Retrieval of Cloud Parameters from Satellite Sounder Data: A Simulation Study

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ABSTRACT

Estimates of cloud-top pressure and effective fractional cloud cover may be retrieved from satellite infrared sounder data. This paper presents the results of a simulation study which provides some insights into the relative performance of different retrieval methods and of different combinations of spectral channels. The "minimum residual method," a variant of a technique described previously by other authors, is presented. It is applied here to groups of HIRS-2 channels and some aspects of its performance for different combinations of channels are examined using simulated data. It is also compared with the "radiance ratioing method." Calculations suggest that the minimum residual method is comparable in performance to the radiance ratioing method for high cloud but better for midlevel cloud. The relationship (and relative performance) of these methods to that used operationally to assign pressures to cloud tracers in Meteosat data is also discussed. The methods presented are for retrieving cloud parameters alone and have practical applications as such. However, they may also be used as a means of obtaining first-guess cloud parameters within satellite sounding inversion schemes which retrieve simultaneously atmospheric temperature and humidity profiles along with cloud and surface parameters.

1. Introduction

Meteorological satellites have had a major impact on weather forecasting through their ability to detect, depict and locate cloud systems on a global basis. There has also been growing interest and application of quantitative estimates of cloud parameters, such as cloud-top height, fractional coverage and emissivity, in a number of areas. First, such quantities are required in climatological studies, both to provide an accurate description of climate and to assess the realism of numerical climate simulation models. Second, cloud parameters are useful in numerical weather prediction (NWP). Probably the major impact to date in this area has been through the derivation of cloud motion vectors from sequences of geostationary satellite images, and the assignment of heights or pressures to these vectors. There is also growing interest in the assimilation of cloud parameters themselves into the models' humidity and cloud fields, particularly in the context of mesoscale NWP. In addition, the accurate detection of clouds is vital for the correct interpretation of satellite data in terms of other atmospheric variables, such as temperature and humidity profiles, and surface parameters.

Many schemes have been devised for estimating cloud parameters from the data of imaging and sounding radiometers. A review of these methods is given by Isaacs et al. (1986) and recently a further scheme has been presented by Susskind et al. (1987). Multi-spectral infrared sounding instruments such as HIRS-2 (the High-resolution Infrared Radiation Sounder, which forms part of the TIROS Operational Vertical Sounder, TOVS—see Smith et al. 1979) are designed primarily to estimate atmospheric temperature and composition. Nevertheless, they are highly sensitive to the effects of cloud and have distinct advantages for the measurement of certain types of cloud compared with conventional imaging radiometers (which sense radiation mainly in atmospheric window regions). Methods based on infrared sounding data can be used both day and night, whereas most techniques based on image data use visible or near-infrared measurements and are prohibited or degraded at night. Although sounding radiometers have relatively poor spatial resolution, their data can be used to derive accurate cloud parameters in the presence of subpixel or semitransparent cloud which often present problems when analyzing imagery. In particular, sounding instruments offer the capability to detect and quantify thin cirrus cloud both

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in terms of its pressure level and its "effective coverage," i.e., the product of its fractional coverage and its emissivity. This measure of effective coverage is obtained as a natural product of these techniques, but it may also be a very useful parameter in studies to quantify the effects on the radiation budget of these types of cloud. Techniques using infrared window channel imagery (around 11 μm wavelength) tend to assign thin cirrus cloud to an erroneously low level in the atmosphere, although some techniques have been proposed to alleviate the problem. Molnar (1983) has explored an extension of the spatial coherence technique (Coakley and Bretherton 1982) to handle subpixel and semitransparent cloud. With Meteosat imagery, it has proved possible to alleviate the problem somewhat in the case of semitransparent cirrus using simultaneous imagery from the "water vapor channel" at 6.7 μm (Cayla and Tomassini 1978; Szejwach 1982).

A method commonly used with sounding data is the radiance ratioing method (also called the "CO_2 absorption" or "CO_2 slicing" technique) first presented by Smith et al. (1970) and later developed by Smith and Platt (1978) and Menzel et al. (1983). A similar technique has been described by McCleese and Wilson (1976). The theoretical performance of methods based on sounding data has been studied by Wielicki and Coakley (1981) who confirmed the strength of such methods for quantifying upper- and midlevel clouds. They studied the sensitivity of the methods to radiometric noise and errors in the atmospheric profiles assumed in the retrieval of cloud parameters.

