Numerical Weather Prediction

Retrieval of Cloud Top Pressure and Cloud Amount from Infrared Sounders

Forecasting Research Technical Report No. 399

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Abstract

Radiances observed with high spectral resolution interferometer sounders such as IASI will contain information on the properties of clouds in the instruments' field of view. Cloud properties (in this case cloud top pressure and effective cloud fraction) may be inferred from the observed radiances using a 1DVar scheme given suitable *a priori* information on the atmospheric state.

In this study, an idealised case is investigated for the 11.8–15.5μm region of the infrared spectrum as observed by IASI using linear 1DVar retrieval theory. The surface emissivity is assumed to be well known and the cloud's spectral properties are assumed to be constant across this range. The effective cloud fraction retrieval accuracy is found to vary between 0.01 and 0.08, depending on the true cloud top height and cloud fraction, while the cloud top pressure retrieval accuracy varies from 10hPa to ¿200hPa.

The expected retrieval errors for cloud top pressure and cloud fraction can be highly correlated with each other and also with the retrieved surface skin temperature. These correlations, and how they vary with the cloud, are presented.

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Introduction.

In this investigation we wish to determine the accuracy with which one can determine the cloud top pressure and effective cloud fraction (true cloud fraction × emissivity) given observations from a nadir-viewing infrared sounding instrument (IASI, AIRS or HIRS with particular emphasis on IASI) and *a priori* information on the atmospheric state from a 6-hour NWP forecast.

Atmospheric and surface temperature and humidity are retrieved along with the cloud parameters to improve the accuracy of the final solution. This closely follows the techniques used by Eyre (1989) to investigate TOVS cloud retrieval properties.

In order to keep the problem simple, the clouds are assumed to be grey (i.e., constant emissivity at all wavelengths) which is a good approximation for water clouds in the mid-infrared window region, but less so for transmissive ice clouds. In order to mitigate the effects of variable emissivity, a limited spectral interval is considered between 645cm^{-1} and 850cm^{-1} (15.5 – 11.8μm). In a real cloud retrieval system one would attempt to model the cloud emissivity explicitly and the error due to inexact knowledge of the cloud emissivity would be added to the assumed forward model error covariance.

Method of Investigating Retrieval Performance.

The best estimate, $\hat{\mathbf{x}}$, of the atmospheric state, $\mathbf{x}$, is in general found by minimising the cost function, $J(\mathbf{x})$, where

$$J(\mathbf{x}) = (\mathbf{x}-\mathbf{x_0})^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_0}) + (\mathbf{y}-\mathbf{y}(\mathbf{x}))^T(\mathbf{O}+\mathbf{F})^{-1}(\mathbf{y}-\mathbf{y}(\mathbf{x})) \quad (1)$$

where the observations, $\mathbf{y}$, 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 $\mathbf{x}$. The error in the calculated radiances arising from the radiative transfer model is given by the matrix $\mathbf{F}$.

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

$$\hat{\mathbf{x}} = (\mathbf{B}^{-1}+\mathbf{H}^T(\mathbf{O}+\mathbf{F})^{-1}\mathbf{H})^{-1}(\mathbf{B}^{-1}\mathbf{x_0}+\mathbf{H}^T(\mathbf{O}+\mathbf{F})^{-1}\mathbf{y}) \quad (2a)$$

and

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

Here, $\mathbf{H} = \nabla_x\mathbf{y}(\mathbf{x})$ is the matrix of observation Jacobians.

In this problem the $\mathbf{x}$ vector consists of the atmospheric temperature and humidity profiles, the skin temperature and the cloud top pressure and effective fraction. The cloud properties have *a priori* errors set very large (meaning we have no prior knowledge of these) which the remaining elements in the B matrix are taken from the appropriate error covariance matrix for a 6-hour global NWP forecast run.

The accuracy with which parameters can be retrieved (and the correlations between the retrieval accuracy of different parameters) can then be inferred through inspection of the A matrix.

Calculation of Retrieval Properties.

The Jacobians, **H**, were calculated for a range of cloud top pressures (10, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000hPa) and effective cloud fractions (0.0, 0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0) using either RTIASI (Matricardi and Saunders, 1999) for the IASI calculations or RTTOV-7 (Saunders *et al.*, 2002) for AIRS and HIRS.

In both RTIASI and RTTOV-7, the clouds used are infinitely thin, non-reflective and black. The clouds may have fractional areal coverage, n, in which case the situation is equivalent to a continuous, non-reflective, grey cloud with emissivity equal to the fractional coverage of the grey cloud.

The observational error covariances **O** are assumed to be diagonal for HIRS and AIRS, while IASI errors are pentadiagonal to allow for the inter-channel correlations introduced by apodisation at level 1c. All channels have a 0.2K uncorrelated forward model error, **F**, added in quadrature.

For the case where retrievals of cloud top pressure and cloud fraction only are performed (i.e., no simultaneous retrieval of atmospheric temperature and humidity), an additional forward model error term, $\mathbf{HBH}^T$, is added to the **F** matrix to allow for the effect on the simulated radiances due to uncertainty in the atmospheric profile.

Results.

Figures 1–3 show the expected retrieval accuracies for cloud top pressure and effective cloud fraction using all channels in the 645-850cm^{-1} region for IASI, AIRS and HIRS. For IASI, 821 channels are used; for AIRS 602; and for HIRS channels 1–8 and channel 10 are used. The profile used is the AFGL Mid-Latitude Winter Profile.

In all three instrument cases the expected cloud top pressure and cloud fraction retrieval accuracies improve as the cloud fraction increases and as the cloud top pressure decreases. This general trend is to be expected, as the main effect of decreasing cloud top pressure and increasing cloud fraction is to increase the cloud signal in the observed spectrum through increased contrast with the surface emission.

IASI and AIRS have very similar performance with cloud fraction retrievals errors better than 10% and cloud top pressure errors better than 50hPa in the majority of cases.

HIRS retrievals are degraded by a factor of two or more relative to the higher resolution instruments. Cloud fraction retrieval errors are over 50% below the 500hPa level probably indicating poor discrimination between the surface and the clouds due to the relatively poor vertical resolution associated with HIRS.

In addition to the standard deviations, the correlations of the retrieval errors are also of interest. Figures 4–6 show how the correlations between three major variables — the skin temperature, cloud top pressure and cloud amount — vary as a function of the true cloud top pressure and cloud amount for IASI and HIRS observations. The IASI and HIRS cases have qualitatively similar variations in these correlations which may be explained as follows (with reference to the example normalised Jacobians in Figures 7):

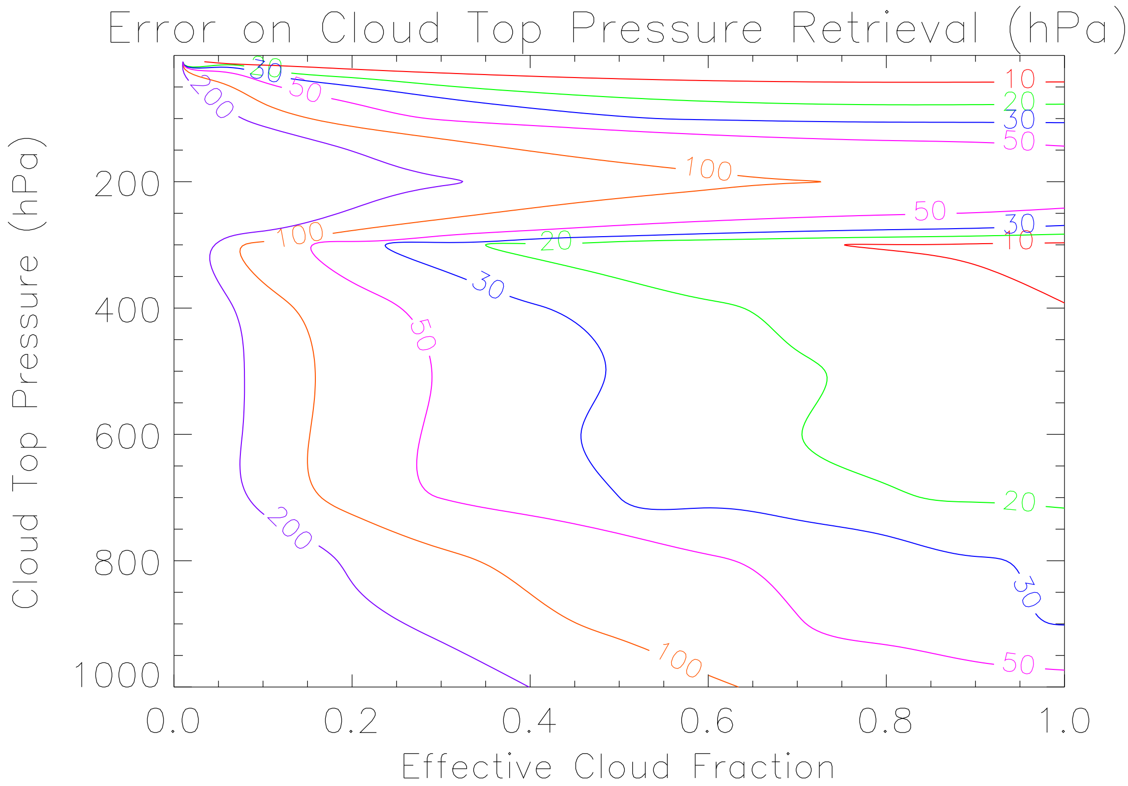

Fig. 1a. Expected error in retrieved cloud top pressure for IASI as a function of true cloud top pressure and effective cloud coverage.

