A sequential estimation approach to cloud-clearing for satellite temperature sounding

By J. R. EYRE and P. D. WATTS

Meteorological Office Unit, Robert Hooke Institute for Co-operative Atmospheric Research, Clarendon Laboratory, Oxford

(Received 10 September 1986; revised 6 February 1987)

SUMMARY

Temperature sounding of the troposphere using satellite-borne infrared radiometers is complicated by the effects of clouds on the measured radiances. If accurate products are to be obtained these effects must first be detected and, if possible, corrections must be made for them in the retrieval procedures. This is normally done by converting the measured radiances to the ‘clear-column’ values which would be observed from the same atmospheric profile in the absence of cloud—a process known as ‘cloud-clearing’.

In this paper a review of cloud-clearing methods is presented. Then a new approach to cloud-clearing, based on the principles of optimal estimation, is developed and applied to data from HIRS (the High-resolution Infrared Radiation Sounder) on the TIROS-N/NOAA satellite series.

Preliminary estimates of clear-column radiances and their expected errors are obtained at each HIRS spot by one of a number of methods, depending on the cloud characteristics. The properties of horizontal consistency expected in the clear-column radiance field are then employed to improve the initial estimates using a sequential estimation procedure. This scheme is intended for implementation in the Local Area Sounding System of the Meteorological Office, which provides satellite soundings of high horizontal resolution for use in operational weather forecasting. Details of the new scheme, and of the old scheme which it replaces, are given. The improvements in clear-column radiances are demonstrated by comparing the products of the old and new schemes with clear-column radiances derived from coincident data of AVHRR (the Advanced Very High Resolution Radiometer).

1. INTRODUCTION

Current techniques for observing the temperature of the atmosphere from satellites are based on measurements of upwelling radiation in the infrared and microwave spectral regions. These radiances are affected, to a greater or lesser degree, by the presence of cloud. At infrared wavelengths the problem is acute since most clouds are almost opaque; in the microwave region clouds often have a negligible effect on the radiances, although problems occur in areas of heavy precipitation. Consequently, when retrieving tropospheric temperature, we must be able to detect clouds which have significant effects on the radiances and, if possible, make allowances for these effects. For infrared soundings, this is usually done by correcting the measured radiances to ‘clear-column’ values, i.e. to the radiances which would be measured from the same temperature and humidity profiles in the absence of cloud. In most retrieval schemes, the inversion process which produces atmospheric profiles operates on clear-column rather than measured radiances, and so a preliminary ‘cloud-clearing’ step is required. In some schemes the inversion and cloud-clearing interact in a complicated manner, but there is usually a cloud-clearing step implicit in the algorithm. It can be seen therefore that cloud-clearing plays a central role in current retrieval schemes. Cloud-clearing algorithms have been developed which are generally successful in providing usable clear-column radiances in moderately cloudy areas. However, weaknesses in the methods used are still major contributors to the errors in the final retrieved temperature profiles, particularly in the lower troposphere. Problems are caused both by deficiencies in the detection of cloud-contaminated radiances and by errors in the corrections made to the radiances identified as cloudy.

Temperature sounding for the purposes of operational weather forecasting is currently performed using the TIROS Operational Vertical Sounder (TOVS) instruments on the TIROS-N series of polar-orbiting satellites (see Schwalb 1978 and Smith et al.)
1979). TOVS consists of three instruments, two of which are used for tropospheric sounding: the High-resolution Infrared Radiation Sounder (HIRS-2) and the Microwave Sounding Unit (MSU). In this paper, we review the methods which have been devised for cloud-clearing sounding data from TOVS and earlier sounding instruments. We then develop an approach to the cloud-clearing problem which should lead to more nearly optimal values for the clear-column radiances, when used in combination with one or more of the methods previously devised. An 'optimal' method in this sense is one which uses estimates of the clear-column radiance from all possible sources, together with their probable errors, and combines them in a statistically optimal manner to obtain the best estimate of the clear-column radiance (together with its probable error). This approach can be applied to cloud-clearing TOVS data, and we have developed a new method for use in the Local Area Sounding System (LASS) of the Meteorological Office to produce real-time satellite sounding data for use in operational weather forecasting (Eyre 1984; Turner et al. 1985). Details of this cloud-clearing scheme are described, and results are presented from an exercise in which data from the Advanced Very High Resolution Radiometer (AVHRR) have been used to validate the new scheme.

Most of the discussion in this paper assumes that our principle problem is to estimate the clear-column radiances for HIRS. The problem as it affects MSU is treated as secondary for two reasons. Firstly, retrievals from HIRS data or HIRS plus MSU data are preferred to retrievals from MSU alone, since MSU has inferior horizontal and vertical resolution compared with HIRS. Secondly, as stated above, the effects of cloud on the microwave radiances are very much less than on the infrared. However, it is expected that the contamination of MSU radiances caused by cloud and precipitation could be treated by a similar optimal approach. Also, the general principles of an optimal method should be applicable to similar sounding systems.

2. REVIEW OF CLOUD-CLEARING METHODS

Before a satellite with temperature sounding capability was launched, Smith (1967) gave an analysis of the cloud-clearing problem and suggested its solution using radiances in adjacent fields-of-view. The same author developed this approach and proposed the so-called $N^*$ method (Smith 1968). This technique has been widely adopted as a basis for other methods, and so it justifies a detailed description.

The measured radiances, $R_1$ and $R_2$, in two adjacent fields-of-view (hereafter referred to as 'spots') of a radiometer channel can, under certain conditions, be expressed as follows:

$$R_1 = (1 - N_1)R_c + N_1 R_o$$
$$R_2 = (1 - N_2)R_c + N_2 R_o$$

where $R_c$ and $R_o$ are the radiances appropriate to clear and completely overcast conditions respectively, and $N_1$ and $N_2$ are the effective fractional cloud coverages in spots 1 and 2. In deriving these equations the following assumptions have been made: that the atmospheric profiles and surface characteristics in the two spots are the same; that only one layer of cloud is present; and that the cloud top has the same height (and temperature) in both spots. These assumptions are necessary if $R_c$ and $R_o$ are to be taken as constant between spots 1 and 2. If the fractional coverages in the two spots are different ($N_1 \neq N_2$), the Eqs. (1) can be solved simultaneously to give the clear radiance:

$$R_c = (R_1 - N^* R_2)/(1 - N^*)$$
where $N^* = N_1/N_2$. Alternatively,
\[ N^* = (R_c - R_1)/(R_c - R_2) \]  
(3)

and so $N^*$ can be found if we have an estimate of the clear radiances in one channel. (Various methods for deriving the clear radiances in one channel are discussed below.) Then, since $N^*$ is equal in all channels of the radiometer, it can be used in Eq. (2) to find the clear radiances in other channels. For infrared radiometers with moderately high horizontal resolution (e.g. HIRS, which has a field-of-view spacing of about 40 km), the inherent assumptions are true sufficiently often for the method to be useful.

McMillin et al. (1973) described an application of this method for the Vertical Temperature Profile Radiometer (VTNR) on the early members of the NOAA series of satellites. The clear-column radiance in one channel required by Eq. (3) was obtained using data from the Scanning Radiometer (a 2-channel instrument of higher horizontal resolution) on the same satellite.

The next two methods outlined were early proposals for cloud-clearing with a single field-of-view approach. Rodgers (1970) proposed a method based on probability density functions for a multi-channel radiometer and cloudy atmospheric profiles. He suggested an implementation based on a 'library' of cases to select the most probable temperature profile and cloud field consistent with the measured radiances. Smith et al. (1970) suggested a technique in which cloud height and coverage are adjusted to give the best agreement with the measured radiances. The method employs an iterative approach: measured radiances are compared with radiances calculated from a first-guess temperature profile, and the profile and cloud parameters are then adjusted iteratively until agreement between measured and calculated values is reached. The solution for the temperature profile below cloud tends to be dependent on the first guess. A review of these early methods is given by Fritz et al. (1972).