In this paper, a different method for cloud parameter retrieval is described. It is similar to the methods outlined by Chahine (1975) and Susskind et al. (1987). In fact, it is a special case of the basic approach Susskind et al. adopt, applied to individual HIRS fields of view with the assumption of a single layer of cloud. The method (hereafter called the "minimum residual" method) is applied here to simulated HIRS data and its performance is compared with the radiance ratioing method. The minimum residual method can be applied with any combination of two or more HIRS channels, and the relative performance of different combinations is assessed. Also, by applying the method using HIRS channels at 11 and 6.7 μm, the "Meteosat method" (Szejwach 1982) is simulated and compared with other techniques.

The simulation method is similar to that adopted by Wielicki and Coakley. However, it differs in a number of respects. Firstly, an ensemble of radiosonde profiles (rather than climatological mean profiles) is used to simulate representative atmospheric conditions. Thus, realistic vertical structure is included. Secondly, realistic errors in the assumed atmospheric profile are simulated using statistics for the vertical error covariance of a 12-h forecast from a NWP model (rather than assuming random errors uncorrelated between adjacent pressure levels).

The method described here was actually developed in this form as a technique for providing first-guess cloud parameters within a TOVS inversion scheme which retrieves simultaneously atmospheric temperature and humidity profiles, surface temperature and microwave emissivity, and cloud-top pressure and amount, using a nonlinear optimal estimation approach (Eyre 1989). Here, it is presented as a "standalone" method for comparison with equivalent techniques. However, the advantages of simultaneous retrieval of atmospheric profile, surface and cloud parameters are discussed.

2. Minimum residual method

The radiance sensed in channel j of a sounding radiometer may often be expressed as

$$R_j = (1 - N)R_j^c + NR_j^o(p), \tag{1}$$

where N is the effective fractional cloud amount, R_j^c is the cloud-free radiance and $R_j^o(p)$ is the radiance corresponding to overcast conditions with cloud-top at pressure p. A single layer of cloud is assumed. For opaque cloud, N is the true fractional cloud amount; for semitransparent cloud, it is the product of the fractional coverage and the cloud emissivity. It is assumed that the cloud emits and absorbs, but that reflection is negligible. Also, it is assumed that N is independent of radiometric channel. This is equivalent to assuming that the channels used are accurately aligned and also, for semitransparent cloud, that the cloud emissivity is independent of wavelength. These assumptions are discussed further in section 5.

Given an estimate of the atmospheric temperature and humidity profiles and the surface temperature (say, from a short-range forecast), we can calculate, using a radiative transfer model, the corresponding value of R_j^c and the values of overcast radiance $R_j^o(p)$ for a range of values of p.

The difference between the measured radiance R_j^m and the calculated radiance R_j is

$$\delta_j = R_j^m - R_j = (R_j^m - R_j^c) - N(R_j^o - R_j^c). \tag{2}$$

We can then define the cloud parameters, N and p, which give the best fit to the measured radiances as those which minimize

$$\sum_j \delta_j^2 = \sum_j [(R_j^m - R_j^c) - N(R_j^o - R_j^c)]^2, \tag{3}$$

where the summation is over two or more channels. Alternatively, if the channels have widely differing noise equivalent radiances σ_j, we might choose $\sum_j (\delta_j/\sigma_j)^2$. In this work, we have chosen to minimize (3). Susskind et al. (1987) chose to minimize residuals in brightness temperature and, given the channels to which it is applied, there is probably little to choose among these methods in practice. Chahine (1975) minimizes the residual in $\sum_j [(R_j^m - R_j)/R_j^m]^2$.

For each cloud-top pressure p, minimizing (3) with respect to N and then solving for N gives

$$N = \frac{\sum_j (R_j^m - R_j^c)[R_j^o(p) - R_j^c]}{\sum_j [R_j^o(p) - R_j^c]^2}. \quad (4)$$

Substituting N back into (3) gives the residual for this cloud pressure:

$$\sum_j \delta_j^2 = \sum_j (R_j^m - R_j^c)^2 - N^2[R_j^o(p) - R_j^c]^2. \quad (5)$$

The value of p which gives the minimum residual and the corresponding value of N are chosen as the retrieved cloud-top pressure and effective fractional coverage.

It is usual to evaluate the radiative transfer equation by summing the contributions of the radiance to space from a number of atmospheric layers bounded by fixed pressure levels (~50 mb apart in the troposphere), and so it is convenient to evaluate overcast radiances for cloud-top at each of these levels only. It is possible to improve the estimate of cloud-top pressure by fitting a curve to the residuals $\sum_j \delta_j^2$ and finding its minimum (and then interpolating N appropriately). In this work, however, the procedure was found to give a negligible improvement in retrieved cloud parameters, and it was not performed for the experiments reported below.