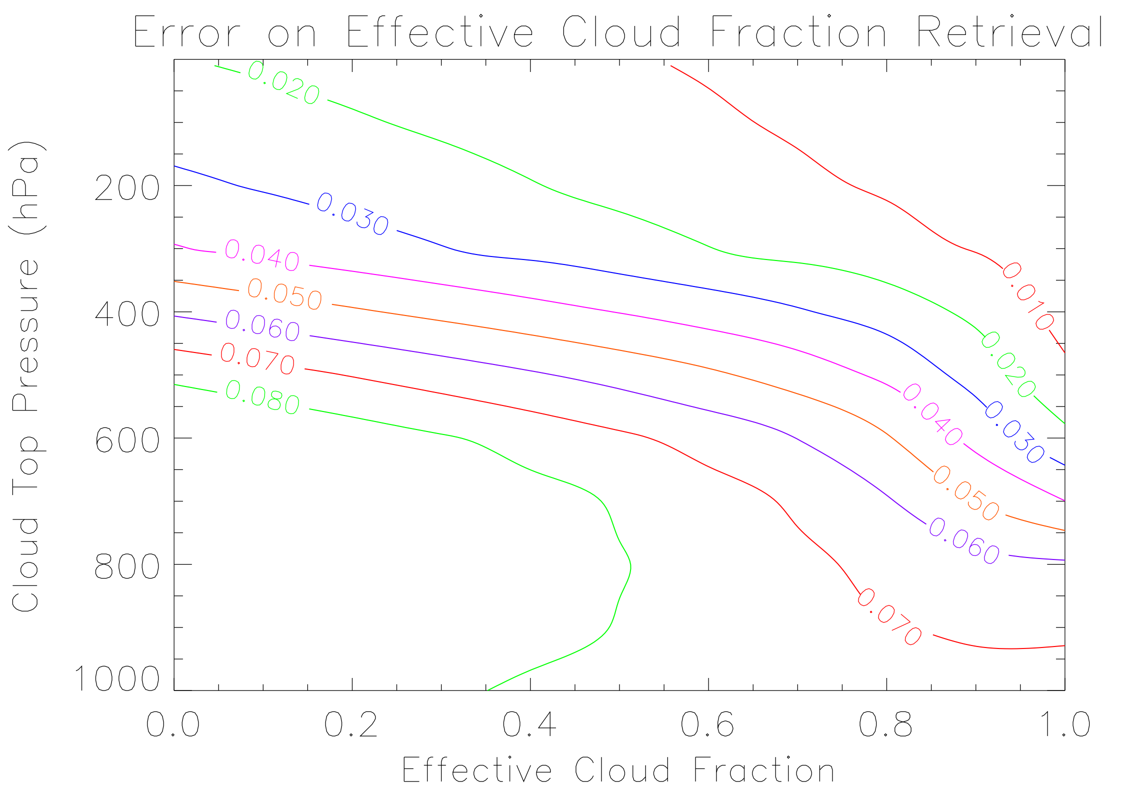

Fig. 1b. Expected error in retrieved effective cloud fraction for IASI as a function of true cloud top pressure and effective cloud coverage.

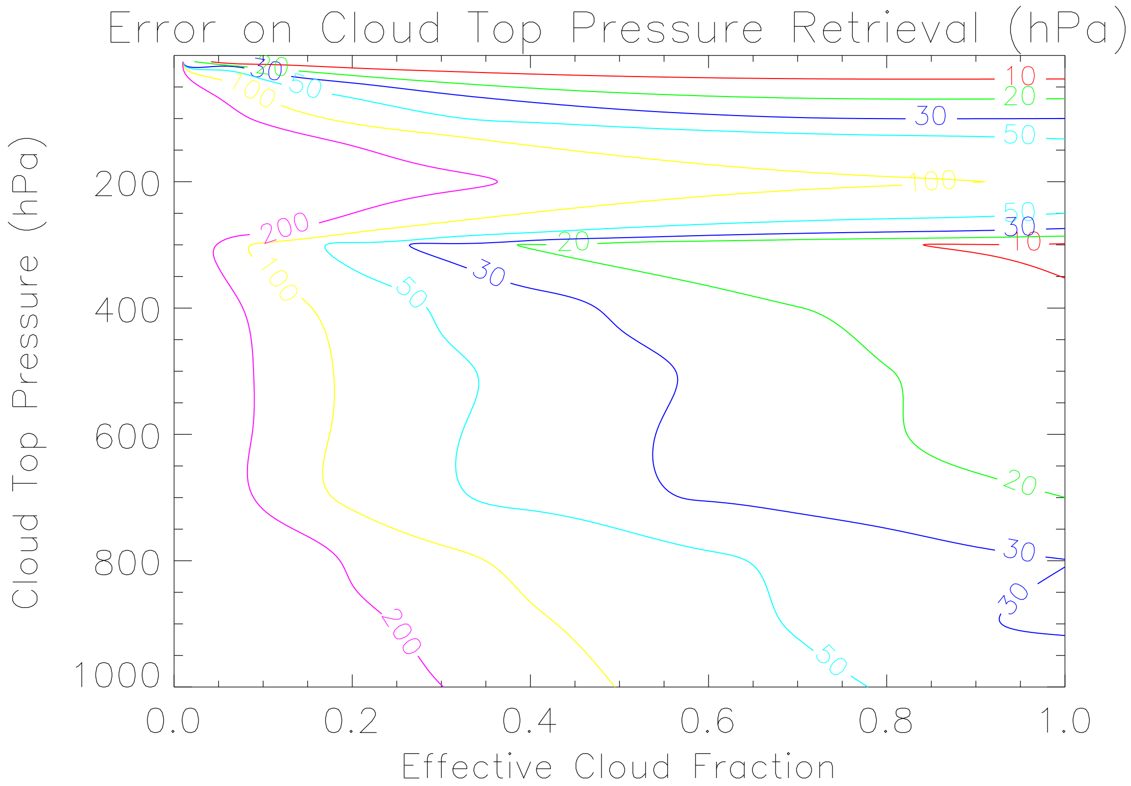

Fig. 2a. Expected error in retrieved cloud top pressure for AIRS as a function of true cloud top pressure and effective cloud coverage.

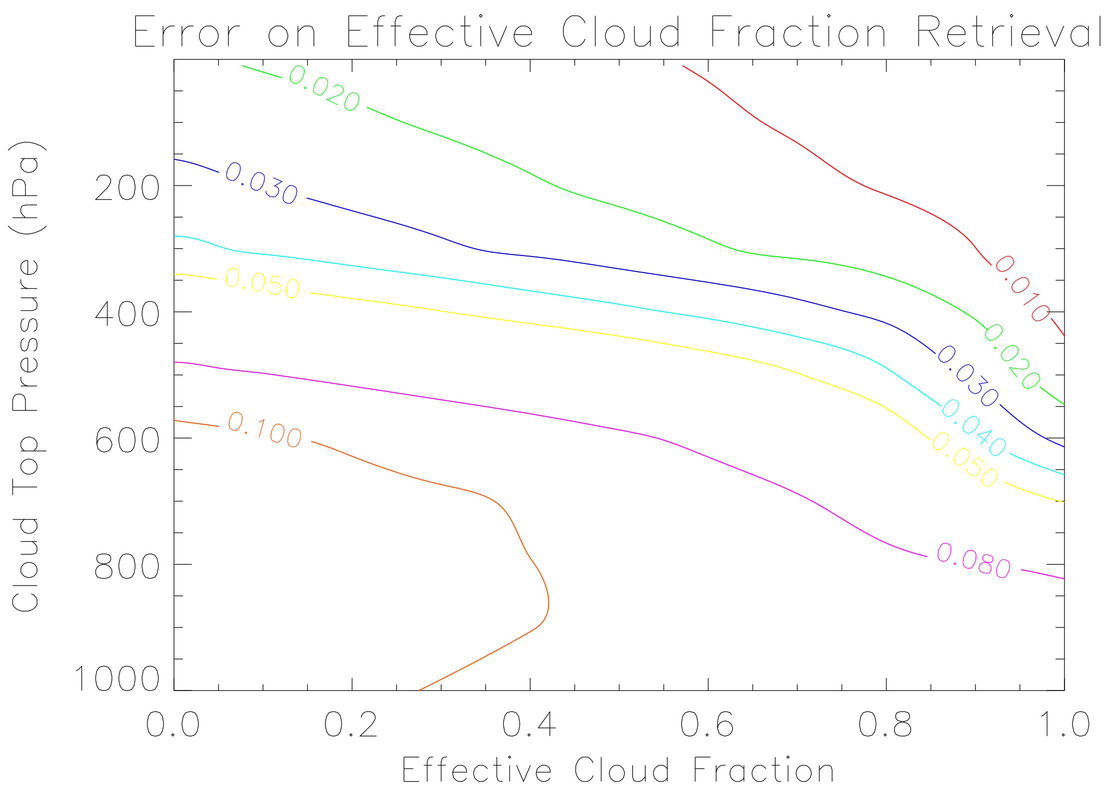

Fig. 2b. Expected error in retrieved effective cloud fraction for AIRS as a function of true cloud top pressure and effective cloud coverage.