Chahine (1970) gave an analysis of the cloud-clearing problem similar to that given by Smith (1968) and later developed an alternative adjacent field-of-view method (Chahine 1974). Equation (2) can be expressed:
\[ R_c = R_1 + \eta(R_1 - R_2). \]  
(4)

Here
\[ \eta = N_1/(N_2 - N_1) \]  
(5)
or
\[ \eta = [R_c(\nu') - R_1(\nu')]/[R_1(\nu') - R_2(\nu')] \]  
(6)

where $\nu'$ is the frequency of a specially selected 'cloud-sounding' channel. In an iterative approach, a first-guess profile is used with a radiative transfer model to generate $R_c(\nu')$. Equation (6) then gives $\eta$ which is used in Eq. (4) to calculate $R_c(\nu_j)$ for other channels at frequencies $\nu_j$. Chahine shows that the method is stable in certain cases, for example when $\nu'$ refers to a channel in the 15 $\mu$m carbon dioxide band, with a weighting function peaking in the lower troposphere, and $\nu_j$ represent a set of channels in the 4-3 $\mu$m carbon dioxide band. This approach is generalized by Chahine (1977) to multiple cloud layers using a group of up to four adjacent spots. Susskind et al. (1982) present details of a scheme for applying the single cloud layer method (Chahine 1974) to HIRS data. HIRS channel 7 at 13-4 $\mu$m is used as the 'cloud-sounding' channel and the 4-3 $\mu$m band channels only (numbers 13 to 17) are used for the temperature retrieval. In addition, when MSU data are available, a similar scheme is employed which solves for the temperature profile and cloud using only MSU and the 4-3 $\mu$m band channels of HIRS. An extension to this method is given by Susskind and Reuter (1985).
McMillin (1978) presents another version of the adjacent field-of-view approach which is closely related to the $N^*$ method. By writing Eqs. (1) for two spots and two frequencies ($\nu_a$ and $\nu_b$), four equations are obtained which may be solved simultaneously to give

$$R_c(\nu_a) = R_1(\nu_a) + S[R_c(\nu_b) - R_1(\nu_b)]$$

(7)

where

$$S = (R_1(\nu_a) - R_2(\nu_a))/(R_1(\nu_b) - R_2(\nu_b)).$$

(8)

Again these equations are valid under the same assumptions as those for which the $N^*$ method applies. McMillin shows that if several adjacent pairs are considered, those pairs for which the assumptions are valid will yield the same value of $S$; other pairs will tend to give different values. Only 'good' values of $S$ are then used in Eq. (7) to generate the clear radiance. The method still requires an estimate of the clear-column radiance in one channel.

Smith and Woolf (1976) develop a variation of the $N^*$ technique for use with HIRS and SCAMS (SCANning Microwave Spectrometer) data from Nimbus 6. In this method $N^*$ is obtained from measured radiances in all channels, infrared and microwave, using eigenvectors of the covariance matrix of clear-column radiances (pre-calculated using a representative set of clear radiances). The microwave data play an important role here; they allow the cloud-clearing to proceed without the need for estimates from other sources of the clear radiance in one infrared channel. From 1978 to 1980 this method formed the basis of the cloud-clearing scheme used with HIRS and MSU data in the operational global retrieval system of NOAA/NESDIS (see Smith et al. 1979).

In 1980 the operational system was changed to incorporate a new cloud-clearing algorithm described by McMillin and Dean (1982). This algorithm is again based on the $N^*$ method but takes great care to allow for the fact that the assumption of equal cloud height in adjacent spots is often invalid. To detect those cases in which the $N^*$ method is applicable a series of checks is made. Firstly, a thorough treatment is given to the detection of clear areas, including inter-channel regression relations between MSU channels, HIRS long-wave (15 $\mu$m) channels and HIRS short-wave (4-3 $\mu$m) channels. In areas found to be partly cloudy, the $N^*$ method is applied with a series of tests to check its validity, including some based on the approach of McMillin (1978). Also, $N^*$ is calculated in two ways: from HIRS and MSU radiances, and from HIRS long-wave and short-wave radiances. The latter approach is an extension of the method developed by Chahine (1974), but it does not require radiative transfer calculations as part of the algorithm. The two values obtained are required to be consistent. Finally, using the best value of $N^*$, the clear column radiances are calculated and another set of checks based on inter-channel regression is performed.

The methods described so far have mainly been developed to tackle the problem of global temperature retrievals in which profiles are required on a scale of about 250 km, which is significantly greater than the scale of the individual soundings (cf. HIRS field-of-view spacing of about 40 km). Smith (1980) presents two cloud-clearing methods more suited to regional or mesoscale applications, in which clear radiances are obtained at higher horizontal resolution. The first algorithm is based on the $N^*$ method applied to a box of 3 x 3 HIRS soundings. This scheme was used for routine TOVS data processing by the Meteorological Office from 1983 to 1986 and is described in detail in appendix A. The second algorithm is a single field-of-view method appropriate to overcast conditions (under which the $N^*$ method fails) and follows the approach of Smith et al. (1970); it is developed further by Smith et al. (1985). The same two approaches are reported by
Hayden et al. (1981) in an application intended for retrieval of high resolution moisture fields from TOVS.

An alternative method is given by Smith et al. (1984). Differences between measured radiances and those computed from a first-guess profile are examined to determine which channels have been contaminated by cloud, and only the uncontaminated channels are used in the inversion. It is a cloud detection scheme but is not strictly a cloud-clearing method.

Another method designed for high resolution applications is the ‘ψ method’ (Chedin and Scott 1984; Chedin et al. 1985). If cloud is detected in a small group of HIRS spots by a series of checks which follow closely the approach of McMillin and Dean (1982), then the ψ method is applied to estimate the clear radiances in a number of HIRS tropospheric channels. Measurements in channels which are not cloud-affected (MSU and stratospheric-sensing HIRS channels), together with ancillary information including forecast fields of surface parameters, are used to select a first-guess profile from a large library of radiosonde data and associated TOVS brightness temperatures calculated from them theoretically. The HIRS channel to be cleared is paired with the MSU channel with the most similar weighting function. Their brightness temperature difference for the profile chosen from the library is added to the measured MSU brightness temperature to yield an estimate of the cloud-free HIRS brightness temperature.

An attractive idea for improving cloud-clearing is to use simultaneously measured, very-high-resolution imagery in conjunction with the sounding data. This offers the opportunity to ‘see’ through holes in cloud fields which occur on scales of the order of the resolution of the sounding system (or even smaller scales), and to provide more information on the characteristics of the cloud field. Aoki (1980, 1982, 1984) develops a method of using AVHRR data to assist in the calculation of clear-column HIRS radiances. In this particular method, AVHRR data are employed to calculate the fractional cloud coverages in a group of HIRS spots. A statistical approach is then used to obtain the best estimate of the clear-column radiances for the group in all channels. The retrieval method reported requires initial estimates of the temperature profile and surface temperature. Recently other groups have initiated alternative approaches to the problem of extracting a small number of parameters from AVHRR pixels co-located with each HIRS spot to improve the cloud detection and clear radiances determination for that spot (Hayden et al. 1985; Taylor et al. 1985; Lloyd et al. 1985).

The problem of obtaining clear-column radiance fields which are horizontally consistent and free from isolated gross errors is examined by Fleming and Hill (1982). They develop a one-dimensional technique which can both detect and correct for rogue points in a field of geophysical data and illustrate it by application to the cloud-clearing problem. The approach has also been extended to more than one dimension (Fleming and Hill 1983).

Two other techniques have recently been proposed which use a sequential estimation approach in order to make use of the horizontal consistency expected in the clear radiances fields. Prata (1985) illustrates the application of a Kalman filter to the original, cloud-contaminated radiances. Eyre et al. (1985) outline a method for applying a sequential estimation filter to a radiances field which has already undergone a preliminary cloud-clearing; this technique is developed and described in detail in the remainder of this paper.
3. THEORY OF AN OPTIMAL APPROACH

In an optimal method, the clear radiances are estimated using all the available information together with estimates of the expected error in each piece of information. Care is taken to account correctly for the inter-dependence (if any) of the different pieces of information. Thus for one radiometer channel, if we have \( i \) independent 'observations' of the clear radiancy, \( x_i \), with errors of Gaussian distribution and variances \( \sigma_i^2 \), we can combine the observations to give the best estimate of the clear radiancy, \( \hat{x} \):

\[
\hat{x} = \left( \Sigma_i \frac{1}{\sigma_i^2} \right)^{-1} \Sigma_i \frac{x_i}{\sigma_i^2}
\]

with variance

\[
\hat{\sigma}^2 = \left( \Sigma_i \frac{1}{\sigma_i^2} \right)^{-1}.
\]

This is the scalar approach appropriate to estimating the clear-column radiancy in one channel independently from the other channels. In principle it would be better to estimate the clear-column radiancy vector for all channels, \( \hat{x} \), from \( i \) independent vectors \( x_i \):

\[
\hat{x} = (\Sigma_i S_i^{-1})^{-1} \cdot (\Sigma_i S_i^{-1} \cdot x_i)
\]

and

\[
\hat{S} = (\Sigma_i S_i^{-1})^{-1}
\]

where \( S_i \) are now the corresponding error covariance matrices and \( ^{-1} \) denotes matrix inverse. Whether this approach is practicable may largely depend on considerations such as the processing time required for the matrix manipulations involved. Also the correlation between errors in different channels may be a strong function of the cloud-clearing method used, and the computation of the \( S \) matrices will not in general be straightforward.