In selecting the best values of p and N, it is possible to apply additional constraints. The fractional cloud amount must lie between zero and one, and the cloud-top pressure must be less than the surface pressure. It is also reasonable to expect it to lie within the troposphere. (In this study, we have considered only midlatitude profiles and have used a constraint, $p \leqslant 200$ mb.)

A complexity arises when a minimum in the residual variance cannot be found (i.e., when the minimum residual occurs at the surface or at the top of the profile). In these cases, we can choose to make no retrieval or else resort to some ad hoc algorithm to handle these cases. In this study, we have taken the latter course in the following manner. For a minimum residual at the top of the profile, the case is taken to be cloud-free if the corresponding fractional cover is less than 0.05. Otherwise, the cloud-top is set at the uppermost level with its corresponding retrieved cloud amount. For a minimum residual at the surface, the case is taken to be cloud-free. It can be seen that there is scope for tuning this decision process to suit the particular application.

3. HIRS Simulation study

The theoretical development in section 2 is quite general and in principle allows us to use any combination of channels, although we must bear in mind the validity of the inherent assumptions. We have restricted consideration to longwave HIRS channels which sound the troposphere (channels 4 to 12). Shortwave channels, particularly the window channels, may be contaminated by solar reflection in the daytime. Also, the assumptions of constant cloud emissivity is more likely to hold over a restricted wavelength range (see section 5 for further discussion of this problem). For reasons discussed below, the principal pair of channels used is HIRS channels 7 and 8 (13.4 and 11.1 μm). Results from the set of five HIRS channels 4–8 (14.2–11.1 μm) are also presented, and other combinations of these channels have been studied. In order to simulate the current operational method for assigning pressures to Meteosat cloud-tracked winds, we have included the pair, HIRS channels 8 and 12 (11.1 and 6.7 μm). Also, for comparison, cloud parameters have been calculated using the radiance ratioing method described by Menzel et al. (1983). Its specific implementation for this simulation study is described in the Appendix.

The retrieval of cloud parameters was simulated as follows. A representative ensemble of "true" atmospheric profiles was taken from a set of radiosonde profiles typical of European and North Atlantic conditions in October (Pescod and Eyre 1983). The "true" surface skin temperature was set equal to the surface air value. The HIRS radiances corresponding to each profile were then calculated using the radiative transfer model, TOVSRAD (Eyre 1984). This is a version (with minor modifications) of the TOVS radiative model which forms part of the International TOVS Processing Package developed at the University of Wisconsin. It is based on the TOVS transmittance routines described by Weinreb et al. (1981). The clear-column radiance model has been modified to calculate the cloudy radiance corresponding to an effective fractional coverage N at pressure p. The values of p and N were specified for each experiment; N was specified exactly, but p was allowed to take a value which varied by a random amount within ±50 mb from the chosen level. This was done in order to minimize any spurious effects arising from the location of the chosen level relative to the fixed pressure levels used in the radiative transfer model. Thus, the "true" radiances corresponding to each "true" profile and cloud state were determined.

The simulated "measured" radiances were calculated by adding Gaussian errors to the true radiances. It is important in studies of this kind to consider all potential sources of error in both the measured and calculated radiances, since it is the radiance difference which determines the retrieved values. Errors in the radiances calculated by the forward model have an effect similar to errors in the measurements. We may assume that, in any operational system, large systematic biases in the calculated radiances may be tuned out. Nevertheless, it is prudent to assume that this cannot be done

TABLE 1. Data used to construct measurement error variance.

HIRS channel	Central wavenumber (cm^{-1})	Central wavelength (μm)	Approximate weighting function peak (mb)	Standard deviation of radiometric error $mW\ m^{-2} \cdot sr^{-1} \cdot [(cm^{-1})^{-1}]$	Standard deviation of forward model error (K)
4	704	14.2	400	0.068	0.2
5	716	14.0	600	0.048	0.2
6	732	13.7	800	0.056	0.2
7	748	13.4	900	0.040	0.2
8	898	11.1	surface	0.019	0.2
12	1484	6.7	500	0.030	0.2

Note: Radiometric errors are typical of NOAA-7 instrument.

perfectly and that a certain level of random error, associated with inaccuracies in the forward model, remains. In this study, we have assumed a forward model error standard deviation of 0.2 K in brightness temperature in all channels. This was converted to an equivalent radiance error through the Planck function evaluated at the temperature equivalent to the true radiance. In addition, the radiometric noise contributes to the error; the values used are given in Table 1. The total error variance was taken as the sum of variances of these two components. In accordance with experience from real HIRS data processing, the forward model uncertainty often dominates the radiometric error for many channels.