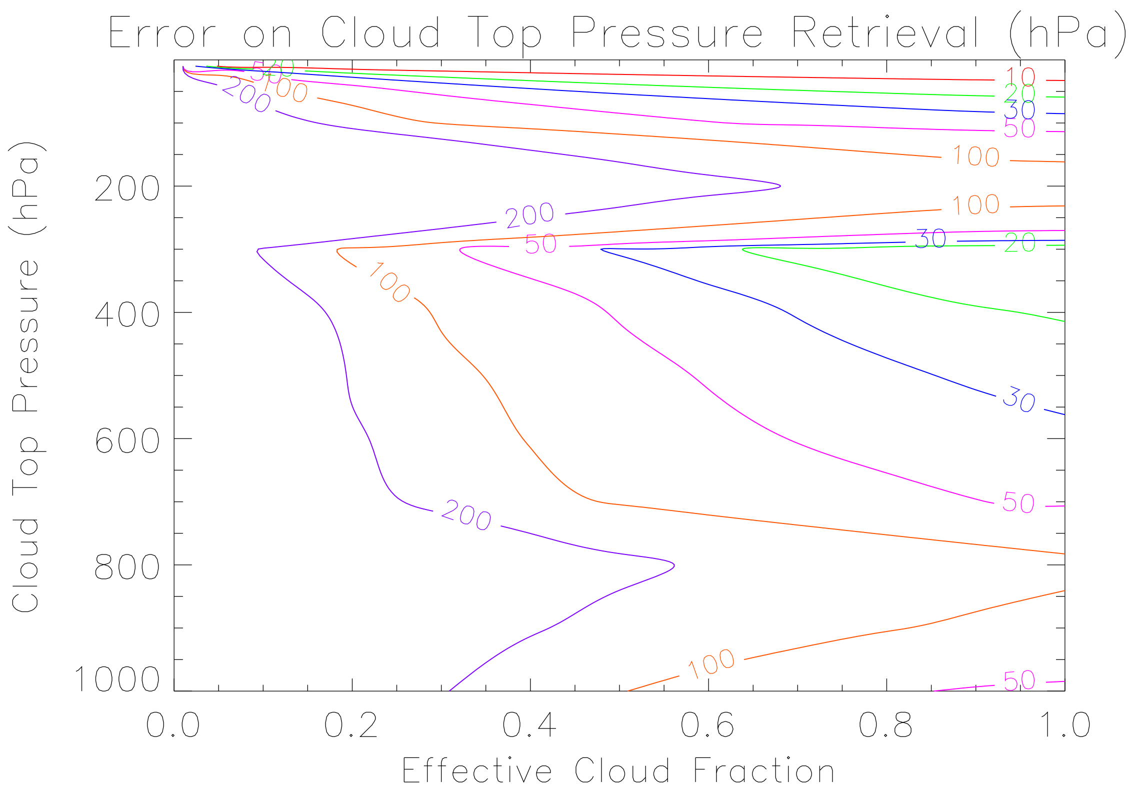

Fig. 3a. Expected error in retrieved cloud top pressure for HIRS as a function of true cloud top pressure and effective cloud coverage.

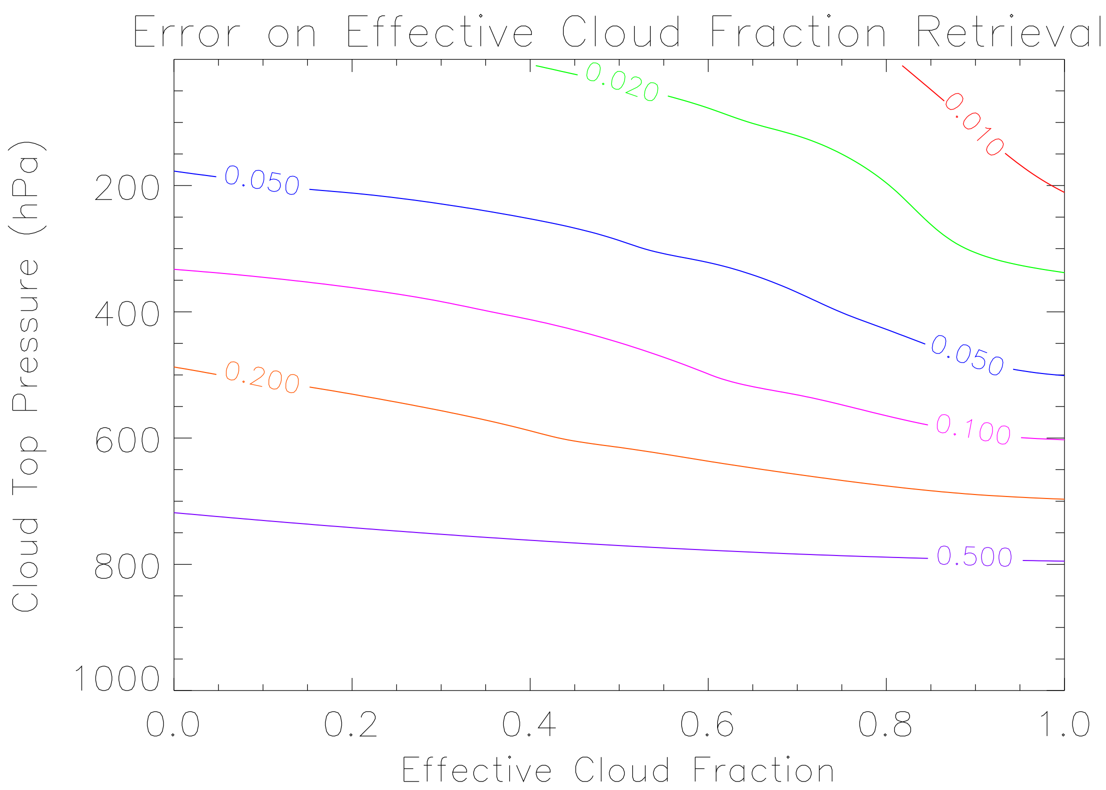

Fig. 3b. Expected error in retrieved effective cloud fraction for HIRS as a function of true cloud top pressure and effective cloud coverage.

Skin Temperature vs Cloud Amount. The main trend in this case is that from low correlations for low clouds to high correlations for high clouds.

The higher correlations for high clouds is a function of the increased contrast between (cold) clouds and the (warm) surface which produces a large signal in the window region. As a high cloud is effectively just obscuring radiation from the surface in the window region (i.e., it has insignificant thermal emission), if one wishes to change the observed window brightness temperatures one must change the cloud fraction (and the amount of surface radiation obscured) rather than the cloud top pressure (and change the relatively small thermal emission from the cloud itself). The converse is, of course, true with an overestimate of high cloud amount having to be countered by an increase in surface temperature to preserve the same observed brightness temperatures in the window region.

For lower clouds, with significant thermal emission in the window region, the contrast is reduced and the possibility of producing a similar signal from cloud top pressure changes (and indeed changes in the atmospheric temperature profile) is increased. Furthermore, as can be seen from Figure 7c, the spectral variation of the Jacobian for cloud fraction is significantly different to that for either skin temperature or cloud top pressure in this case (this is for IASI, the effect is less so for HIRS due to the reduced number of channels). Both of these effects result in a lower correlation between cloud amount and skin temperature retrieval errors.

Finally, this correlation is reduced to zero as the cloud coverage approaches unity. This is simply because one cannot retrieve the surface if one cannot see it and so the error stays close to the *a priori* value and is uncorrelated with the other retrieved values (except for residual correlations from the *a priori* error covariance matrix).

Skin Temperature vs Cloud Top Pressure. These two values are anti-correlated in the lower troposphere and correlated at higher altitudes. The difference is best explained by exploring what would happen if the skin temperature were over-estimated in high cloud and low cloud cases.

In the high cloud case, we have already seen how the cloud fraction is the retrieval variable that is mostly correlated with the skin temperature. An over-estimate of the skin temperature will therefore result in a similar over-estimate of the cloud fraction in order to preserve the same total observed brightness temperature in the window. This over-estimate cloud amount will mean that the brightness temperatures observed in channels with Jacobians that peak above the cloud will be increased, so the cloud needs to be moved downwards (i.e., the cloud top pressure is increased) to correct for this. Therefore, the cloud top pressure error is correlated with the skin temperature error.

In the low cloud case, an over-estimated skin temperature can be corrected by either raising the cloud amount, as previously discussed, or by raising (and thus cooling) the cloud top or, more probably, both. Hence in this case cloud top pressure and skin temperature retrieval errors are anti-correlated.

Cloud Amount vs Cloud Top Pressure. These variables are anti-correlated in the lower troposphere and correlated elsewhere. The anti-correlation in the lower troposphere can be explained by noting that if the surface temperature is over-estimated, the cloud amount will also be over estimated to compensate, while the cloud top pressure will be underestimated, resulting in the last two being anti-correlated. The correlation between these variables in the rest of the atmosphere is explained through the same argument that explains the Skin

Temperature - Cloud Top Pressure correlation above.

One factor that may have a significant effect on cloud retrieval errors is the accuracy with which the skin temperature can be determined. Figure 9 illustrates the effect of increasing the error in the *a priori* knowledge of the skin temperature by a factor of 5 (2.24K increased to 11.20K). Above the 600hPa level, there retrieval accuracies are very similar to those with the smaller skin temperature error. The lower tropospheric cloud fraction retrievals are degraded but only around 10%. This initially surprising result may be understood with reference to Figure 9, which shows how the emission from the surface and emission from the clouds can be clearly disentangled through their different emissivity spectra.* The lower tropospheric cloud top pressure retrievals are affected, however, with retrievals errors typically increasing by a factor of two.

