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TOWARDS AN OPTIMAL APPROACH TO CLOUD-CLEARING FOR SATELLITE TEMPERATURE SOUNDING

by

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1. INTRODUCTION

Current techniques for observing the temperature of the atmosphere from satellites are based on measurements of upwelling radiation in the infra-red and microwave spectral regions. These radiances are affected, to a greater or lesser degree, by the presence of cloud. At infra-red wavelengths the problem is acute since most clouds are almost opaque; in the microwave region clouds usually have a negligible effect on the radiances, although problems occur in areas of heavy precipitation. Consequently the data processing routines used in the retrieval of tropospheric temperature must be able to detect clouds which have significant effects on the radiances and, if possible, make allowances for these effects. For infra-red 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 converts clear-column radiances to atmospheric temperatures 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. If in the future numerical forecasts models are to assimilate radiances, rather than retrieved temperatures, it is probable that they too will require clear-column radiances as input.

It can be seen therefore that cloud-clearing plays a central role in current retrieval schemes. Cloud-clearing algorithms have been developed which are surprisingly 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.

This paper reviews the methods which have been devised for cloud-clearing. It then develops an approach to the cloud-clearing problem which should, when used in combination with one or more of the methods previously devised, lead to more nearly optimal values for the clear-column radiances. 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). The purpose of this paper, therefore, is not to propose any particular algorithm as a preferred method but to present an approach in which information from different sources processed by preferred algorithms is combined to improve the result.

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 instuments, two of which are used for tropospheric sounding: the High-resolution Infra-Red Sounder (HIRS-2) and the Microwave Sounding Unit (MSU). 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+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 in the infra-red. However it is expected that the contamination of MSU radiances caused by 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 2 adjacent fields-of-view (hereafter referred to as "spots") of a radiometer channel can, under certain conditions, be expressed as follows:

$$\left.\begin{aligned} R_1 &= N_1 R_{cloudy} + (1 - N_1) R_{clear} , \\ R_2 &= N_2 R_{cloudy} + (1 - N_2) R_{clear} , \end{aligned}\right\} \qquad \ldots 2.1$$

where R_{clear} and R_{cloudy} 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 2 spots are the same,
- that only one layer of cloud is present,
- that the cloud top has the same height (and temperature) in both spots.

If the fractional coverages in the 2 spots are different ($N_1 \neq N_2$), then equations 2.1 can be solved simultaneously to give the clear radiance:

$$R_{clear} = \frac{R_1 - N^* R_2}{1 - N^*} , \qquad \ldots 2.2$$

where $N^* = N_1 / N_2$. Alternatively,

$$N^* = \frac{R_{clear} - R_1}{R_{clear} - R_2} , \qquad \ldots 2.3$$

and so N* can be found if we have an estimate of the clear radiance in one channel. Then, since N* is channel-independent, it can be used in equation 2.2 to find the clear radiance in all other channels. For infra-red radiometers with moderately high horizontal resolution (e.g. HIRS-2, 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 (VTPR) on the early members of the NOAA series of satellites. The clear-column radiance in one channel required by equation 2.3 was obtained using data from the Scanning Radiometer (a 2-channel instrument of higher horizontal resolution) on the same satellites.

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 the cloud height 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 2.2 can be expressed:

$$R_{clear} = R_1 + \eta (R_1 - R_2) \qquad \ldots 2.4$$

Here
$$\eta = \frac{N_1}{N_2 - N_1} \qquad \ldots 2.5$$

or
$$\eta = \frac{R_{clear}(\nu') - R_1(\nu')}{R_1(\nu') - R_2(\nu')}, \qquad \ldots 2.6$$

where ν' 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 $R_{clear}(\nu')$. Equation 2.6 then gives η which is used in equation 2.4 to calculate $R_{clear}(\nu_j)$ for other channels at frequencies ν_j. Chahine shows that the method is stable if ν' refers to a channel in the 15µm carbon dioxide band, with a weighting function peaking in the lower troposphere, and ν_j represent a set of channels in the 4.3µm carbon dioxide band. This approach is generalised by Chahine (1977) to multiple cloud layers using a group of up to 4 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 13.4µm) is used as the "cloud-sounding" channel and the 4.3µm 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 4.3μm band channels of HIRS.