To obtain a realistic first guess profile, we have simulated errors in the true profile with statistical properties typical of NWP 12-h forecast errors in Northern Hemisphere midlatitudes. If $\boldsymbol{C}$ is a matrix representing the covariance of forecast error at discrete levels in the vertical, then a realistic forecast profile vector, $\boldsymbol{x}^b$, is obtained by adding an increment to the true profile vector, $\boldsymbol{x}^t$:

$$\boldsymbol{x}^b = \boldsymbol{x}^t + \sum_i \epsilon_i \lambda_i^{0.5} \boldsymbol{v}_i \qquad (6)$$

where $\boldsymbol{v}_i$ and λ_i are, respectively, the eigenvectors and eigenvalues of $\boldsymbol{C}$, and ϵ_i is a random number drawn from a normally distributed population of unit standard deviation. In this way, the ensemble of perturbations has covariance $\boldsymbol{C}$. A value of $\boldsymbol{C}$ typical of 12-h forecast errors from the U.K. Meteorological Office operational regional model was obtained as described by Eyre et al. (1986). The standard deviations of first guess errors (i.e., the square roots of the diagonal elements of $\boldsymbol{C}$) are given in Table 2. The guess profile and its error covariance were extended to the full set of levels used in the radiative transfer model in the manner described by Eyre (1989).

The surface skin temperature error given in Table 2 is rather low; it is perhaps typical of NWP model errors over the ocean but not over land. Consequently, the simulations have been repeated using a value more typical of land: the surface skin error variance was set equal to the surface air error variance plus 8 K^2, giving a standard deviation for surface skin temperature error of 3.67 K. The covariances of surface skin errors with those at other levels were set equal to the corresponding surface air values. [Note also that the increments to the first guess profile error in (6) will now be different, because the eigenvectors of $\boldsymbol{C}$ have changed.]

The profile $\boldsymbol{x}^b$ was used as the guess profile for the retrieval simulation, and from it the corresponding clear radiances were calculated along with the overcast radiances for cloud at each of the fixed pressure levels used in the radiative transfer model. The simulated values of measured and guess radiance were then applied in (4) and (5) to obtain the retrieved cloud parameters for each combination of channels under test. They were also applied in the equivalent algorithm for the radiance ratioing method. The retrieved cloud parameters were then compared with the "true" cloud parameters to assess the accuracy of the method for each combination of channels.

TABLE 2. Standard deviation of first-guess profile error.

Variable	Level (mb)	Error
Temperature (K)	50	2.03
	70	2.08
	100	1.90
	150	1.72
	200	1.99
	250	2.69
	300	1.90
	400	2.03
	500	1.75
	700	1.90
	850	2.15
	1000	2.53
ln$q$	300	0.54
	400	0.59
	500	0.53
	700	0.46
	850	0.37
	1000	0.30
Surface air temperature (K)	—	2.34
Surface ln$q$	—	0.31
Surface skin temperature (K)	—	1.74

q = water vapor mixing ratio in g/Kg.

Finally, a comment regarding the statistical comparison of retrieved and true cloud-top pressures: when a case is declared cloud-free, it poses a problem because it does not have a cloud-top pressure. Equally, to exclude these cases from the statistics creates a problem because different algorithms will no longer be compared over the same sample. In this study, we have assigned these cases a cloud-top pressure of 1000 mb and included all cases in the statistics. The consequences of this must be borne in mind when interpreting the results. It tends to show the algorithms to be worse than they really are, but it should preserve the relative performance of different algorithms.

4. Results

Radiances were simulated and cloud parameters retrieved for 200 profiles for each combination of three cloud-top pressures (350, 600 and 850 mb corresponding to high-, medium- and low-level cloud) and five fractional cloud amounts (0, 0.2, 0.5, 0.8 and 1.0). Retrievals were made using the following algorithms:

1) the minimum residual method using HIRS channel 7 and 8

2) the minimum residual method using channels 4, 5, 6, 7 and 8,

3) the minimum residual method using channels 8 and 12, and

4) the radiance ratioing method using channels 4–8 as described in the Appendix.

These results are presented below. In addition, the new method was tested with channel combinations 6 and 7, 5 and 6, 4 and 5, and 5 and 7. These results are not reported in detail; they were consistent with and helped to confirm the conclusions discussed below. The calculations made use of the radiance error and first guess error data described in section 3.