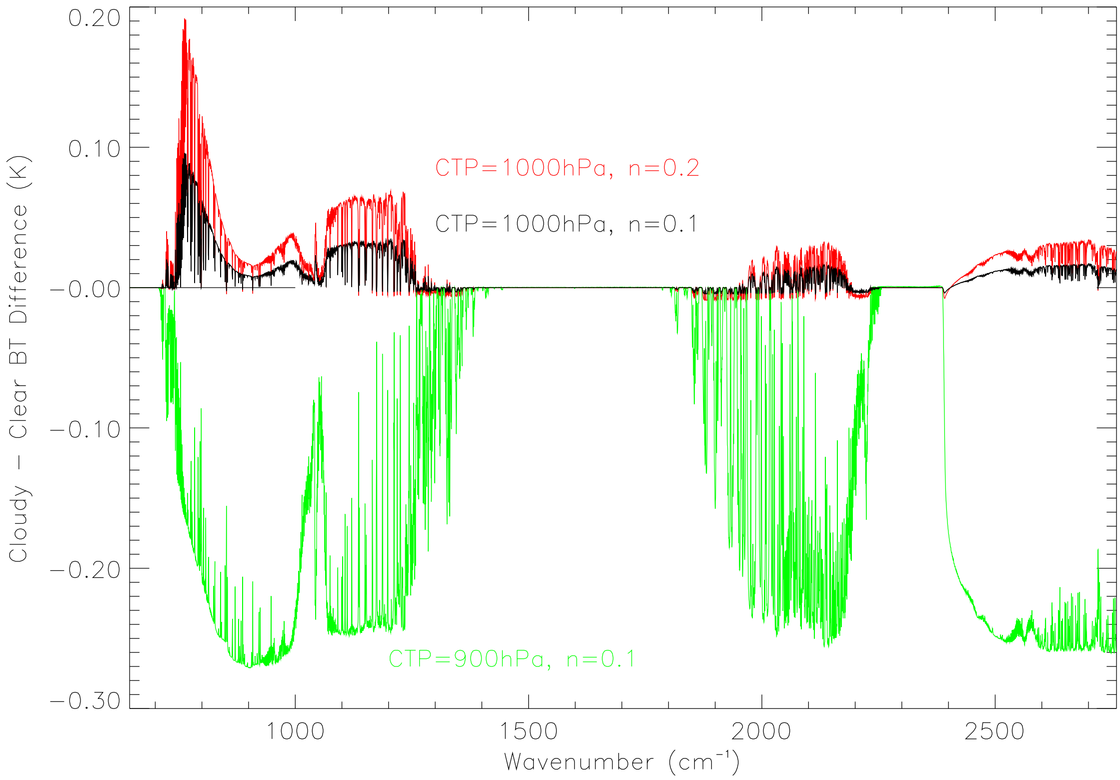

Fig. 8. The impact on observed brightness temperatures due to small amounts of low cloud. The signal due to very low cloud (1000hPa) is almost entirely due to the different emissivities of the surface and cloud, while the signal from the 900hPa cloud is dominated by their different emitting temperatures.

Figure 10 shows the expected accuracy on retrieving cloud properties without simultaneous retrieval of the atmospheric profile (with the profile uncertainty being added to the assumed forward model error). The degradation in retrieval accuracy relative to the full retrieval is generally small and is nowhere much larger than a factor of two. Figure 11 shows the error correlation between retrieved cloud top pressure and cloud amount in this case. They are qualitatively similar to the case where the other atmospheric parameters are being retrieved although the magnitude of the correlations are significantly larger in the upper troposphere (as there is no longer any correlation with the retrieved local atmospheric temperature).

* Clearly to achieve the full potential accuracy on retrieval of the cloud amount for low clouds, one must be able to accurately model both surface and cloud emissivities.

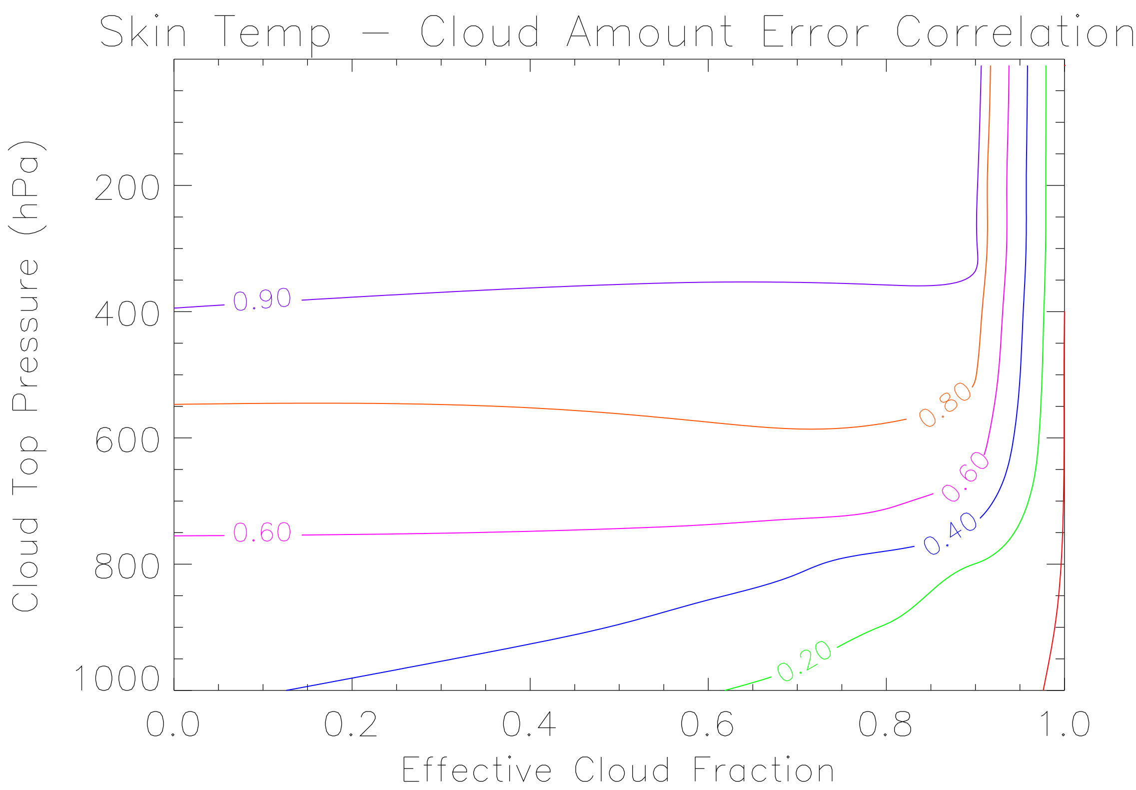

Fig. 4a. The retrieval error correlation between skin temperature and cloud amount as a function of true cloud top pressure and true cloud amount for IASI.

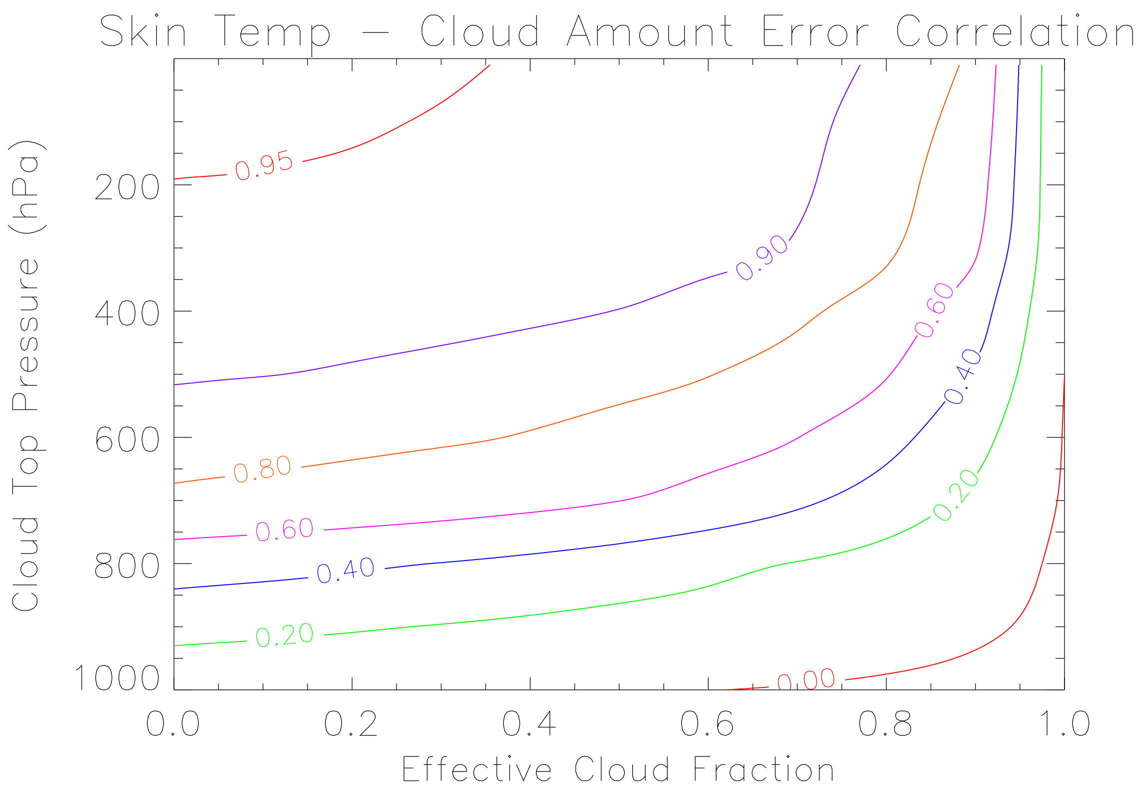

Fig. 4b. The retrieval error correlation between skin temperature and cloud amount as a function of true cloud top pressure and true cloud amount for HIRS.