McMillin (1978) presents another version of the adjacent field-of-view approach which is closely related to the N* method. By writing equations 2.1 for 2 spots and 2 frequencies (ν_a and ν_b), 4 equations are obtained which may be solved simultaneously to give:

$$R_{clear}(\nu_a) = R_1(\nu_a) + S\left[R_{clear}(\nu_b) - R_1(\nu_b)\right], \quad \ldots 2.7$$

where
$$S = \frac{R_1(\nu_a) - R_2(\nu_a)}{R_1(\nu_b) - R_2(\nu_b)} . \quad \ldots 2.8$$

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 equation 2.7 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, infra-red 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 infra-red channel. From 1978 to 1980 this method formed the basis of the cloud-clearing scheme used with HIRS-2 and MSU data in the operational global retrieval system of NOAA/NESS (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 more thorough treatment is given to the detection of clear areas, including inter-channel regression relations between MSU channels, HIRS longwave (15μm) channels and HIRS shortwave (4.3μm) 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 2 ways: from HIRS and MSU radiances, and from HIRS longwave and shortwave 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 2 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, perhaps, 250 km, which is significantly greater than the scale of the individual soundings (cf. HIRS-2 field-of-view spacing of about 40 km). Smith (1980) presents 2 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 3x3 HIRS soundings. This scheme is currently used for routine TOVS data processing by the Meteorological Office and is described in detail in Annex 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). The same two approaches are reported by Hayden et al. (1981) in an application suitable for retrieval of high resolution moisture fields from TOVS.

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 vary 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. In 2 papers (1980 and 1982), Aoki develops a method for using Advanced Very High Resolution Radiometer (AVHRR) data to assist in the calculation of clear-column HIRS-2 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.

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 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.

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 pieces of information. Thus for one radiometer channel, if we have i independent "observations" of the clear radiance, x_i, with variances, σ_i^2, we can combine the observations to give the best estimate of the clear radiance, $\hat{x}$:

$$\hat{x} = \left(\sum_i \frac{1}{\sigma_i^2} \right)^{-1} . \sum_i \frac{x_i}{\sigma_i^2} , \qquad \ldots 3.1$$

with a variance,

$$\hat{\sigma}^2 = \left(\sum_i \frac{1}{\sigma_i^2} \right)^{-1} . \qquad \ldots 3.2$$

This is the scalar approach appropriate to estimating the clear-column radiance in one channel independently from the other channels. In principle it would be better to estimate the clear-column radiance vector for all channels, $\hat{\underline{x}}$:

$$\hat{\underline{x}} = \left[\Sigma_i \ \underline{S}_i^{-1} \right]^{-1} . \left(\Sigma_i \ \underline{S}_i^{-1} . \underline{x}_i \right), \qquad ...3.3$$

$$\text{and} \quad \hat{\underline{S}} = \left[\Sigma_i \ \underline{S}_i^{-1} \right]^{-1}, \qquad ...3.4$$

where $\underline{S}_i$ are now the corresponding error covariance matrices. Whether this approach is practicable may largely depend on considerations such as the processing time required in the matrix manipulations involved.

This approach is discussed further by Rodgers (1976) in the general context of retrieval theory for remote sounding.

4. APPLICATION TO HIRS CLOUD-CLEARING

The HIRS instrument has 20 channels of which 19 are situated in the infra-red between 15µm and 3.7µm (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 15 km and a spacing between fields-of-view 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 infra-red imaging radiometer with a pixel size of about 1 km (see Schwalb, 1978).

Let us now consider the pieces of information which may be useful for the present problem of finding the clear-column radiance in a given HIRS spot (field-of-view):

(a) The most obvious piece of information is that used in all current methods, i.e. the measured, cloud-contaminated (or, at least, potentially cloud-contaminated) radiance at that spot. In addition, we need some algorithm for converting this to a clear-column radiance. All such algorithms will require ancillary information, such as:
- measured radiances in adjacent spots,
- MSU radiances (preferably tested and, if necessary, corrected for contamination by 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 dew point).

Calculating the expected error in the clear radiance estimate from these data will involve consideration of:
- the instrumental error (noise),
- the additional "noise" introduced by any pre-processing which has been performed to correct the measured HIRS radiance for various effects such as those caused by scan angle, water vapour or surface emissivity,
- the expected errors in the ancillary information,
- 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) are 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, we might choose to process at every second spot along each scan line and every second scan line, and to use truly adjacent spots as ancillary information in (a). This is illustrated in figure 1. 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 radiance field (and radiance changes with scan angle, if the data have not already been corrected for this effect). A priori information on the radiance 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. An interesting consequence of using this source of information might be to facilitate the use of clear radiances for direct input to a numerical model, since information would already have been assimilated in the horizontal and each clear radiance value would carry with it an estimate of its error.