Figures 1 and 2 show the r.m.s. retrieval errors for cloud-top pressure and cloud amount using algorithms 1–4. For high cloud, all methods show considerable skill in retrieving both cloud-top pressure and amount. As expected, errors increase as the cloud amount decreases. Method 3 degrades faster than the others in this respect. For medium-level cloud, the performance of all methods is not as good, but errors in cloud-top pressure retrieval are still quite low (<100 mb r.m.s.) for moderate to large cloud amounts with methods 1, 2 and 4. Method 1 is significantly better than the others, and method 3 is considerably worse. For low cloud, all methods give poor results. Methods 1 and 4 are least poor in cloud-top pressure retrieval for large cloud amounts, with method 4 significantly better at small cloud amounts. Cloud amount retrievals at this level are so poor as not to merit detailed discussion. However, they do show that, when faced with the decision of whether to opt for no cloud or large amounts of low-level cloud, method 1 tends to opt for the former and method 4 the latter. Moreover, these tendencies result largely from the logic of the algorithms when a minimum residual in (5), or its equivalent in method 4, cannot be found; these could easily be changed by tuning.

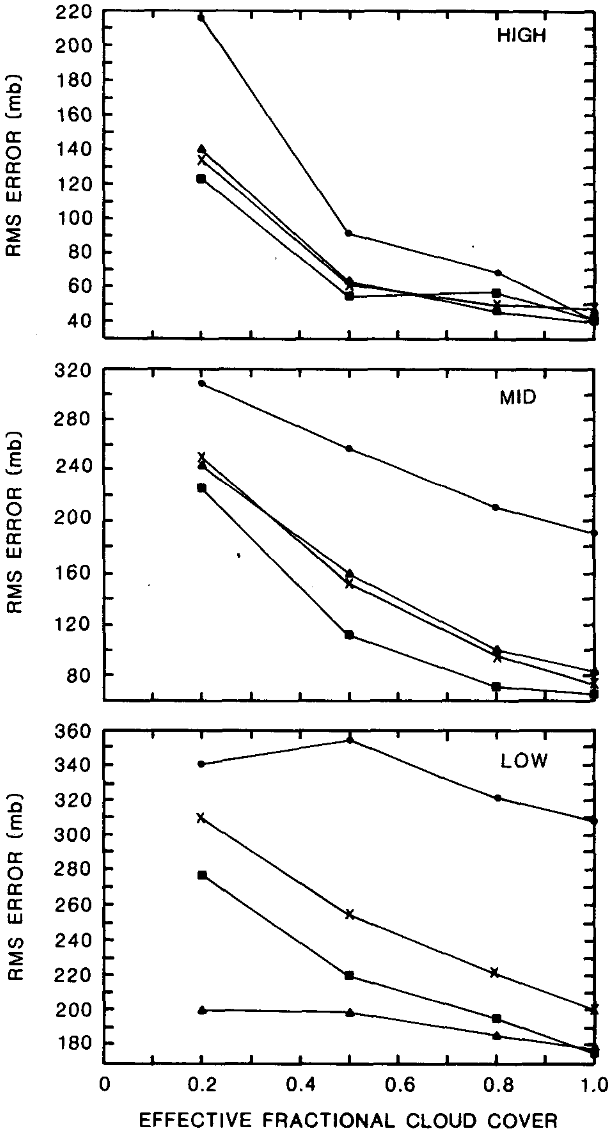

FIG. 1. Error in retrieved cloud-top pressure for high-, mid- and low-level cloud. ■: method 1; ×: method 2; ●: method 3; ▲: method 4. (See text for description.)

Wielicki and Coakley (1981) commented on the importance of first guess error in determining the performance of such algorithms. Our experiments confirm this finding and we illustrate this with the example of increased surface skin temperature error discussed in section 3. The retrieval simulations were repeated with the increased value and the results for cloud-top pressure errors are given in Fig. 3. The effect of the increased error is to degrade retrievals in partly cloudy conditions.