The approach to the optimal combination of information from different sources is widely used. Its application in the general context of retrieval theory for remote sounding is discussed further by Rodgers (1976). The same approach provides the basis for many methods of objective analysis used in numerical weather prediction (see, for example, Lorenz 1986).

4. APPLICATION TO HIRS CLOUD-CLEARING

The HIRS instrument has 20 channels of which 19 are situated in the infrared between 15 and 3-7 \( \mu m \) (see Smith et al. 1979). Of these, four are sensitive almost entirely to stratospheric emission and are therefore unaffected by cloud in the vast majority of cases. This leaves 15 channels, numbers 4–16 and 18–19, which are tropospheric and surface sensing channels subject to cloud contamination. HIRS has a field-of-view with a size at the earth's surface of about 17 km and a spacing between field-of-view centres of about 40 km. On the same satellite sounding simultaneously with HIRS are MSU, a 4-channel radiometer with a spacing between field-of-view centres of about 170 km, and AVHRR, a visible and infrared imaging radiometer with a pixel size of about 1 km (see Schwalb 1978). The scan patterns of HIRS and MSU are shown in Fig. 1.

The pieces of information which may be useful for the present problem of finding the clear-column radiancy in a given channel in a given HIRS spot are as follows:
(a) The most obvious information is that used in all current methods, i.e. the measured, potentially cloud-contaminated radiances at that spot. In addition, we need some algorithm for converting this to a clear-column radiances. All such algorithms will require ancillary information, such as: measured radiances in other channels and in adjacent spots; MSU radiances (preferably tested and, if necessary, corrected for any contamination by cloud and precipitation); AVHRR radiances in the region of the HIRS sounding; an a priori estimate of the atmospheric profile, from a numerical forecast model for example, together with a radiative transfer model from which radiances may be calculated; surface observations or analyses (of skin temperature and surface air temperature and dewpoint). Calculating the expected error in the clear radiances estimate from these data will involve consideration of the instrumental random error (noise), the additional ‘noise’ introduced by any pre-processing (which has been performed to correct the measured HIRS radiances for various effects such as those caused by scan angle or surface emissivity), the expected errors in the ancillary information, and the way in which the algorithm amplifies these error components.

(b) Useful sources of information unused by most cloud-clearing schemes (except as a final quality control) and the clear radiances in previously processed, nearby spots. ‘Nearby’ in this context need not necessarily refer to adjacent spots but to those HIRS spots on which similar cloud-clearing processes are centred. For example, clear radiances determination could be attempted at every other spot and line, as in the scheme described in appendix A. Care must be taken to assess the inter-dependence of the different information depending on the chosen processing pattern. The previous estimates in ‘nearby’ spots constitute estimates for the current spot with their variances suitably increased to account for horizontal variation in the radiances field. A priori information on the radianc gradients could also be used here to adjust both the estimate and the variance. The degree of sophistication used in the interpolation procedures implied here will depend on practical constraints such as computer processing time.

(c) AVHRR data may be used directly in the estimation of HIRS clear radiances for the window channels. If AVHRR data are also used in (a), a careful treatment of the inter-dependence would be required.
(d) Clear radiances calculated using a radiative transfer model from the forecast or analysed fields of a numerical weather prediction model also constitute valid information. However, the problem of information inter-dependence may be particularly acute here. Not only must we take account of the effect of using the same information in (a), but we must consider the use to which the products will be put. If they are used as input data to the same forecast model without due care, then undesirable correlations may arise between retrieval errors and errors in the model’s background field into which they are to be assimilated.

(e) MSU radiances can be used, for example through a regression relation, to predict the clear radiances in HIRS channels. The residual errors in such a regression, and hence the error in the estimate from this source of information, will tend to be higher than the errors in measured HIRS radiances. However, these data can play a useful role as an effective ‘background’ field for the cloud-clearing process.

In a real cloud-clearing scheme, the details of the information used will depend on practical considerations such as which pieces of information are readily available, how much computer processing is required to make use of them, and what are the desired characteristics of the final product (in horizontal resolution, smoothness, independence from forecast models, etc.). One practical scheme is described below; it could easily be adapted to include additional sources of information. Also, similar schemes based on the same basic principles could be devised.

5. A NEW HIRS CLOUD-CLEARING SCHEME

The method described here has been developed to address some of the deficiencies in the old cloud-clearing scheme (discussed in appendix A) and to replace it in the Local Area Sounding System. The new scheme consists of two parts: an algorithm to obtain preliminary estimates of clear-column brightness temperatures (and their estimated errors), followed by a sequential estimator to improve the values in the preliminary field. The cloud detection and $N^*$ algorithm in the new scheme are similar to the corresponding parts of the old scheme; the method of obtaining HIRS estimates from MSU data when the $N^*$ algorithm fails and the sequential estimation scheme are both new. Also, the new scheme provides estimates of HIRS brightness temperatures in all channels at every HIRS spot on every line, compared with the old scheme which attempts retrievals at every other spot and line, and even on this grid leaves gaps in heavily clouded areas.

In its present implementation, the scheme uses data which have been pre-processed in the same manner as in the old scheme. HIRS and MSU data have been corrected for scan angle effects and MSU data also for surface emissivity and antenna pattern effects, i.e. corrected to the brightness temperatures which would be observed from the same atmospheric profile at nadir with a very narrow field of view if the earth’s surface were black. MSU data have also been mapped to HIRS locations.

(a) Preliminary estimates of clear-column brightness temperatures

The clear-column HIRS brightness temperature in each channel is estimated, along with its expected error, at every HIRS spot by one of four routes:

(i) Clear conditions. Clear spots are identified by a cloud detection algorithm very similar to the old scheme. A linear combination of HIRS brightness temperatures is used to predict an MSU channel-2 brightness temperature (hereafter abbreviated ‘MSU(2)’ and similarly for other MSU and HIRS channels), using a regression relation which has a
residual error of about 0.8 K for clear-column brightness temperatures. The coefficients for the regression are calculated from theoretically computed brightness temperatures for a representative set of historical radiosonde profiles for the appropriate month for the European/N Atlantic area (Watts 1984). If predicted MSU(2) is colder than measured MSU(2) by more than the residual error in the regression, then the HIRS measurements are assumed to be contaminated by cloud. Also a test is made for excessive contamination by solar radiation: if HIRS(19) − HIRS(18) is greater than 10 K or HIRS(18) − HIRS(8) is greater than 20 K then the brightness temperatures in all HIRS channels are rejected. At night, an additional check on the brightness temperature difference between channels in the 11 and 3-7 μm window regions can be used. This employs the signature of low-level water cloud through its lower emissivity in the shorter wavelength region (Eyre et al. 1984). If HIRS(8) − HIRS(18) exceeds 2 K then the radiances are flagged as cloud contaminated.

If the data pass these tests, they are assumed to be clear and the measured (pre-processed) HIRS brightness temperatures are taken as the preliminary estimates of the clear-column values. In this case the estimated errors are comparatively low. However, they are not simply the instrument noise, since our ability to determine that the measurements are truly cloud-free is limited by the sensitivity of the cloud detection process. Also, pre-processing errors for both HIRS and MSU contribute to the uncertainty. Radiometric noise, limb correction error and cloud detection sensitivity are all taken into account in the error estimate scheme. Full details of this procedure, and equivalent procedures for other cloud clearing routes, are given by Watts (1985).

(ii) Parity cloudy conditions — N* method. If cloud is detected, the clear radiance determination is attempted by the N* method (described in appendix A) using the HIRS spot in question with one of its eight adjacent spots. The most suitable partner is first identified. The partner must be colder, to ensure that the same pair of spots is not used again when the partner is itself the central spot. Also the warmer spot is the more appropriate position to assign to the clear radiance as it contains a greater proportion of cloud-free area. If more than one colder partner is found then the one which gives the best agreement between N* values calculated separately for HIRS long-wave and short-wave channels is chosen. Moreover, values of N* greater than 0.75 and long-wave − short-wave differences in N* greater than 0.1 are not used. The N* algorithm fails if a suitable partner cannot be found. It may also fail if the clear-column brightness temperatures do not pass certain checks. Excess contamination by reflected solar radiation is tested as described above. Also HIRS(8) is compared with a corresponding value predicted from MSU data (as explained below) and the radiances rejected if the absolute difference is excessive.