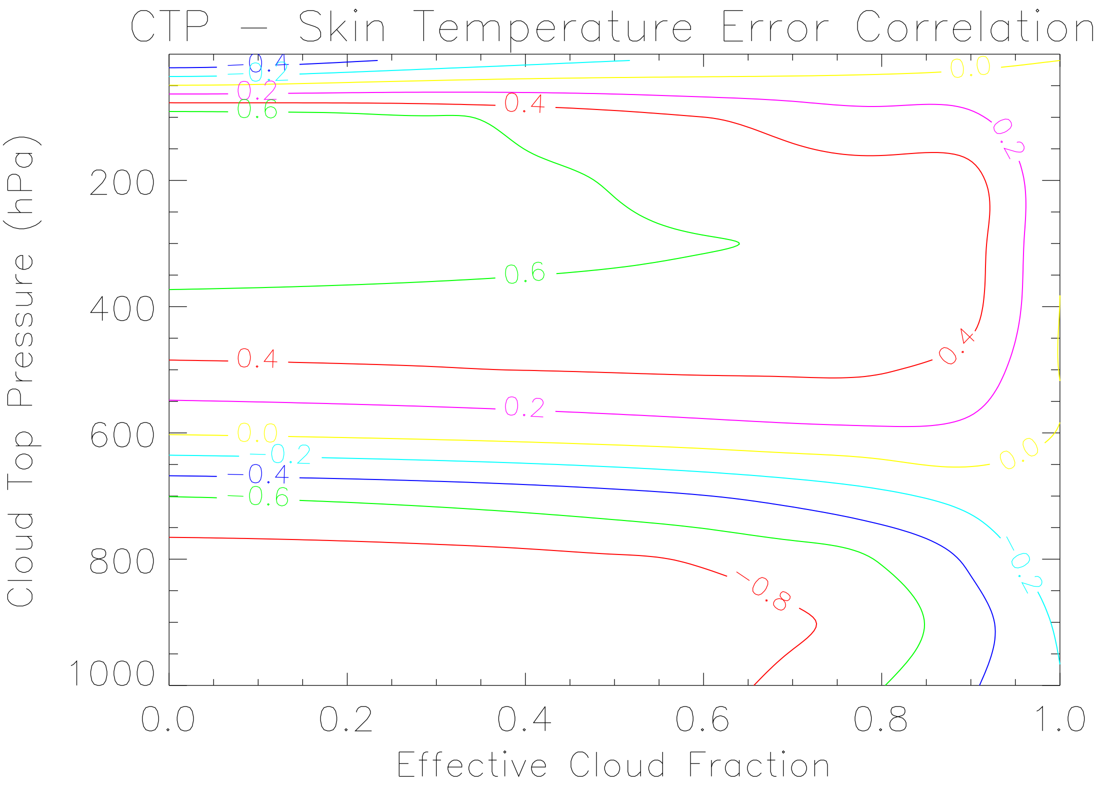

Fig. 5a. The retrieval error correlation between skin temperature and cloud top pressure as a function of true cloud top pressure and true cloud amount for IASI.

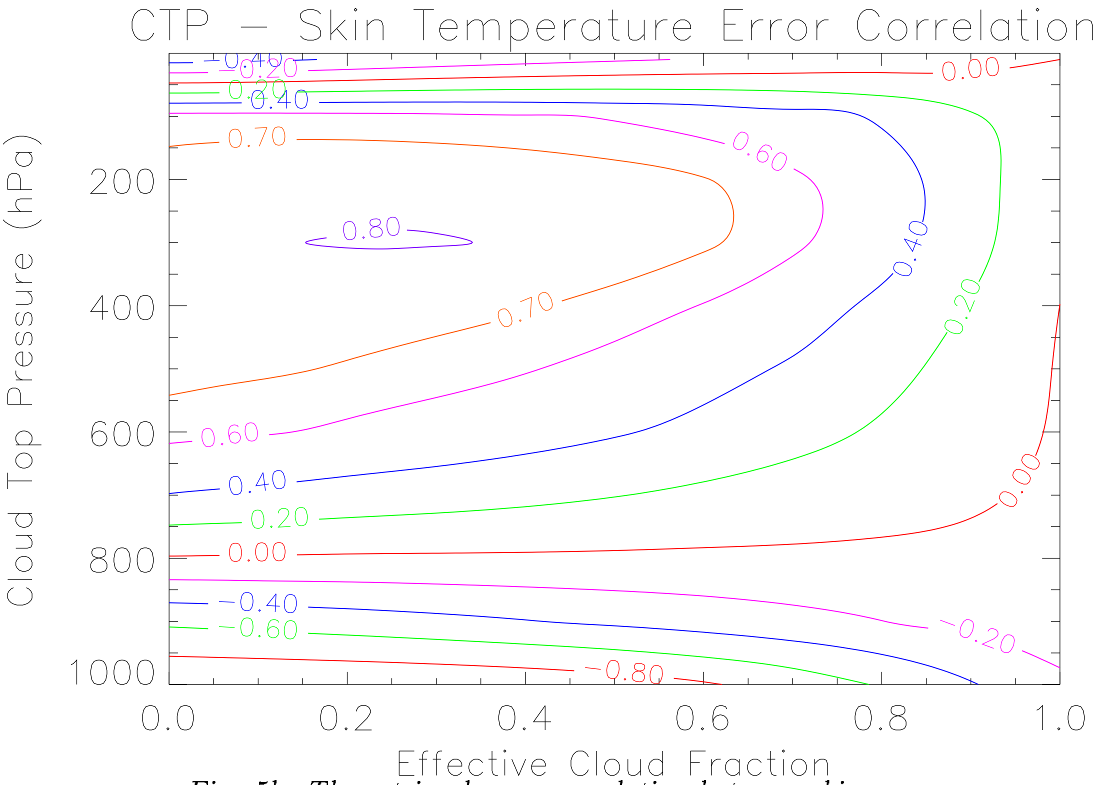

Fig. 5b. The retrieval error correlation between skin temperature and cloud top pressure as a function of true cloud top pressure and true cloud amount for HIRS.

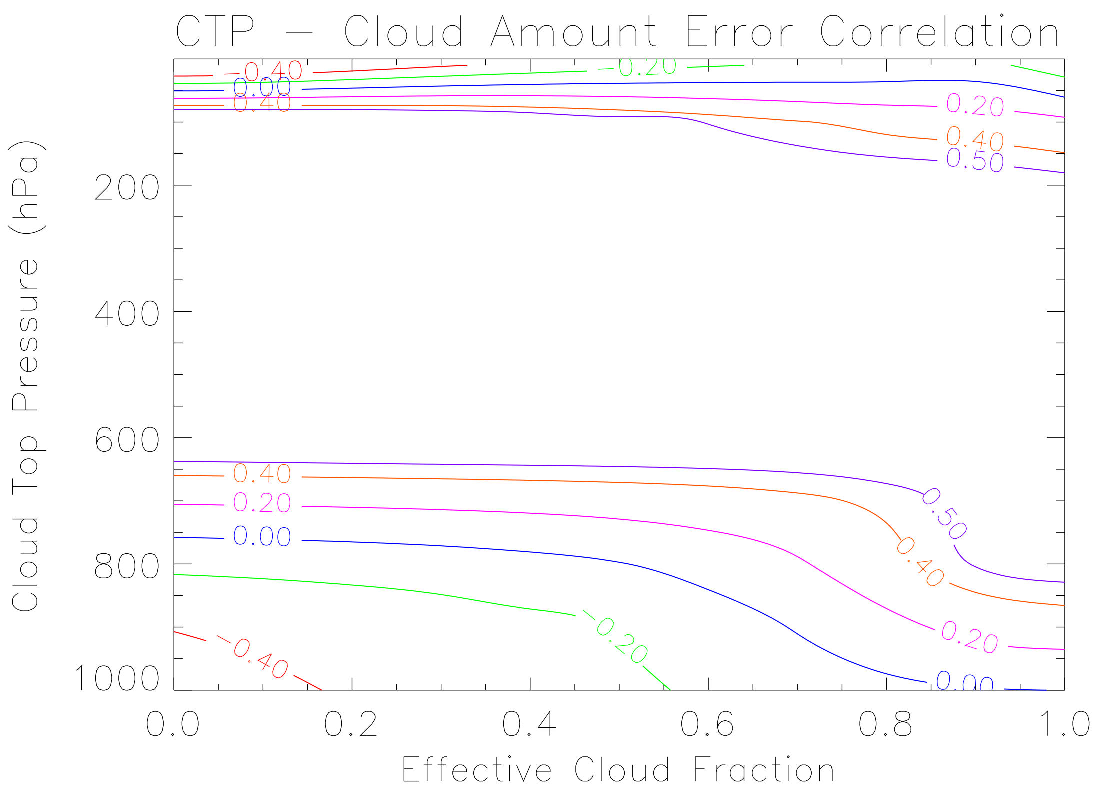

Fig. 6a. The retrieval error correlation between cloud top pressure and cloud amount as a function of true cloud top pressure and true cloud amount for IASI.

