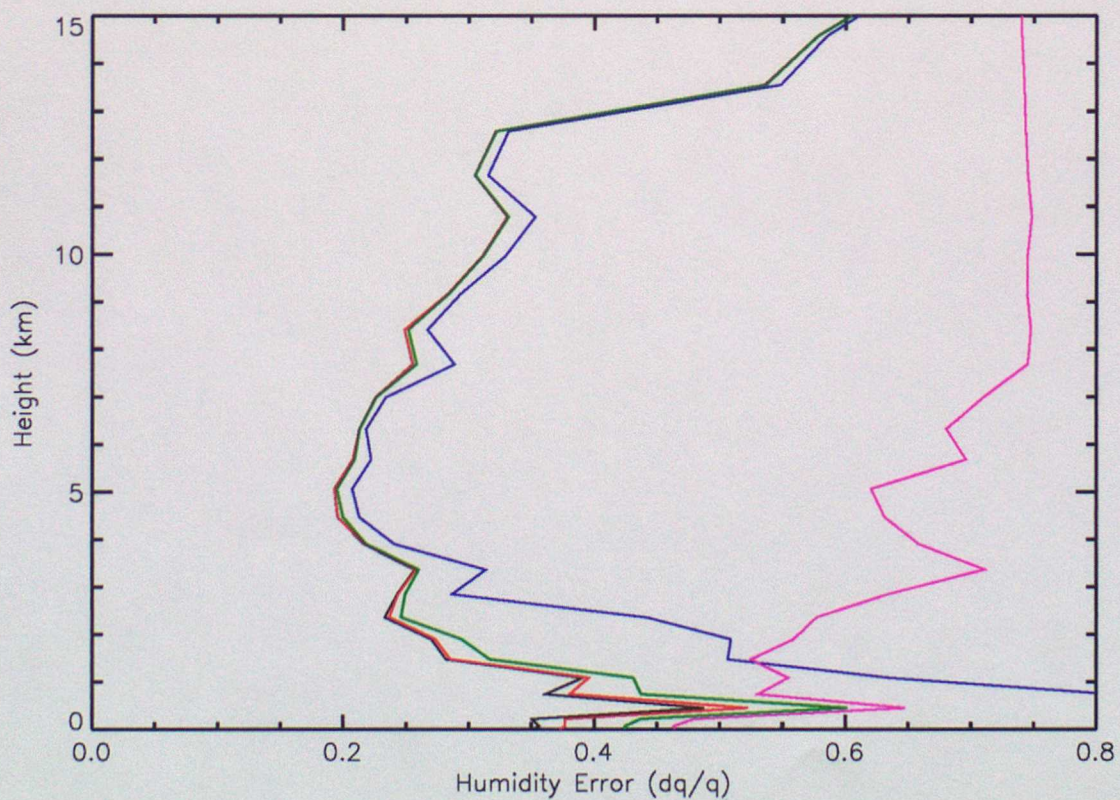
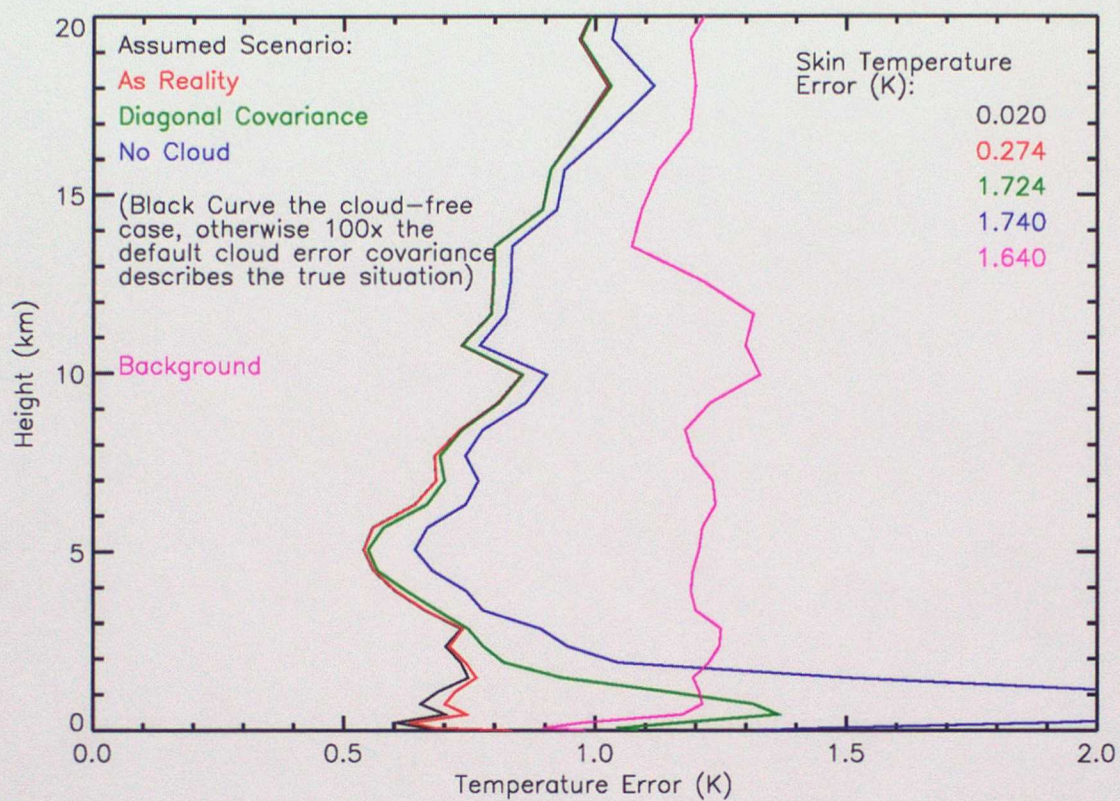