The errors in the clear-column brightness temperatures derived by the N* method depend on the errors in the values of R1, R2 and N* used in Eq. (2) and on the way in which this equation amplifies these errors. R1 and R2 contain error contributions from radiometric noise and pre-processing, both of which may be estimated. The error in N* is determined by the errors of the terms used in Eq. (3), including the residual error in the prediction of MSU(2) from HIRS values. The error analysis is complicated by the correlations between the components of error in these equations, and it is difficult to assess absolute error levels accurately. However, it can be seen that the error amplification in Eq. (2) is very variable and becomes acute as N* approaches unity. For this reason, the method is deemed to fail if N* is greater than 0.75. Additional errors arise when the conditions required for the N* algorithm, concerning the profiles and cloud cover in adjacent spots, are not satisfied. No attempt has been made to quantify these errors;
they will tend to have statistical properties which are difficult to accommodate in this approach. However, the quality checks described above are used to minimize the problems arising from this source.

(iii) Cloudy conditions—MSU regression method. If cloud is detected and the $N^*$ method fails, the clear-column HIRS brightness temperatures are estimated from the MSU data using a regression relation:

$$\hat{T}_{ij}^N = b_{0j} + \sum_i b_{ij} T_i^M$$  \hspace{1cm} (13)

where $\hat{T}_{ij}^N$ is the estimated HIRS brightness temperature in channel $j$ ($j = 4$ to 16), $T_i^M$ is the measured MSU brightness temperature in channel $i$ ($i = 2$ to 4) and coefficients $b_{ij}$ are obtained by regression on brightness temperatures calculated from a large set of representative radiosonde profiles. This approach is adopted principally to obtain an estimate on every HIRS spot for the purposes of the sequential estimation which follows. Retrievals from preliminary estimates of HIRS brightness temperatures obtained in this manner would be approximately equivalent to MSU-only retrievals. However, in combination with the 'HIRS – MSU bias' and sequential estimation schemes described below, information on the vertical profile structure can be 'advected in' from nearby HIRS spots from which HIRS information is available, leading to a more effective and more nearly optimal method of using MSU information in cloudy areas.

Errors in the HIRS estimates obtained by the method arise from radiometric and pre-processing errors in the MSU data and from the residual errors in the regression. These can be assessed and give the values used in the subsequent filtering. However, the sequential estimator assumes that errors in adjacent spots are uncorrelated. This is not the case for HIRS values estimated from MSU because the errors in the regression are locally consistent—they are caused mainly by vertical profile structure which is resolved by HIRS but not by MSU. Also, the horizontal resolution of MSU is less than that of HIRS, and so one MSU spot dominates the MSU values interpolated to several HIRS spots. These problems are discussed in more detail in section 5(c)(ii). Suffice it to say here that it has been found necessary to estimate and correct for the locally correlated component of error in HIRS brightness temperatures obtained from MSU. This allows the residual errors to be treated as largely uncorrelated. In principle they should also be of lower magnitude than the residual error in the regression. However, because of the problems of locally correlated error and the need to avoid underestimating its effect, we have chosen to err on the side of overestimating errors and have used the regression residual error as the error value in the subsequent filter.

(iv) MSU data missing. On the infrequent occasions when no MSU values have been mapped to a HIRS spot (thus precluding both the $N^*$ method and the MSU regression method), MSU and HIRS values for a nearby HIRS spot are used and their expected errors are suitably increased. Failing this, climatological mean values are the last resort with the climatological variance supplying the expected error. Again, the reason for adopting this approach is for convenience in the subsequent filter, which requires a HIRS brightness temperature estimate and an expected error at every spot.

Figures 2 and 3 illustrate the results of the preliminary cloud-clearing for a typical pass of data. Figure 2 is an AVHRR image showing qualitatively the location and structure of the cloud fields. Superimposed on this image are the locations of HIRS fields-of-view. Figure 3 is a character map indicating the outcome of the preliminary cloud-clearing procedure at each spot for this pass.
Figure 2. AVHRR channel 1 (visible) image and HIRS field-of-view locations. Part of overpass at 13 GMT on 16 April 1985.

(b) Sequential estimation procedure

The preliminary cloud-clearing algorithms provide estimates of the HIRS brightness temperature and its error at each HIRS spot in all channels. To improve the estimate at a given spot we could combine the initial estimate with those from all nearby spots, with their errors suitably increased to allow for the horizontal separation, as proposed in section 3. A simple and efficient way of approximating this approach is through a two-dimensional sequential estimation filter, as illustrated in Fig. 4. The filter runs along the scan lines in alternate directions as shown. At spot \((m, n)\) we combine the initial estimate of brightness temperature \(T_{m,n}(-)\), and its expected error variance \(\sigma_{m,n}^2(-)\), with improved estimates from the preceding spot on the same line, \(T_{m,n-1}(+)\), and the equivalent spot on the preceding line, \(T_{m-1,n}(+)\), and we obtain an improved estimate at \((m, n)\), \(T_{m,n}(+)\), and its expected error variance, \(\sigma_{m,n}^2(+)\):

\[
\frac{T_{m,n}(+)}{\sigma_{m,n}^2(+)_{F}} = \frac{\mu T_{m,n}(-)}{\sigma_{m,n}^2(-)} + \frac{\lambda T_{m,n-1}(+)}{\sigma_{m,n-1}^2(+)_{F}} + \frac{\lambda T_{m-1,n}(+)_{F}}{\sigma_{m-1,n}^2(+)_{F} + \beta^2}
\]  

(14)
\[
\frac{1}{\sigma_{m,n}(+)_{F}} = \frac{\mu}{\sigma_{m,n}(-)} + \frac{\lambda}{\sigma_{m,n-1}(+)_{F} + \beta^2} + \frac{\lambda}{\sigma_{m-1,n}(+)_{F} + \beta^2}.
\] (15)

(-) and (+) indicate 'before' and 'after' filtering respectively. Parameters \(\mu\), \(\lambda\) and \(\beta^2\) determine the weights given to the data and are discussed further below. Subscript \(F\) indicates that this is the 'forward' filtering process. A similar process is run along the pass in the opposite direction to give 'backward' estimates: \(T_{m,n}(+)_{B}\) and \(\sigma_{m,n}(+)_{B}\). The forward and backward estimates are then combined to give the final estimate and its expected error:

\[
\frac{T_{m,n}(+)}{\sigma_{m,n}(+)} = \frac{T_{m,n}(+)_{F}}{\sigma_{m,n}(+)} + \frac{T_{m,n}(+)_{B}}{\sigma_{m,n}(+)}
\] (16)

\[
\frac{1}{\sigma_{m,n}(+)} = \frac{1}{\sigma_{m,n}(+)} + \frac{1}{\sigma_{m,n}(+)}.
\] (17)

If care is taken to ensure that the forward and backward filters process a given line from opposite ends, then the combined filter advects information almost uniformly from all directions.

The choice of a sequential estimation approach, rather than some other method of objective analysis, was influenced by the availability of data on a regular grid. The technique described here is not an 'optimal' method as described in section 3: only data

Figure 4. Illustrating the application of the sequential estimation scheme. The solid spots at the top indicate the HIRS spots used in the 'forward' estimation of the adjacent dotted spot. The arrows indicate the direction of progression of the sequential estimator. The corresponding pattern at the bottom is for the equivalent 'backward' filter. The spots marked in the centre illustrate the symmetric nature of the combined forward and backward filters.

Figure 3. Continued  
S  MSU regression: excessive solar reflection  
I  MSU regression: long-wave and short-wave \(N^*\)s inconsistent  
s  MSU regression: excessive solar reflection after \(N^*\) route  
E  MSU regression: rogue value of \(N^*\)  
?  MSU regression: no suitable pair for \(N^*\) method  
#  MSU regression: low cloud test  
c  No MSU value: search nearby spots  
C  No MSU value: use climatological values
from adjacent spots are used directly, and information from other nearby spots has influence only indirectly through the sequential nature of the method. In common with the other objective analysis methods, it is necessary to consider the trade-off between this loss of optimality and any advantages of the technique. The main advantage is the computational speed through the use of only adjacent spots. To use all the available information 'optimally' would require knowledge of appropriate error covariances between all pairs of spots, and these cannot be assessed accurately for this problem. They are, however, effectively included, albeit rather crudely, through the $\sigma^2$ values and the $\beta^2$ parameter.