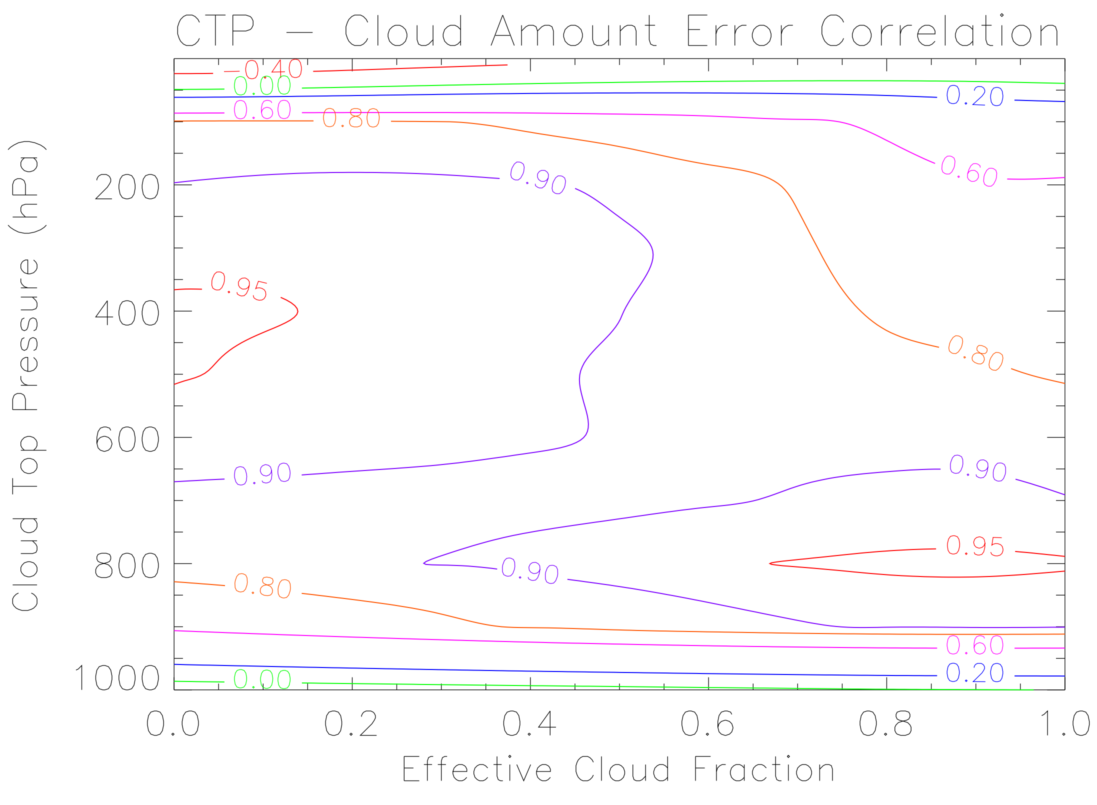

Fig. 6b. The retrieval error correlation between cloud top pressure and cloud amount as a function of true cloud top pressure and true cloud amount for HIRS.

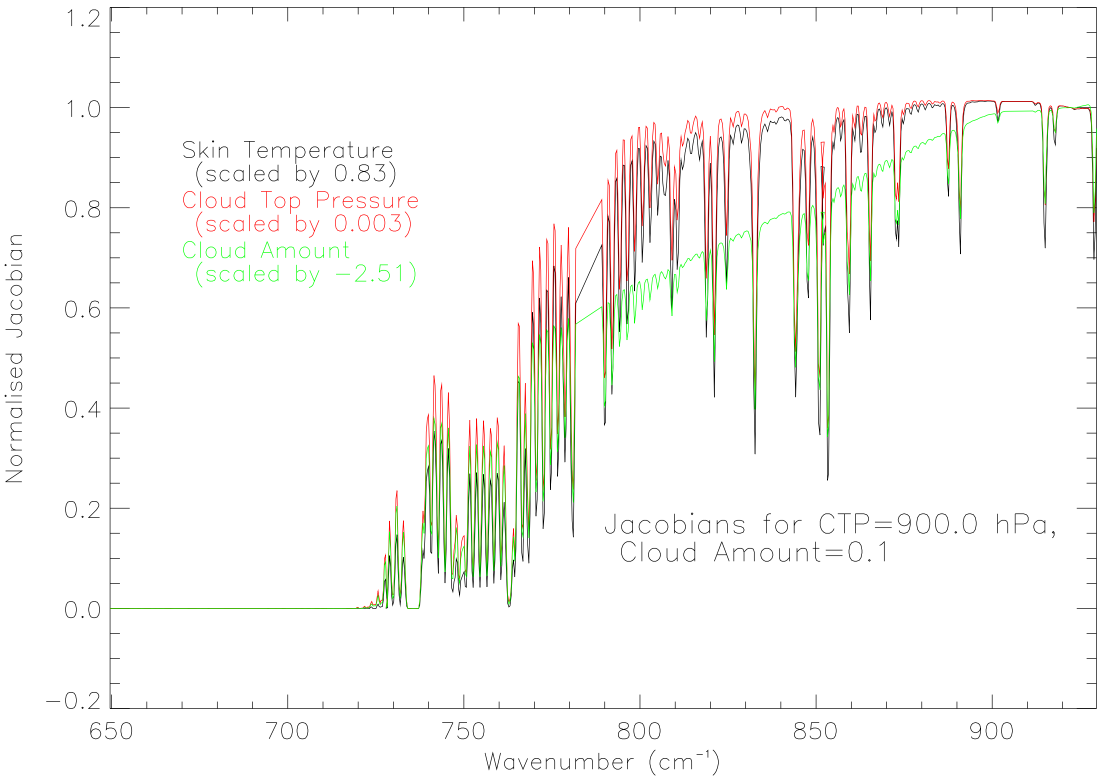

Fig. 7a. A comparison of the IASI Jacobian values (as a function of frequency) for cloud fraction, skin temperature and cloud top pressure for a low, thin cloud. The slope across the window region of the cloud fraction Jacobian is a result of the non-linearity if the Planck function and results in it being possible to disentangle cloud fraction information from the other parameters.

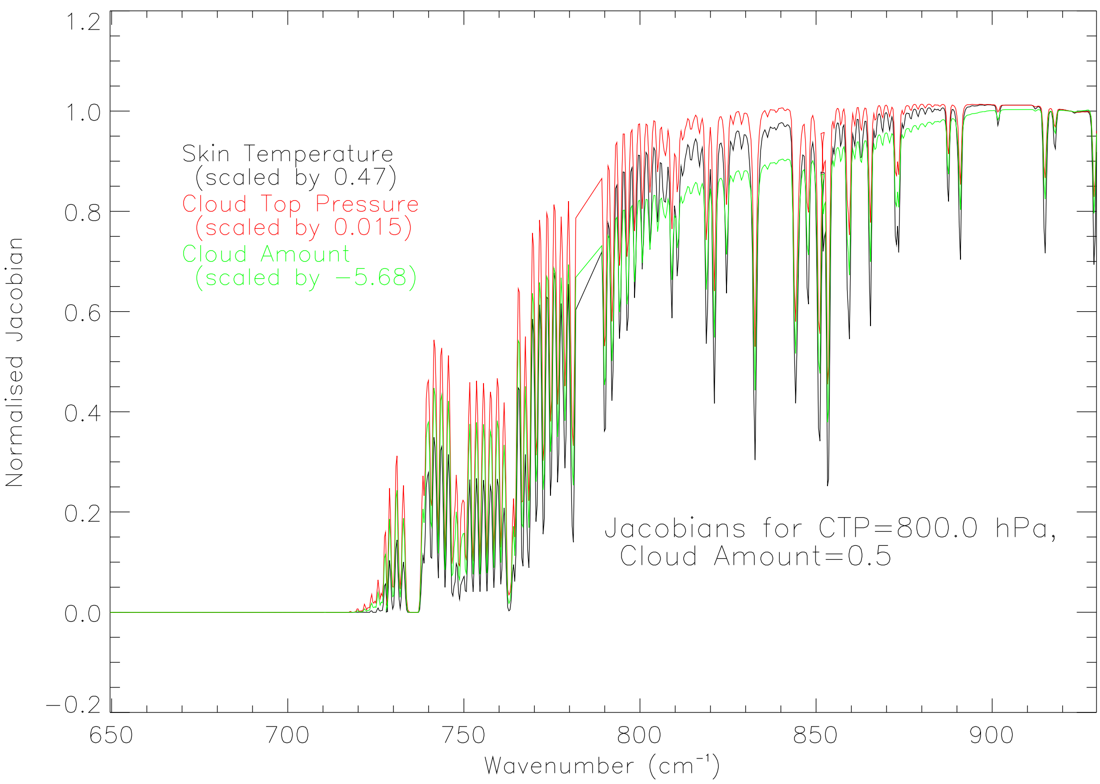

Fig. 7b. A comparison of the IASI Jacobian values (as a function of frequency) for cloud fraction, skin temperature and cloud top pressure for a 800hPa, moderately thick cloud.