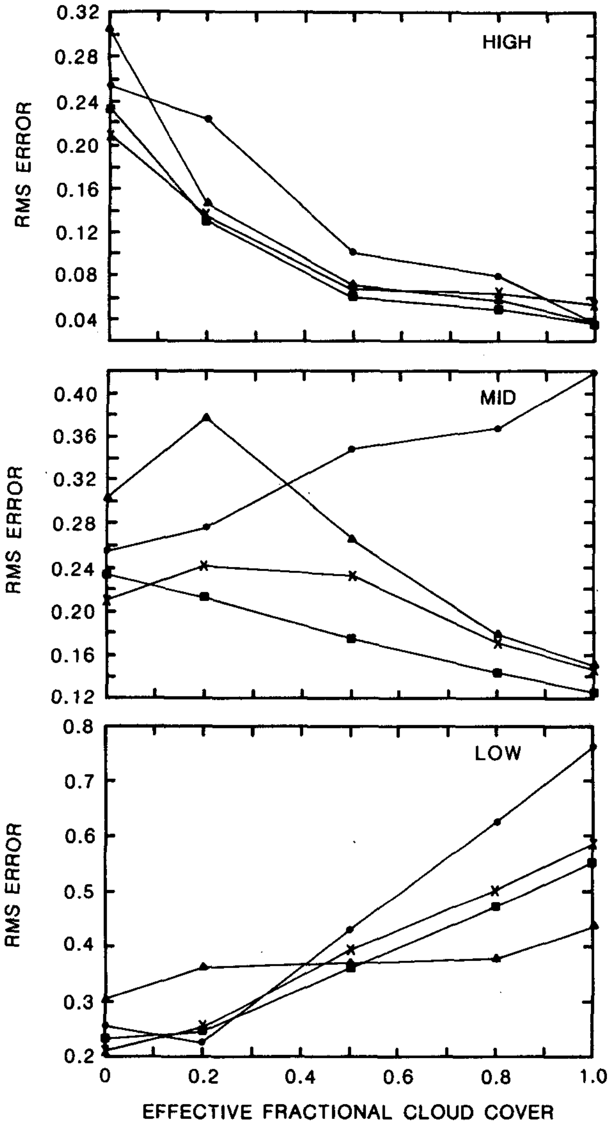

FIG. 2. Error in retrieved fractional cloud amount. Symbols as in Fig. 1.

There is also a tendency for method 1 to degrade more than methods 2 and 4, although method 1 still retains its superiority for midlevel cloud.

5. Discussion

These results demonstrate that the minimum residual method is effective in retrieving cloud parameters for mid- and upper-level cloud. These experiments, and equivalent ones with other combinations of HIRS channels, show that the best combination is the pair, 7 and 8 (i.e., the lowest-sounding carbon dioxide channel and a window channel). This combination gives results comparable with the CO$_2$ absorption method for high cloud and improves upon it for midlevel cloud.

The superiority of method 1 with 2 channels over method 2 with 5 channels is interesting and counterintuitive; one might expect that additional channels could only improve the performance. The reason seems to be related to the inherent assumption that the first guess profile is correct, whereas it is actually in error. Errors in mid- to upper-tropospheric temperature profiles have a much larger effect on calculated radiances in HIRS channels 4, 5 and 6 than in 7 and 8. Errors in the calculated radiances propagate through into errors in the retrieved cloud parameters. For the same reason, an increased error in skin temperature is likely to degrade method 1, with its reliance on window

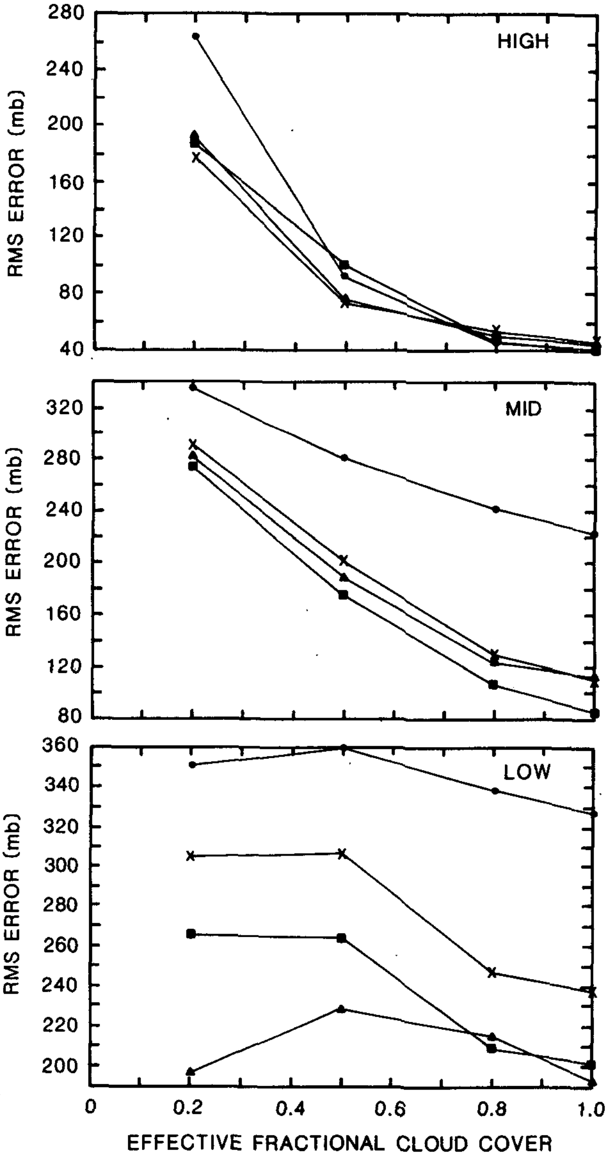

FIG. 3. Error in retrieved cloud-top pressure with high surface skin temperature errors. Symbols as in Fig. 1.