(c) Further details

(i) Filtering parameters. The parameters $\mu$, $\lambda$ and $\beta^2$ in Eqs. (14) and (15) determine the weights given to different pieces of information by the sequential estimation filter. In the limit that the initial error at spot $(m, n)$ is very much less than that at other spots, we require $\sigma^2_{m,n}(+) \rightarrow \sigma^2_{m,n}(-)$. From Eqs. (15) and (17) we then obtain $\mu = 0.5$. Therefore $\mu$ is simply interpreted as allowing for the double use of the spot $(m, n)$ in both the forward and backward filters.

$\beta^2$ is included to represent the increase in error variance for a spot when it is used as an estimate for its neighbour and is related to the expected horizontal variations in the cloud-free brightness temperature field. Because the combined forward and backward filter is symmetric, linear gradients in the field are preserved by the filter. $\beta^2$ therefore represents horizontal variations of second or higher order. In obtaining values of $\beta^2$, it has to be recognized that the atmospheric and surface contributions to the cloud-cleared radiance have different horizontal properties and that there are significant differences for the surface contribution between land and sea. The assessment of appropriate values for $\beta^2$ is not straightforward, and we have looked both at derivatives of fields of preliminary estimates of HIRS cloud-cleared brightness temperatures in all channels and

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\lambda$</th>
<th>$\lambda_{\text{land}}$</th>
<th>$\beta^2_{\text{land}}$</th>
<th>$\beta^2_{\text{sea}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIRS-1</td>
<td>0.40</td>
<td>0.40</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>HIRS-2</td>
<td>0.40</td>
<td>0.40</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>HIRS-3</td>
<td>0.40</td>
<td>0.40</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>HIRS-4</td>
<td>0.40</td>
<td>0.40</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>HIRS-5</td>
<td>0.40</td>
<td>0.38</td>
<td>0.22</td>
<td>0.05</td>
</tr>
<tr>
<td>HIRS-6</td>
<td>0.40</td>
<td>0.35</td>
<td>0.48</td>
<td>0.09</td>
</tr>
<tr>
<td>HIRS-7</td>
<td>0.40</td>
<td>0.27</td>
<td>1.18</td>
<td>0.19</td>
</tr>
<tr>
<td>HIRS-8</td>
<td>0.40</td>
<td>0.06</td>
<td>3.20</td>
<td>0.48</td>
</tr>
<tr>
<td>HIRS-9</td>
<td>0.40</td>
<td>0.20</td>
<td>1.87</td>
<td>0.29</td>
</tr>
<tr>
<td>HIRS-10</td>
<td>0.40</td>
<td>0.12</td>
<td>2.65</td>
<td>0.43</td>
</tr>
<tr>
<td>HIRS-11</td>
<td>0.40</td>
<td>0.38</td>
<td>0.34</td>
<td>0.18</td>
</tr>
<tr>
<td>HIRS-12</td>
<td>0.40</td>
<td>0.40</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>HIRS-13</td>
<td>0.40</td>
<td>0.19</td>
<td>1.94</td>
<td>0.30</td>
</tr>
<tr>
<td>HIRS-14</td>
<td>0.40</td>
<td>0.28</td>
<td>1.14</td>
<td>0.18</td>
</tr>
<tr>
<td>HIRS-15</td>
<td>0.40</td>
<td>0.37</td>
<td>0.27</td>
<td>0.06</td>
</tr>
<tr>
<td>HIRS-16</td>
<td>0.40</td>
<td>0.40</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>HIRS-17</td>
<td>0.40</td>
<td>0.40</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>HIRS-18</td>
<td>0.40</td>
<td>0.03</td>
<td>3.42</td>
<td>0.51</td>
</tr>
<tr>
<td>HIRS-19</td>
<td>0.40</td>
<td>0.03</td>
<td>3.41</td>
<td>0.51</td>
</tr>
<tr>
<td>MSU-1</td>
<td>0.40</td>
<td>0.13</td>
<td>2.55</td>
<td>0.39</td>
</tr>
<tr>
<td>MSU-2</td>
<td>0.40</td>
<td>0.37</td>
<td>0.34</td>
<td>0.07</td>
</tr>
<tr>
<td>MSU-3</td>
<td>0.40</td>
<td>0.40</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>MSU-4</td>
<td>0.40</td>
<td>0.40</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>
at fields of cloud-cleared HIRS(8) estimated from AVHRR data (see section 6). We have also taken into account the average ratio of atmospheric and surface contributions in each channel. Using a somewhat ad hoc approach based on this information, the values of \( \beta^2 \) given in Table 1 have been derived.

\( \lambda \) has been included in the scheme principally to compensate for overuse of data; the mechanics of the two-dimensional filter allow one spot to affect another on a different line by more than one route. The effective weight of one spot on its neighbours is illustrated in Fig. 5 for the limiting case of \( \beta^2 = 0 \). Conversely, this can be thought of as the effect of the neighbours on the central spot in the limits of \( \beta^2 = 0 \) and equal initial errors at all spots. It can be shown that the filter is unstable for \( \lambda \approx 0.5 \); given an initial field of uniform errors, the final error estimates become vanishingly (and unrealistically) small in the body of the field. \( \lambda \) may also be used to compensate, in a general manner, for any tendency of adjacent spots to have correlated errors. We have found empirically that \( \lambda = 0.4 \) gives stable and reasonable results.

Where we have \textit{a priori} knowledge of discontinuities or large gradients in the radiance field, we can reduce the filtering strength accordingly. At present this is applied only at coastlines where we expect the surface contribution to the measured radiance to
change sharply. Assuming that the change in atmospheric contribution is generally much smaller, and in order not to reduce the filtering strength for channels with weighting functions peaking away from the surface, we reduce $\lambda$ over coastlines by a factor proportional to the atmospheric absorption in the channel:

$$\lambda_{\text{coast}} = \lambda(1 - \tau_j)$$

(18)

where $\tau_j$ is the atmospheric transmittance in channel $j$. Mean values of $\tau_j$ are currently used and the resulting values of $(\lambda_{\text{coast}})_j$ are given in Table 1.

(ii) The HIRS − MSU bias problem. In section 5(a)(iii) it was noted that HIRS values estimated from MSU data contain errors which are highly correlated locally. Straightforward use of the sequential estimator on a field containing these data produces unsatisfactory results; a bias remains in the final field and the error is underestimated. It is desirable, therefore, to compensate for these biases if possible. At spots where HIRS brightness temperatures are obtained by the clear or $N^*$ route, we can also obtain values by the MSU regression route and hence derive estimates of the bias between the two. Because the bias is locally coherent, particularly within areas of the same air mass, these sparse estimates of ‘HIRS − MSU bias’ (i.e. the bias between measured HIRS brightness temperatures and those estimated from MSU) can be filtered using a similar sequential estimator to obtain values for the bias field at all spots. Where it is available, the initial bias estimate is assigned an expected error equal to the expected error in the HIRS estimate. At other spots the initial estimate is set to zero with a very large expected error. The horizontal consistency of the bias field allows us to use a very high value for the filtering parameter $\lambda$ (a value of 0.48 being used at present). The same values of $\beta^2$ are used for the bias field as for the HIRS brightness temperature field itself. The filtered values of bias are then used to adjust brightness temperatures predicted from MSU and to make them consistent with neighbouring values obtained by the clear or $N^*$ route. The mechanics of the bias field filtering are described in more detail by Watts (1985). The effect of this procedure is not only to produce more horizontally consistent fields but also to advect information on vertical structure from clear and partly cloudy spots into surrounding areas where only preliminary estimates from MSU are available.

Figure 6 illustrates the effect of the filtering for a single scan line of HIRS data. It shows the preliminary estimates and the final estimates, all with their expected errors. The estimated HIRS − MSU biases for the same line are shown in Fig. 7. The sparse preliminary bias estimates are used to obtain the final filtered bias estimates at all spots, which are then applied as corrections to HIRS values estimated from MSU and are included in the final estimates shown in Fig. 6. The removal of local biases between HIRS estimates from MSU and by other routes can be seen. In both Fig. 6 and Fig. 7 it should be remembered that the filtering is a two-dimensional procedure and also uses information from neighbouring scan lines (not shown).