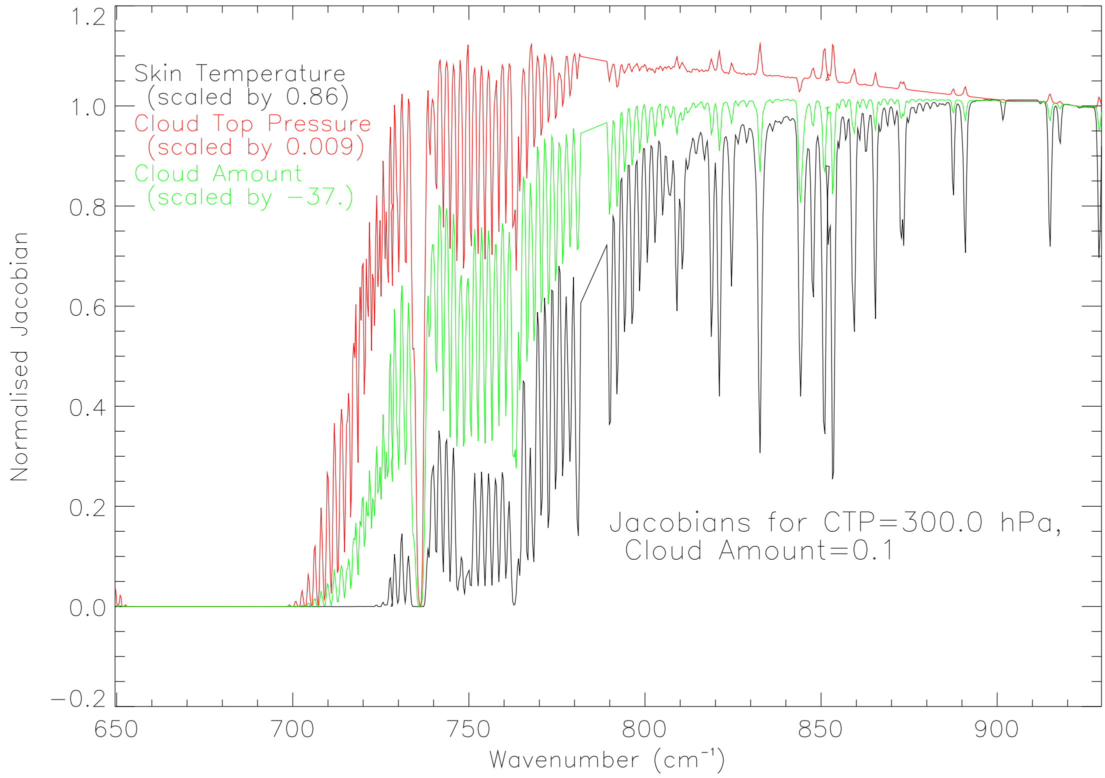

Fig. 7c. A comparison of the IASI Jacobian values (as a function of frequency) for cloud fraction, skin temperature and cloud top pressure for a high, thin cloud. Comparing the scale factors for these Jacobians with those in the previous two figures shows how the sensitivity to cloud top pressure is very low in this case.

Conclusions and Future Work.

The above investigations illustrate that infrared sounding instruments can be used to infer cloud properties for a wide range of cloud conditions.

Future investigations in this field should concentrate on the effects of frequency-dependent emissivity and reflectivity for both the clouds and the surface and especially the effect of errors in the estimation of these properties.

The RTTOVCLD facility in RTTOV-7 would be a useful tool to aid in the investigation of the effect of more complicated cloud optical properties. One complicating factor, however, would be how to correctly define the cloud top pressure for a transmissive cloud with finite thickness.

If the spectral variation of the errors in the optical properties of cloud and surface can be properly modelled, one may then safely extend the spectral range that is employed in these studies to the full IASI, AIRS or HIRS spectrum, which may allow one to fully exploit the non-linearity of the Planck function as a function of wavelength (although care must be taken when using the shortest wavelength regions of the spectrum in daylight).

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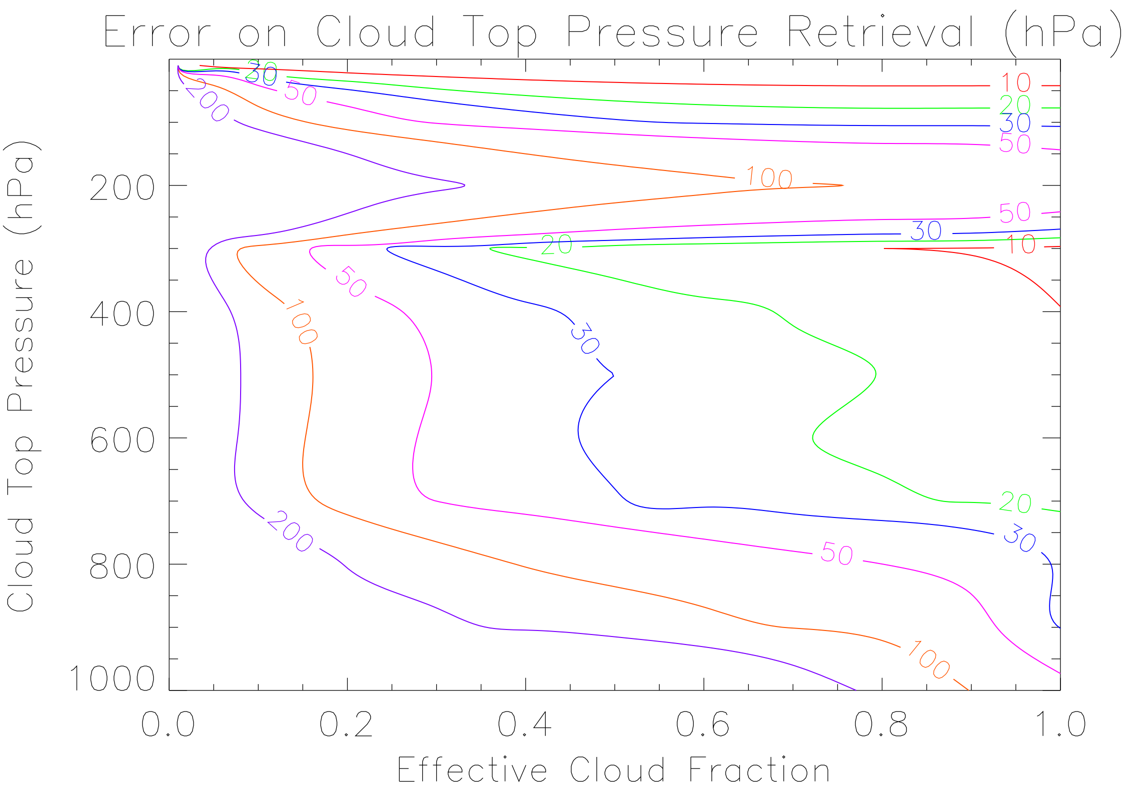

Fig. 9a. Expected error in retrieved cloud top pressure for IASI as a function of true cloud top pressure and effective cloud coverage with 5 times the default assumed a priori skin temperature error.

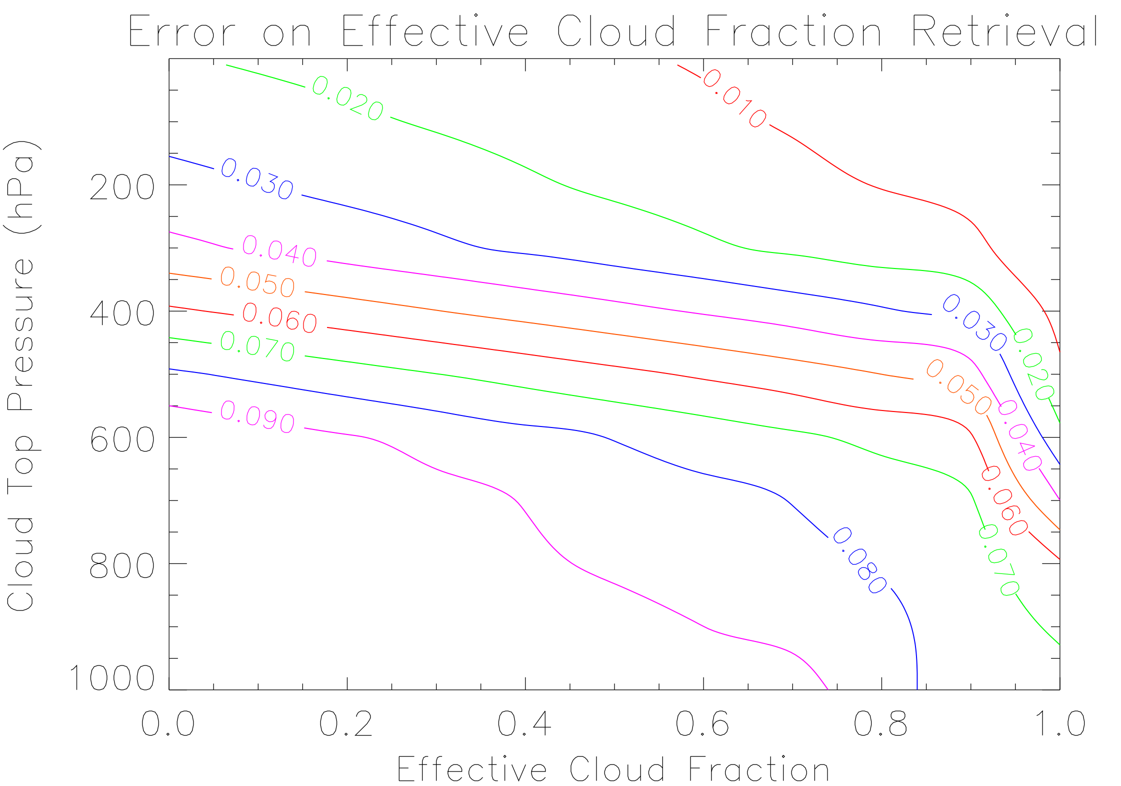

Fig. 9b. Expected error in retrieved effective cloud fraction for IASI as a function of true cloud top pressure and effective cloud coverage with 5 times the default assumed a priori skin temperature error.