Fig. 11b. As Figure 9b except only low stratus is considered.



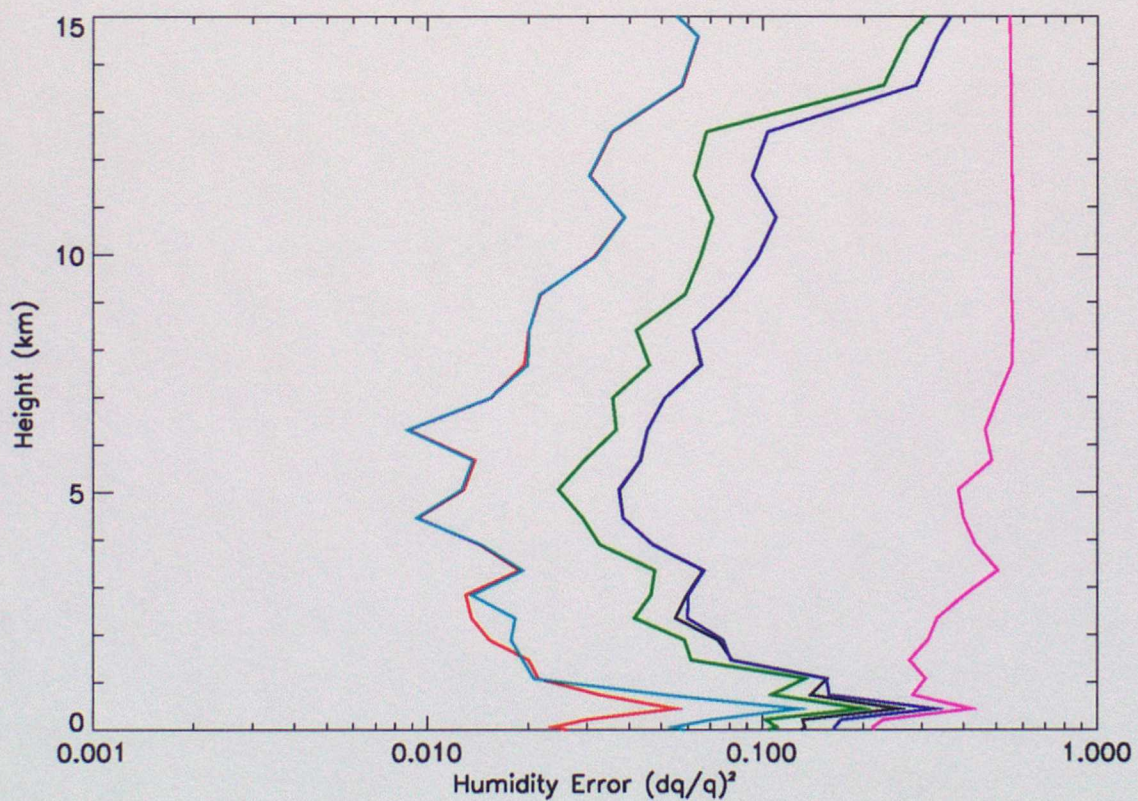
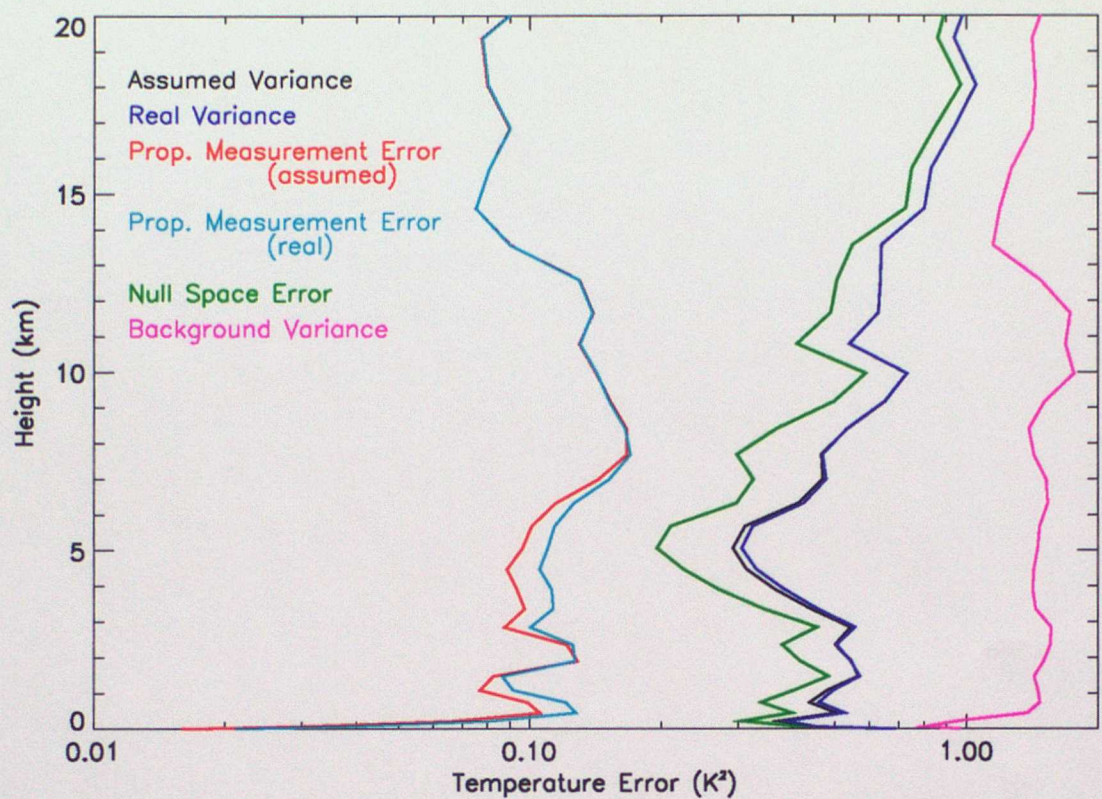