6. Validation

Assessing the effectiveness of a cloud-clearing scheme is not a simple matter as independent measurements of the ‘true’ clear-column radiances are usually not available. Previous authors (e.g. McMillin and Dean 1982) have often compared the temperature profiles retrieved from the clear radiances generated by a new cloud-clearing scheme with co-located radiosonde profiles. This approach tends to suffer from a low sensitivity to any real improvements made for a number of reasons. Firstly, improvements to cloud clearing usually affect a relatively small number of soundings, albeit often in meteo-
Figure 6. Cloud-clearing results for one scan line (line 8 in Fig. 3) for HIRS channel 6. Symbols indicate the preliminary cloud-clearing route. Upper and lower graphs show before and after filtering respectively. Values in K.

logically interesting areas. Secondly, there are many reasons for differences between retrieved profiles and radiosondes which are not caused by cloud-clearing errors. Differences are introduced by the co-location tolerances in space and time required to obtain an adequate sample for statistical evaluation, and by differences in scale between radiosonde and satellite measurements. Also the limited vertical resolution of the passive sounding technique ensures that the retrieved profile contains less vertical structure than the radiosonde profile and is sensitive to the first-guess profile used in the inversion process (Rodgers 1976; Eyre 1987). The differences introduced by the inversion process may be overcome by comparing measured radiances with those computed using a radiative transfer model from co-located radiosonde data (e.g. Chedin and Scott 1984). This is usually a very instructive exercise, particularly for studying deficiencies in the radiative transfer model, but interpretation of the results in terms of cloud clearing errors is complicated by these deficiencies and by the other problems given above. Also radiosonde reports (over land) do not provide the (ground) surface temperature, which is required for an accurate simulation of radiances in surface-sensing channels.

Because of these problems we have chosen a more direct approach to validation through comparison with AVHRR data. AVHRR has a resolution of about 1.1 km and
five spectral channels in visible and infrared window regions (Schwalb 1978). Its high spatial resolution allows cloud to be detected with much greater accuracy than is possible with TOVS. Various techniques are available for detecting cloud contamination of AVHRR radiances including radiance threshold, spatial coherence and inter-channel methods. We have used the scheme described by Saunders (1986) which generates a cloud mask at pixel resolution. This scheme was primarily designed for identifying cloud-free pixels and tends to err on the conservative side—the number of cloud-free pixels will be underestimated but a high degree of confidence can be placed on the pixels passed as cloud-free.

The nominal HIRS field-of-view can be co-located with AVHRR to within 1 km (Aoki 1984; Lloyd et al. 1985). This allows the AVHRR pixels associated with each nominal HIRS field-of-view to be determined. Multi-spectral AVHRR data (channels 3, 4 and 5 at night, channels 1, 2, 4 and 5 during the day) are used to identify the cloud-free pixels, for which the mean cloud-free brightness temperatures in AVHRR channels 4 and 5 (AVHRR(4) and AVHRR(5)) are then calculated. AVHRR channels 4 and 5

Figure 7. As Fig. 6, except for the HIRS – MSU bias.
and HIRS channel 8 all lie in the 11 μm window region; they are centred at about 930, 840 and 900 cm\(^{-1}\) respectively. Therefore the average values of AVHRR(4) and AVHRR(5) at zenith angle \(\theta\), \(T_4(\theta)\) and \(T_5(\theta)\) respectively, can be used to predict the cloud-free HIRS(8) value at \(\theta\), \(\hat{T}_8(\theta)\), using a regression relation:

\[
\hat{T}_8(\theta) = a_0 + a_1 T_4(\theta) + a_2 T_5(\theta).
\]  

(19)

The coefficients, \(a_0\), \(a_1\) and \(a_2\), are assumed to be independent of \(\theta\) and are calculated using co-located HIRS and AVHRR data with a residual error in the regression of about 0-2 K. Only cloud-free HIRS spots for which the associated AVHRR pixels have a brightness temperature standard deviation less than 0-2 K are used in this exercise. This method of deriving the coefficients effectively allows also for any relative calibration error between HIRS and AVHRR, although this is not found to be a serious problem.

Equation (19) gives the expected clear-column HIRS(8) value at the angle of measurement, whereas our HIRS cloud-clearing scheme produces clear-column estimates corrected to nadir, \(T_8(0)\). To compensate for the difference, the values of AVHRR(4) and AVHRR(5) can also be used to estimate the surface skin temperatures:

\[
\hat{T}_s = b_0(\theta) + b_1(\theta) T_4(\theta) + b_2(\theta) T_5(\theta)
\]  

(20)

where the coefficients \(b_i(\theta)\) are the ‘split-window’ coefficients given by Llewellyn-Jones et al. (1984), which are intended primarily for sea surface temperature estimation. Since the weak absorption in atmospheric window regions is approximately proportional to the path length, the ‘atmospheric correction’ in HIRS(8), i.e. the difference between the surface skin temperature and the measured brightness temperature, is approximately proportional to the secant of the zenith angle of the path:

\[
T_s - T_8(\theta) = \sec \theta \cdot \{T_s - T_8(0)\}.
\]  

(21)

This may be re-arranged to give

\[
T_8(0) = T_8(\theta) + (1 - \cos \theta) \{T_s - T_8(\theta)\}.
\]  

(22)

Substituting estimates for \(T_8(\theta)\) and \(T_s\) from Eqs. (19) and (20) into Eq. (22), we obtain an estimate of the limb-corrected brightness temperature in HIRS channel 8 from AVHRR data. This value can then be compared with the HIRS(8) estimate obtained using the old or the new HIRS cloud-clearing scheme. In practice it is found that the corrections for limb effect and for HIRS - AVHRR spectral difference are small in mid-latitudes when compared with the magnitude of cloud-clearing error we are attempting to measure. Nevertheless the corrections have been made.

The new HIRS cloud-clearing scheme generates an estimate of HIRS(8) at every spot. The old scheme does not; clear radiance calculations are attempted only at one in four HIRS spots and many of these fail because of excessive cloud contamination. Also, in overcast areas, no HIRS(8) estimate can be obtained from the AVHRR data. Using data from one pass of NOAA-9 TOVS and AVHRR data over western Europe (16 April 1985 at 13 gmt), the mean and standard deviation of the difference between HIRS(8) estimates obtained from TOVS data and from AVHRR data were calculated. At those HIRS spots on which the old scheme provided data, and on which AVHRR estimates were also available, the statistics were computed for both the old and new schemes. Values were also derived for all spots on which AVHRR estimates were present for the new scheme only. These were subdivided into land and sea categories. In addition, statistics were computed for the new scheme on estimates both before and after the sequential estimation procedure. The results for this pass are summarized in Table 2. Other passes have been processed in a similar manner with comparable results.
From Table 2 it can be seen that the new scheme improves considerably on the old over the spots for which comparable results are available. Both the bias and standard deviation of difference from the AVHRR estimates are reduced. Over all spots for which AVHRR estimates are available, the performance of the new scheme is not so good. This is to be expected as the new scheme is more ‘ambitious’ than the old; the much smaller number of spots on which the old scheme provides estimates will be less cloudy on average. Nevertheless the new scheme’s performance over all spots is still superior to the old scheme’s performance over its limited sub-set in both bias and standard deviation. Separate statistics for land and sea reveal superior performance of the new scheme for HIRS(8) over the sea. This probably occurs because the inherent assumption of horizontal coherence in the brightness temperature fields to be estimated is more valid over the sea for a window channel. The role of the sequential estimator is illustrated by the difference between statistics from filtered and unfiltered data. For both land and sea the filter reduces the standard deviation of the difference. The most important function of the filtering is found to lie in the estimation of the HIRS — MSU bias field which considerably improves HIRS estimates obtained from MSU, although estimates obtained by the $N^*$ route are also improved significantly. On the other hand, there is a tendency of some estimates obtained by the ‘clear’ route to be degraded by the filtering. For this particular pass the bias over land is increased by the filter. A more detailed analysis of the results showed that failure to detect low cloud in preliminary estimates obtained by the ‘clear’ route was the main cause of this problem. These estimates are themselves too cold and also result in surrounding estimates from MSU, after bias correction, being pulled too cold. On average, estimates by the ‘clear’ route are biased cold by residual cloud contamination, whereas $N^*$ estimates tend to have larger errors but of unbiased distribution.