(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 from surface observations and a forecast profile using a radiative transfer 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. Undesirable correlations may result if the retrievals based on these data are to be used to initialise the numerical forecast model from which the profiles were taken.

(e) MSU radiances can be used, for example through a regression equation, 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 probably be too high for this information alone to give satisfactory results. However it could 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,
- what are the desired characteristics of the final product (in horizontal resolution, smoothness, independence from forecast models, etc.).

For instance, one practical scheme might include:

From (a) N* cloud-clearing based on adjacent HIRS soundings with ancillary information on the clear-column window channel radiance from AVHRR.

From (b) a filter/estimation scheme to provide clear-column radiance estimates from nearby spots. A Kalman-Bucy filter, such as that described by Ledsham and Staelin (1978), may be appropriate, although a simpler filter will probably be adequate. Additionally a system for detection and correction of gross errors (see Fleming and Hill, 1982) may also be useful. The filter should be applied in such a way as to "advect" information from all directions.

From (e) a regression estimate from MSU as a "background" field.

Numerous other combinations of information sources could be devised.

5. SUMMARY AND CONCLUSIONS

This paper proposes an overall approach to the problem of cloud-clearing which seeks to use the information available in an optimal way. Methods based on this approach will have the following strengths:

(a) They will achieve horizontal consistency in the clear radiance field (although care must be taken to ensure that this does not occur at the expense of losing real small-scale features in the radiance field).

(b) They will have the flexibility to include estimates from as many data sources as are available. If the clear-radiance algorithm (section 4(a) above) fails in a particular area, a clear radiance will be generated but with a suitably larger expected error.

(c) They will provide an estimate of the clear-column radiance error which can be used for quality control purposes and carried through the inversion algorithm, if required, to give an estimate of the error in the retrieved profile. This feature also offers a self-checking method for the cloud-clearing process as a whole: if estimates from different information sources differ by more than, say, twice the sum of their expected errors, it is highly probable that one of the estimates is grossly in error (due perhaps to the failure of an algorithm) or that the estimates of the expected error are too low. In either case this information would provide an effective route for diagnosing the source of the problem.

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ANNEX A CLOUD-CLEARING METHOD USED IN ROUTINE TOVS DATA PROCESSING BY U.K. METEOROLOGICAL OFFICE

This method was devised by the NOAA/NESDIS group 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. It is the method currently used by the Meteorological Office for routine processing of TOVS data.

The method is described briefly by Smith (1980) and is a variant of the N* technique first formulated by Smith (1968). 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 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 brightness temperature in MSU channel 2. The coefficients of the linear combination are pre-calculated from a regression of MSU channel 2 against clear HIRS values. If the linear combination of HIRS brightness temperatures is colder than MSU channel 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 beyond a given threshold.

(b) A cloud-clearing algorithm based on the N* method is then used. The additional piece of information required, i.e. the clear radiance in one HIRS channel or "pseudo-channel", is obtained from the measured MSU channel 2 brightness temperature, which acts as a "pseudo-channel" corresponding to the linear combination of HIRS channels described in (a). The N* method is applied to a box of 3x3 HIRS spots (and the MSU value interpolated to the location of the central HIRS spot). N*, and hence clear radiances, are calculated 8 times: the central spot is used with each of its neighbours. In the present implementation of this method N* is calculated separately for the HIRS longwave tropospheric channels (4-12) and the shortwave tropospheric channels (13-16) in an attempt to allow for an instrumental effect which may cause small differences in field-of-view location in the two wavelength regions. For each pair of spots the processing is only allowed to continue 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 apply. Also, as in (a), a solar reflection check is made using the cloud-cleared brightness temperatures in the HIRS window channels.

From the sets (up to 8) of cleared HIRS radiances generated in (b), plus the set of "clear" radiances given by (a) if they were judged cloud-free, the 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 5 lowest tropospheric standard pressure levels). 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.

The weaknesses of the present method are as follows:

- The checks in (a) can pass a HIRS sounding as clear when there is some contamination, particularly by low cloud. In tackling this problem AVHRR data could be expected to make a positive contribution.

- 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,
  - 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.

- The N* 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.

- No attempt is made (at the cloud-clearing stage) to maintain horizontal consistency in the clear radiance field.

- 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 cloudy radiances is questionable. It would be preferable for the cloud-clearing process to precede any scan angle correction.

- 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.

FIGURE 1

A possible pattern for a HIRS cloud-clearing algorithm