channel information, more than other methods. However, the removal of channel 8 from the method would reduce even further the sensitivity to low-level cloud. It should be noted that these effects will be less pronounced if a more accurate temperature profile (from a retrieval or analysis) is used rather than a forecast profile.

Method 3 is shown to be comparable with other methods for large amounts of high cloud, but to degrade faster at reduced cloud amount and for lower level clouds. These findings are relevant to the selection of channels for future imaging radiometers which will supply data for generating cloud-tracked winds and assigning heights to them.

The poor performance of all the algorithms for low-level cloud is not surprising. Methods relying solely on longwave infrared radiances have difficulty in detecting the presence of low cloud, particularly when the atmospheric profile is uncertain and may contain detailed vertical structure and low-level inversions. However, HIRS does contain other channels in which such cloud has a more recognizable signature. For example, in the daytime, the visible channel may be used. At night, cloud can be recognized through the brightness temperature difference between shortwave and longwave window channels which results from the lower emissivity (higher reflectivity) of water clouds at the shorter wavelength (Eyre et al. 1984). Also, the Advanced Very High Resolution Radiometers (AVHRR) on the same satellites yield such information at higher spatial resolutions. Therefore, at the expense of more complicated algorithms, recognition and analysis of low-level cloud could be much improved, or these additional sources of information could be used for quality control.

The methods discussed here all make the assumption that the effective fractional cloud cover (and hence the cloud emissivity) is independent of wavelength. This may cause problems when the methods are applied to real data, particularly semitransparent ice cloud. Wu (1987) has presented theoretical calculations which suggest significant effects from emissivity differences between the wavelengths of the channels considered in this study. The effect is also apparent in data from the 11 and 12 μm channels of AVHRR (for example, see Inoue 1985). On the other hand, this phenomenon does not appear to have caused noticeable problems with multichannel methods for cloud-top pressure determination, and the magnitude of the effect will be sensitive to the microphysical properties of the cloud. In general, the possibility of such effects suggests that we should base multichannel methods on channels which are as close together in frequency as possible. Later versions of the HIRS instrument are expected to include a 12 μm channel in addition to those considered here. For these instruments, it will probably be desirable to use the 12 μm channel instead of the 11.1 μm (HIRS channel 8), since the former is closer in wavelength to HIRS channel 7 at 13.4 μm.

The methods discussed here make a number of other assumptions which may not be valid. Firstly, only one layer of homogeneous cloud is assumed. Because the method is applied to single HIRS fields of view, the assumption is likely to hold more often than in similar methods using groups of fields of view. Eyre et al. (1986) have shown, using AVHRR and HIRS data, that the assumption of a single cloud layer with a uniform cloud-top height usually holds within a HIRS field of view but seldom holds between adjacent fields of view. The problem of multilayer cloud has been considered further by Eyre (1989) in the context of simultaneous retrieval of cloud and profile parameters. The results suggest that TOVS is relatively insensitive to the presence of multilayer cloud. The results of Susskind et al. (1987) would seem to confirm this, although they do show some skill in detecting and retrieving these conditions. Secondly, surface emissivity is assumed constant in this study. It is not necessary to do this and a different value could be assumed (for example, from knowledge of the surface type). However, errors in the assumed surface emissivity and its spectral dependence will lead to errors in cloud parameters.

For these and other reasons, there is often scope for errors in the retrieval cloud parameters and so quality control is a vital part of any method applied to real data. The appropriate method will depend very much on the application of the product, and so a full discussion is beyond the scope of this paper. However, we agree with Susskind et al. (1987) that a high residual variance can indicate that some of the assumptions are not valid. The residual variance will also depend on the accuracy of the assumed profile, and so the value of residual variance compared with neighbouring values may be more useful than the absolute value.