The major limitation of this validation method is its restriction to HIRS channel 8. (It could also be applied to the other window channels, 18 and 19, although these are not currently used in the subsequent inversion.) It cannot be extended to the main tropospheric sensing channels because no AVHRR channels with comparable weighting functions are available. This limitation is not serious; window channels are affected most acutely by cloud contamination and are sensitive indicators of the cloud-clearing performance as a whole. All the cloud-clearing routes place high reliance on MSU data,

<table>
<thead>
<tr>
<th></th>
<th>Number in sample</th>
<th>Old cloud clearing</th>
<th>New cloud clearing (filtered)</th>
<th>New cloud clearing (unfiltered)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LASS* retrieval spots only</td>
<td>154</td>
<td>3-5 (-1.2)</td>
<td>2.4 (-0.1)</td>
<td></td>
</tr>
<tr>
<td>Retrieval spots of new scheme</td>
<td>All</td>
<td>1311</td>
<td>3.1 (-0.4)</td>
<td>4.0 (-0.6)</td>
</tr>
<tr>
<td></td>
<td>Land</td>
<td>781</td>
<td>3.5 (-1.2)</td>
<td>4.7 (0.0)</td>
</tr>
<tr>
<td></td>
<td>Sea</td>
<td>530</td>
<td>1.3 (0.8)</td>
<td>2.2 (1.5)</td>
</tr>
</tbody>
</table>

Means and standard deviation of cloud-cleared HIRS(8) minus HIRS(8) estimated from AVHRR.
Upper value: standard deviation of difference in K.
Lower value (in parenthesis): mean difference in K.
* Meteorological Office Local Area Sounding System.
particularly on MSU(2), which is not well suited to 'clearing' an infrared window channel, since its weighting function peaks above low-level cloud. Consequently HIRS(8) is not well handled by the current technique as the overall standard deviation of 3.1 K in Table 2 reveals. However, it will be atypical of other channels in this respect. Also it is the channel for which the assumptions of a horizontally consistent clear radiance field hold least well, particularly over land and coastlines, and so will show less benefit from the sequential estimation filter than other channels. For these reasons, we can be confident that the improvement in cloud-clearing of HIRS(8) demonstrated here will be reflected equally in other channels, if not accentuated.

7. FUTURE DEVELOPMENTS

The new scheme described above has been shown to be superior to the old scheme in the Local Area Sounding System and is expected to replace it in this system during 1987. Nevertheless, within the basic framework of the new scheme, there is scope for changes of detail to address some of the problems found during the development and validation process.

Minor changes to the cloud detection procedure are possible, particularly to trap contamination by low cloud. For example, in the daytime the HIRS visible channel (20) could be exploited. In addition those checks employed by McMillin and Dean (1982) which are not currently used here could be investigated.

The current application of the $N^*$ technique also leaves room for improvement. The theoretical deficiency discussed in appendix A should be rectified. Also the role of clear radiances obtained by the $N^*$ method within the overall scheme merits careful consideration. Present indications are that these radiances have higher errors than those obtained by other routes, but that they are still useful in determining the HIRS — MSU bias field.

In the sequential estimator, current values of the filtering parameters appear to give satisfactory results. However, the roles of $\lambda$ and $\beta^2$ merit further study. Theoretical analysis suggests different values for $\lambda$ in the along and across track directions, and other sophistications may be warranted.

The filtering procedure is most successful when the errors in the preliminary estimates have Gaussian distributions and are uncorrelated in neighbouring spots. In particular, 'rogue' spots of unusually large error are potentially very damaging. Some attempt has been made to detect these in the $N^*$ route, but a more systematic rogue detection scheme would be useful. It may be possible to extend the sequential estimator to incorporate rogue detection based on the expected error characteristics, along the lines suggested by Purser (1984).

The new scheme in its current form operates on data corrected for scan angle (i.e. corrected for limb-darkening effects to the values which would be observed at nadir). This procedure utilizes inter-channel regression relations which are strictly applicable only to cloud-free data. Consequently the cloud-clearing should precede any scan angle correction. Moreover, even for cloud-free data, the scan angle corrections have their own inherent errors (LeMarshall and Schreiner 1985) and hence contribute to the error in the preliminary estimates. Scan angle correction errors will tend to be locally coherent and so will not be suppressed by the sequential estimator. For these reasons, it would be desirable to remove the scan angle correction completely and to perform the cloud-clearing and subsequent inversion on radiances at the angle of measurement. Minor adjustments to the sequential estimation scheme would be necessary to allow for the expected variations in the brightness temperature field with scan angle.
Finally, the flexibility in the new scheme could be used to incorporate additional sources of information. In the longer term, the most obvious inputs are products derived from AVHRR data. Their potential benefits have been clearly demonstrated, but their use in near real-time is hampered by logistical problems of AVHRR data processing. Other sources of information which may prove valuable in the cloud-clearing process include fields of surface temperature from a numerical forecast model (particularly over the sea where the temporal variations are small and slow).

8. CONCLUSIONS

We have demonstrated how the principle of optimal estimation may be applied to the problem of cloud-clearing infrared tropospheric sounding measurements. A method based on a sequential estimation approach has been developed for use with TOVS data in the context of a scheme for deriving soundings of high horizontal resolution. These are employed in operational weather forecasting by the Meteorological Office. The scheme shows a marked improvement over the previous cloud-clearing scheme (described in appendix A). The principal innovation of the new method is its use of the spatial continuity expected in atmospheric fields and the corresponding clear-column radiance field as a priori information. This ensures greater horizontal consistency in the clear-column radiance fields derived from the data, although care must be taken that this does not occur at the expense of real small-scale features in the field. In addition we have developed a method for estimating HIRS brightness temperatures from MSU data with little local bias, which represents an improved use of MSU data in cloudy areas.

The basic approach has the flexibility to include information from many data sources. In addition, the cloud-clearing algorithm yields estimates of the errors in the clear-column radiance field. These values are products of the cloud-clearing algorithm and have not so far been used further, but they should prove useful as quality indicators and, if required, could be carried through to influence the subsequent inversion stage.

ACKNOWLEDGMENTS

We should like to acknowledge the help of our colleagues, Dr R. W. Saunders (Meteorological Office) and Dr J. J. Barnett and Miss P. E. Lloyd (Oxford University) on the exploitation of AVHRR data in the validation exercise. We thank Dr A. J. Prata (CSIRO) for useful discussions which led to the formulation of the sequential estimation method. Two anonymous referees provided very helpful comments on the text. Finally, we are most grateful to Dr W. L. Smith and colleagues at CIMSS, Madison, for providing the original TOVS processing software used in this work.

APPENDIX A

Cloud-clearing method used by the Meteorological Office, 1983–86

This method was devised by the NOAA/NESDIS Development Laboratory at the Co-operative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin, Madison, and the TOVS processing software which includes this cloud-clearing scheme was kindly supplied by that group. The method was changed slightly as described below and has been used by the Meteorological Office for routine processing of TOVS data from 1983 to 86.

The method is described very briefly by Smith (1980) and is a variant of the N* technique first formulated by Smith (1968). Prior to the cloud-clearing stage, the TOVS
data used have already been pre-processed in the following ways. The HIRS radiances have been converted to brightness temperatures and corrected for scan angle. MSU brightness temperatures have been corrected for scan angle, antenna gain pattern and the earth’s surface emissivity, and they have been interpolated to HIRS spot locations. The problem of cloud-contaminated HIRS radiances is then tackled by one of three paths:

(a) HIRS brightness temperatures are tested for cloud contamination. If they are judged to be cloud-free they may be used directly in the inversion. The test involves taking a linear combination of measured HIRS brightness temperatures which, if cloud-free, should approximate to the measured values of MSU(2):

$$\hat{T}^{M2} = a_0 + \sum a_i T^H_i$$  \hspace{1cm} (A1)

where $\hat{T}^{M2}$ is the estimated MSU(2) and $T^H_i$ are the measured, pre-processed brightness temperatures in a group of HIRS channels. The coefficients, $a_i$, are obtained by linear regression on clear-column brightness temperature values calculated from a large set of representative radiosonde profiles (Watts 1984). In the initial implementation of the scheme the coefficients were obtained from NOAA/NESDIS, Washington D.C., where they are updated weekly by regression on a large set of clear-column brightness temperatures obtained from real TOVS data as part of the operational TOVS processing scheme (Smith et al. 1979). If the linear combination of HIRS brightness temperatures is lower than MSU(2) by more than a certain amount (the residual error in the above-mentioned regression), the HIRS sounding is treated as cloud-contaminated. Additional checks are performed using HIRS window channels (numbers 8, 18 and 19) to ensure that the HIRS data are not contaminated by solar reflection.