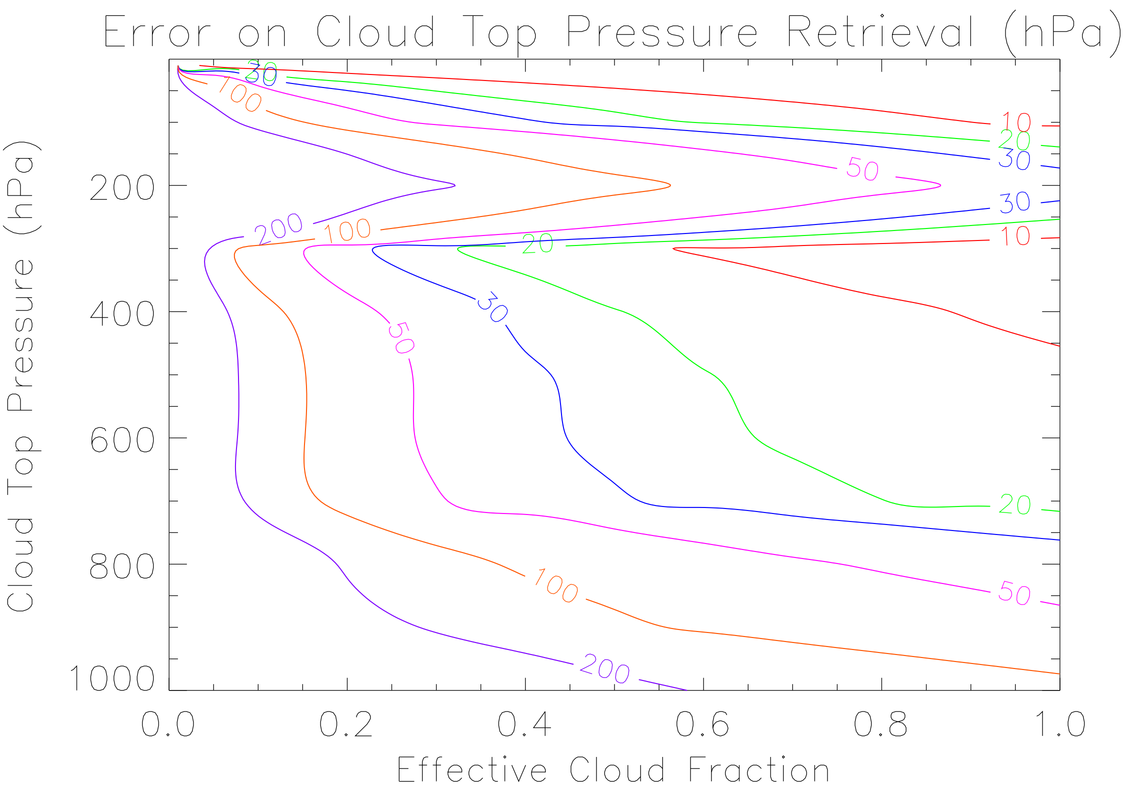

Fig. 10a. Expected error in retrieved cloud top pressure for IASI as a function of true cloud top pressure and effective cloud coverage where only these two parameters are retrieved.

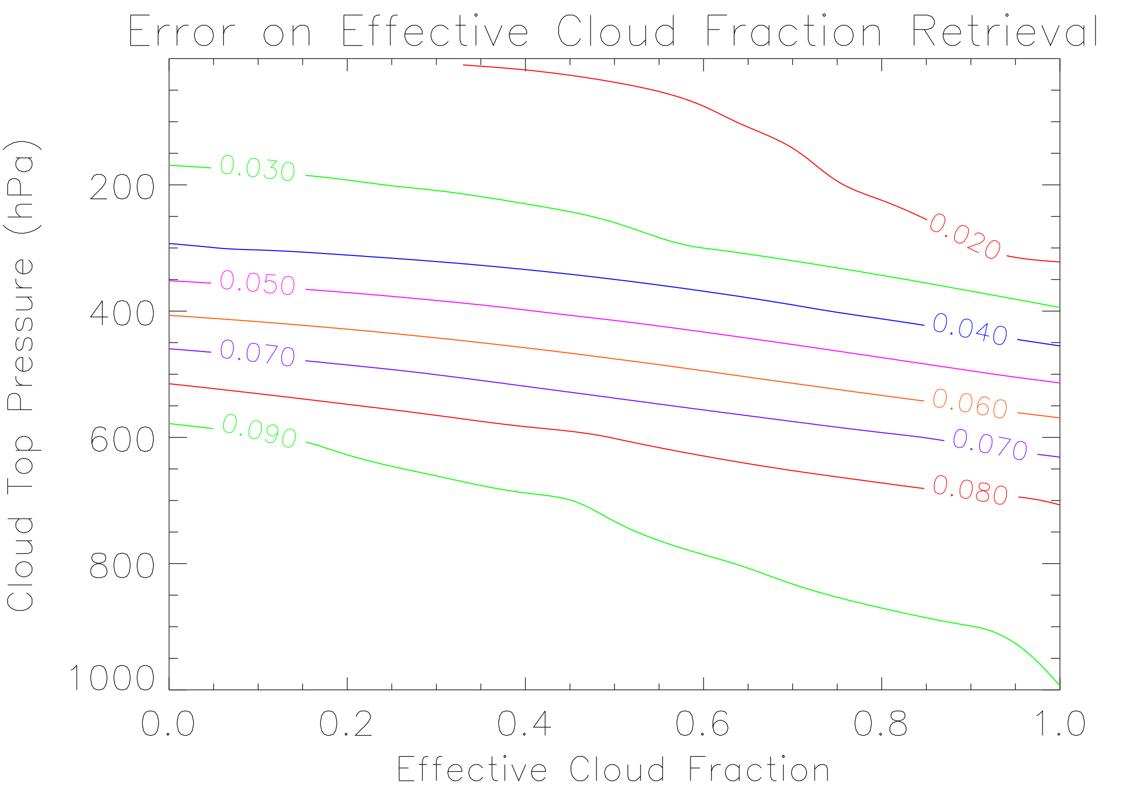

Fig. 10b. Expected error in retrieved effective cloud fraction for IASI as a function of true cloud top pressure and effective cloud coverage where only these two parameters are retrieved.

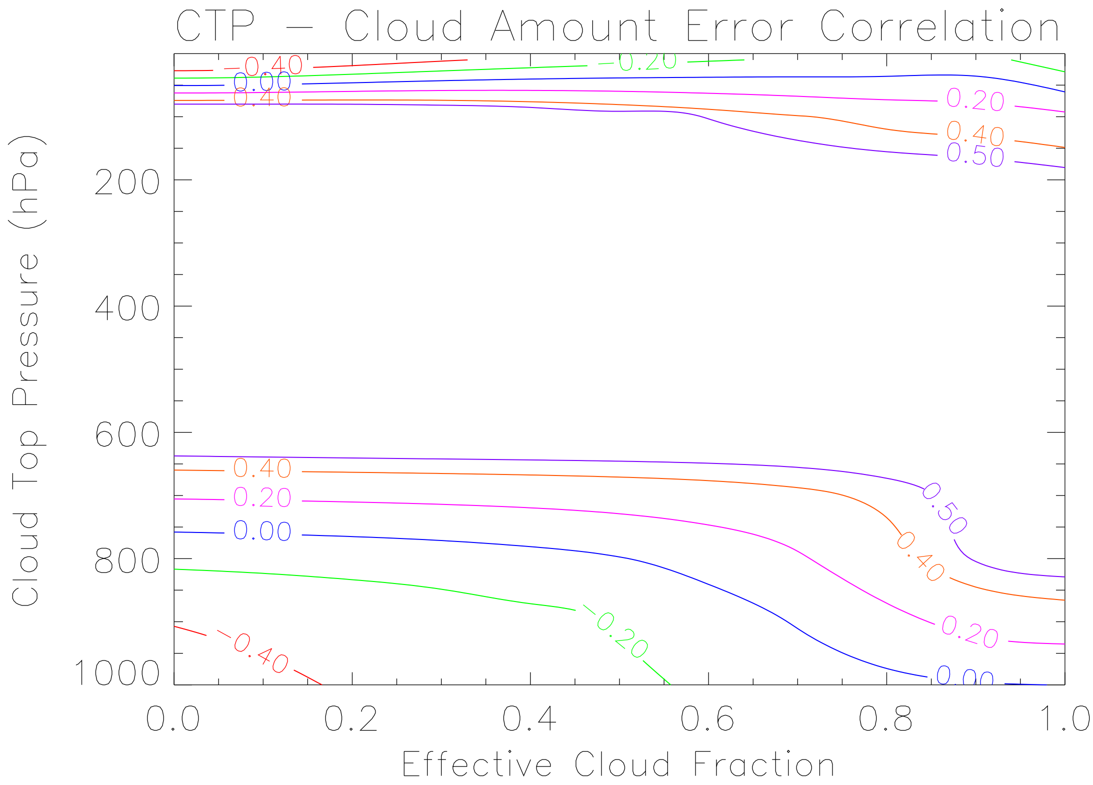

Fig. 11. The retrieval error correlation between cloud top pressure and cloud amount as a function of true cloud top pressure and true cloud amount for IASI when only these two parameters are retrieved.

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