As noted in the Introduction, the method described here was developed as part of scheme in which cloud parameters are retrieved simultaneously with atmospheric profile and surface parameters using HIRS and MSU (Microwave Sounding Unit) data. Within this scheme, method 1 is used to provide the first-guess cloud parameters. The development of the scheme and its error characteristics are reported fully elsewhere (Eyre 1989); it is shown that a simultaneous retrieval of all parameters yields cloud parameters of much greater accuracy than the "stand-alone" method. Most of the improvement arises from the combined use of microwave and infrared channels. For example, with a cloud-top at 350 mb and a fractional coverage of 0.5, the simultaneous method gives r.m.s. errors of 18 mb in pressure and 0.03 in fractional coverage (compared with 54 mb and 0.06 in this study). At 600 mb, corresponding values are 44 mb and 0.09 (compared with 112 mb and 0.18), and comparable improvements are obtained for all cloud conditions. Other schemes using TOVS data in which cloud parameters are retrieved concurrently with profile information (e.g., Susskind et al. 1984, 1987; Huang and Smith 1986) should give comparable results. On the other hand, the stand-alone scheme does not require a lengthy retrieval and so is much simpler and less demanding of computer resources. It also has application to multispectral high-resolution image data in which the full range of sounding channels are not available.

The study reported here has used simulated data. By doing so, it has been possible to compare the behavior and error characteristics of different methods in a way which is almost impossible with real data, because of the difficulties associated with validation and the lack of independent observations of the "truth." It has also been possible to explore some aspects of the behavior of these schemes which are obscured when a complicated method is applied to real data. Simulation studies have their weaknesses, as it is difficult to address all the problems which arise with real data, and the results must be treated with caution for this reason. The application of this or similar methods to real data remains a considerable challenge, particularly if on a global scale, and the work of Susskind et al. (1987) represents a significant step along this path. The object of the study presented here has been to address some of the characteristics and limitations of these methods, which allow them to be better understood and improved.

In summary, the simulation experiments reported here confirm that infrared sounding data offer the potential for cloud parameter retrievals of useful accuracy. They are complementary to conventional image data through their ability to generate accurate products for broken or semitransparent clouds at middle and upper levels.

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APPENDIX

Application of Radiance Ratioing Method to HIRS

Menzel et al. (1983) described the application of the radiance ratioing ("carbon dioxide absorption") method to data from the Visible Infrared Spin Scan Radiometer Atmospheric Sounder (VAS) on the GOES satellite series. The method used here is essentially the same, but we describe its specific formulation as an algorithm applied to HIRS data.

First, a check for clear conditions is made: using the notation of section 2, if $(R_8^m - R_8^c) > -1$ mW m^{-2} sr^{-1} (cm^{-1})$^{-1}$ or RU, then the cloud amount is set to zero.

Otherwise, the radiance ratio method is applied to a pair of HIRS channels, i and j, in the following way: the pressure level is found for which

$$|(R_i^m - R_i^c)[R_j^o(p) - R_j^c] - (R_j^m - R_j^c)[R_i^o(p) - R_i^c]| = \text{minimum}. \quad \text{(A1)}$$

This is equivalent to solving the radiance ratio equation [Menzel et al., Eq. (1)]. The pressure level which satisfies (A1) is found for each of the following pairs of HIRS channels: 4 and 5, 5 and 6, 6 and 7, and 5 and 7. For each pair, the corresponding fractional cloud cover N is obtained by solving the radiative transfer equation for channel 8:

$$N = \frac{R_8^m - R_8^c}{R_8^o(p) - R_8^c}. \quad \text{(A2)}$$

[If $|R_8^o(p) - R_8^c| < 0.1$ RU, then N is set equal to zero.] Then N is substituted back into the radiative transfer equation for channels 4–7 at the corresponding cloud-top pressure, to find the channel pair which gives the least discrepancy between measured and simulated radiances:

$$\sum_{k=4}^{7} \{(R_k^m - R_k^c) - N[R_k^o(p) - R_k^c]\}^2 = \text{minimum}. \quad \text{(A3)}$$

The values of p and N for the pair of channels which minimizes (A3) are chosen as the best values. However, the following checks are also performed. Erroneous high cloud is screened by a check on HIRS channel 5: if $(R_5^m - R_5^c) \geqslant 1$ RU and $p < 300$ mb, then the cloud amount is set to zero.

If the ratioing algorithm has suggested a cloud-top at the surface, then the best level is calculated using HIRS channel 8 above: the pressure level is chosen for which

$$|R_8^m - R_8^o(p)| = \text{minimum} \quad \text{(A4)}$$

and N is calculated from (A2). Finally, the constraint $0 \leqslant N \leqslant 1$ is applied.

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