(b) A cloud-clearing algorithm based on the $N^*$ method is then used. The additional piece of information required, i.e. the clear radiances in one HIRS channel or ‘pseudo-channel’, is obtained from the measured MSU(2), which acts as a ‘pseudo-channel’ corresponding to the linear combination of HIRS channels described in (a). Equation (3) is approximated as

$$N^* = (T^{M2} - \hat{T}^1)/(T^{M2} - \hat{T}^2)$$  \hspace{1cm} (A2)

where $T^{M2}$ is the measured value of MSU(2), and $\hat{T}^1$ and $\hat{T}^2$ are the values of MSU(2) predicted from HIRS data for spots 1 and 2 respectively using Eq. (A1). The spots are labelled such that spot 1 is warmer ($\hat{T}^1 > \hat{T}^2$). The $N^*$ method is applied to a box of 3×3 HIRS spots (and the MSU value interpolated to the location of the central HIRS spot). $N^*$, and hence clear radiances, are calculated eight times: the central spot is used with each of its neighbours. In this implementation of the method, $N^*$ is calculated separately for the HIRS long-wave tropospheric channels (4–12) and the short-wave tropospheric channels (13–16) in an attempt to allow for any cloud property differences or field-of-view mismatch between the two wavelength regions. For each pair of spots the processing is allowed to continue only with values of $N^*$ less than 0.75. If $N^*$ is greater than 0.75, the error amplification is considered to be too large; physically, the spots are too similar for the $N^*$ technique to succeed. Also, as in (a), a solar reflection check is made using the cloud-cleared brightness temperatures in the HIRS window channels.

Because of the role of adjacent spots in the $N^*$ algorithm, application of this method at all spots could lead to an overuse of data. Primarily for this reason, paths (a) and (b)
are attempted only at every other HIRS spot and line as illustrated in Fig. A1. From up to eight sets of cleared HIRS radiances generated in (b), plus the set of 'clear' radiances given by (a) if they were judged cloud-free, that set is chosen which leads to the best agreement between HIRS + MSU retrieval and MSU-only retrieval (measured by the sum of the squares of the retrieved temperature differences for the five lowest tropospheric standard pressure levels: 1000, 850, 700, 500, 400 mb). Retrievals obtained from the radiances generated by (a) or (b) are subjected to other quality controls: they are checked more stringently against MSU-only retrievals and the local variability of HIRS + MSU retrievals is examined for rogue points. Then:

(c) In areas where (a) and (b) have failed, leaving gaps in the retrieved fields, the cloud problem is 'solved' by resorting to MSU-only retrievals. (It would be possible to use, in addition, those stratospheric HIRS channels unaffected by cloud.) A surface-fitting routine is used to correct these retrievals for biases with respect to nearby HIRS + MSU retrievals.

This method has several weaknesses. Firstly, the checks in (a) can pass a HIRS sounding as clear when there is some contamination, particularly by low cloud. The method as applied here relies heavily on MSU channel 2 which has a weighting function centred around 700 mb with a width of about 600 mb. Thus it is not sufficiently sensitive to the radiation from the surface to be ideal for cloud-clearing. Coincident AVHRR data would be particularly useful for tackling this problem.

Secondly, the N* method works well only when the following conditions are true: the atmospheric profiles and surface properties are equal in adjacent fields of view; there is only one layer of cloud; and the cloud top has the same height and temperature but different fractional coverages in the two spots. Consequently problems occur with variable surface temperature, type or elevation and with cloud height which is variable either within a spot or between adjacent spots. The quality control procedures applied do not always eliminate poor retrievals caused by these problems. Again, AVHRR data could be used to assist in recognition of cloud and surface characteristics suitable for the N* method.

Thirdly, the measured brightness temperatures used have already been corrected for scan angle by regression against other channels. The inevitable residual variance in this regression increases the effective noise in the corrected brightness temperatures. Also the validity of performing such a regression-based correction on cloud-contaminated radiances is questionable. It would be preferable for the cloud-clearing process to precede any scan angle correction.

---

**Figure A1.** Processing pattern of the HIRS cloud-clearing scheme.
No attempt is made (at the cloud-clearing stage) to maintain horizontal consistency in the clear radiance field, and the method yields little indication on the quality of the clear-column radiances, i.e. on the probable error introduced by the cloud-clearing process. The need to alleviate these problems, together with a wish to improve the clear radiance quality control in general, is the main motivation for the work described in this paper.

Finally, there is a theoretical deficiency in the $N^*$ algorithm as employed in the scheme described above. Equation (A2) is an approximation of Eq. (3); they are identical only when there is a linear relationship between radiance and brightness temperature, which is not the case in the infrared region. It is employed in this form because there exists a good linear relationship between MSU and HIRS brightness temperatures but not between their radiances.

The magnitude of the errors caused by this approximation can be assessed. Let us consider a hypothetical HIRS channel of brightness temperature $T^H$ which matches MSU(2) to the extent that $T^H = T^{M2}$. Now consider an atmospheric profile for which the value of $T^H$ would be 270 K in clear conditions but 230 K in overcast conditions (uniform high cloud). For two adjacent spots, let $N_1 = 0.5$ and $N_2 = 1.0$, such that the true value of $N^*$ is 0.5. Given a wavelength for the hypothetical channel, we can calculate the clear radiance and the radiances in spots 1 and 2, which can all be converted to brightness temperatures (see appendix B). These can then be applied in Eq. (A2) to yield values for $N^*$. For typical HIRS long-wave and short-wave channels at 716 and 2240 cm$^{-1}$ respectively, this calculation gives $N^*$ values of 0.455 and 0.310 respectively compared with the true value of 0.5. When these values are used in Eq. (2) to generate the clear column radiance and hence the clear-column brightness temperature, errors of 2.8 K and 6.1 K result. This illustrates that serious errors can arise from this approximation, particularly for the short-wave $N^*$ and where the cloud top is high.

McMillin and Dean (1982) have recognized this problem and formulated a solution. They convert the measured value of MSU(2) to an equivalent HIRS radiance (at a frequency appropriate to either long-wave or short-wave HIRS channels) and then express this radiance as a linear combination of clear HIRS radiances through a regression relation. This allows $N^*$ to be found without approximations other than those arising from the residual errors in the regression.

**APPENDIX B**

**Some relationships between radiance and equivalent black body temperature (brightness temperature) for HIRS channels**

The monochromatic radiance emitted at wavenumber $\nu$ by a black body at temperature $T$ is given by the Planck function:

$$R(\nu, T) = \frac{c_1 \nu^4}{\exp(c_2 \nu/T) - 1} \quad (B1)$$

where $c_1 = 1.1911 \times 10^{-8}$ W m$^{-2}$ sr$^{-1}$ (cm$^{-1}$)$^{-4}$, $c_2 = 1.4388$ K (cm$^{-1}$)$^{-1}$, and $T$, $\nu$ and $R(\nu, T)$ have units of K, cm$^{-1}$ and W m$^{-2}$ sr$^{-1}$ (cm$^{-1}$)$^{-1}$ respectively. For a radiometer channel of narrow spectral width, a similar expression may be used to a very good approximation. For
radiometer channel $i$,  

$$R_i(T) = \frac{c_1 \nu_i^3}{\exp(c_2 \nu_i/T_i') - 1}$$  \hspace{1cm} (B2)$$

where $\nu_i$ is the nominal central wavenumber of channel $i$ and

$$T_i' = A_i + B_i T.$$  \hspace{1cm} (B3)$$

$A_i$ and $B_i$ are known as 'band correction coefficients'. They can readily be calculated given the spectral response profile of the channel by fitting Eq. (B2) to radiances calculated at a range of temperatures by an accurately weighted spectral integration of Eq. (B1). They are tabulated for HIRS radiometers on TIROS-N/NOAA satellites by Lauritsen et al. (1979) and updates to that document. For the relatively narrow spectral bands used by HIRS, $B_i = 1$ and $A_i \ll T$.

The inverse Planck function appropriate to a HIRS channel is obtained by inverting Eq. (B2) to give the brightness temperature in channel $i$, $T_i(R_i)$, as a function of measured radiance $R_i$:  

$$T_i(R_i) = \frac{c_2 \nu_i}{B_i \ln(1 + c_1 \nu_i^3/R_i)} - A_i.$$  \hspace{1cm} (B4)$$

REFERENCES

Aoki, T.  

1982  An improved method to retrieve the clear radiance from partially cloudy spots of radiometer on board satellite. ibid., 60, 758–764


Chahine, M. T.  


1977  Remote sounding of cloudy atmospheres. II: Multiple cloud formations. ibid., 34, 744–757

Chedin, A. and Scott, N. A.  

Chedin, A., Scott, N. A., Wahiche, C. and Moulinier, P.  

Eyre, J. R.  


Eyre, J. R., Brownscombe, J. L. and Allam, R. J.  


Rodgers, C. D. 1984 'A new approach to optimal assimilation of meteorological data by iterative Bayesian analysis'. Pp. 102–105 in Preprints 10th Conference on Weather Forecasting and Analysis; American Meteorological Society


Watts, P. D. 1984 'A study of local area synthetic coefficients for use in the LASS system.' Meteorological Office internal report. Met. O. 19 Branch Memo. 76