Fig. 12a. The situation displayed in Figure 8a showing the contributions of the propagated measurement and null-space error. The "assumed variance" case here is the situation where only the diagonal elements of the cloud error covariance are used.



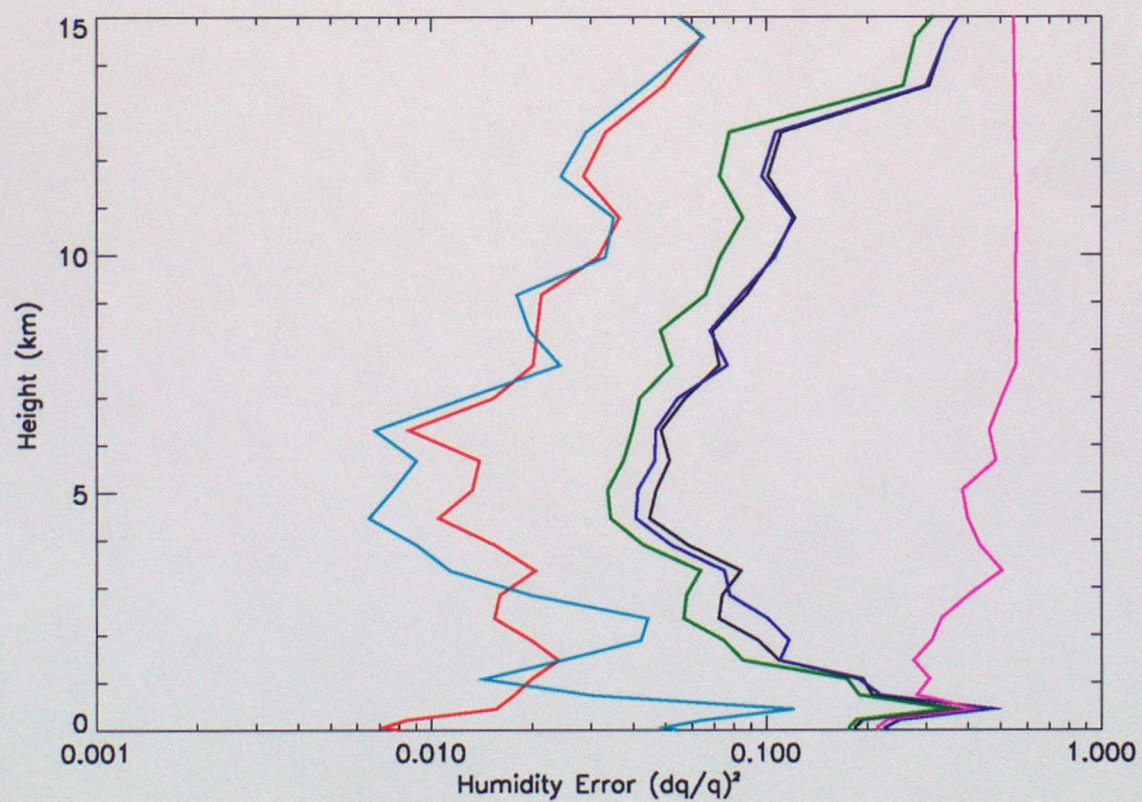
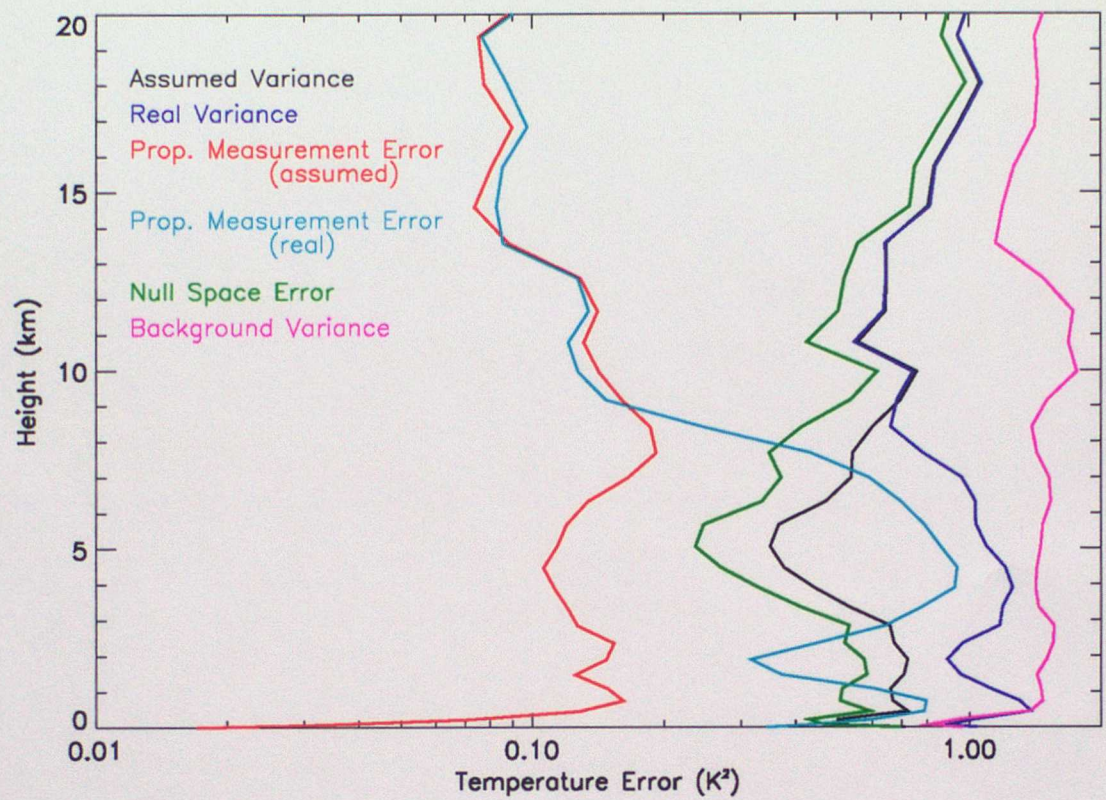


Fig. 12b. As Figure 12a except the cloudy error covariance is multiplied by a factor of one hundred.



## Conclusions.

This preliminary investigation indicates that the effect of undetected cloud on temperature and humidity retrieval performance will be small provided that the error characteristics of the clouds are correctly specified.

While the examples given are necessarily largely qualitative, this report shows how one may determine whether the chosen cloud detection scheme will be adequate to allow accurate retrievals of humidity and temperature profiles, provided an estimate of the residual cloud error covariance is available. The degree to which the assumed forward model error covariance need be modified by the presence of cloud error may also be estimated, bearing in mind that it is undesirable to add significantly to the complexity of the pre-existing  $\mathbf{O}$  matrix.

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