A New Cloud Clearing Approach for NESDIS

By

Larry M. McMillin

National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Satellite Research Laboratory, Washington, DC

1. INTRODUCTION

Satellite measurements that are made in the infrared region are attenuated by any clouds that are in the field-of-view. This means that if these measurements are to be used to retrieve atmospheric temperatures they must be cloud free or the clouds must be incorporated into the retrieval process. At NESDIS, infrared retrievals are made from clear (cloud free) radiances.

The NESDIS approach (McMillin and Dean 1982) obtains clear radiances in two ways. First a series of tests is performed to determine if a given spot is clear. If it passes these tests, it is determined to be cloud-free and the measured values are used for the retrieval.

If a spot fails any of the tests, it is assumed to be contaminated by clouds, and an attempt is made to adjust the measured radiances to clear values. This is done by finding two adjacent spots that are contaminated by different amounts of cloud, but with the same cloud height and other parameters. If such conditions are satisfied, then the N' technique developed by Smith (1968) is used to determine the clear value. If the adjusted clear value passes certain tests, it is passed on to the retrieval as clear. If it fails, or if the conditions for the N' technique are not met, a retrieval is made using the microwave and infrared channels responding to the upper atmosphere. Measurements for these channels are not affected by most clouds.

Use of the current NESDIS technique has shown that some of its
components can be improved. One of the most obvious is the procedure for angle correcting the radiances. Presently all measurements are adjusted to nadir before the cloud clearing is done. The correction is done with a regression. The problem is not that regression is used, but that the regression is applied to cloudy radiances. This means that the regression must account for both clouds and angle in one step, and it has difficulty doing both at once. The alternative is to adjust adjacent spots to a single angle in the cloud clearing step, adjust the radiances for cloud attenuation at the measured angle, then adjust the clear radiances to the nadir direction. Alternatively, the adjustment to nadir can be skipped and retrievals can be performed at the measured angles. The angle correction of cloudy radiances is regarded as the largest error source in the present procedure.

Presently three related cloud clearing approaches are being developed at NESDIS. One is the development of a new retrieval system known as Revised TOVS (RTOVS). This is being done in preparation for the Advanced TOVS retrieval system and can be characterized as those changes that are best made as part of new system rather than as a change to an existing system, but which do not depend on data from the Advanced Microwave Sounder Unit (AMSU). The important characteristic of this approach is that the science was determined some time ago and fixed. Thus it is not an appropriate place for development. Of course, science did not stop when the design was fixed and desirable alternatives have been developed since that time.

The second approach is part of a joint NASA-NOAA effort to improve retrievals by combining the best features of the interactive techniques used by Susskind et al. (1984) at Goddard Space Flight Center and operational techniques used at NOAA/NESDIS. This is a developmental approach and is being used to investigate techniques that are not included in the RTOVS effort.
The third approach is part of the Atmospheric InfraRed Sounder (AIRS) effort. It is primarily devoted to techniques required to use the large number of AIRS channels and will not be discussed in this paper.

2. REVIEW

The NESDIS cloud clearing is based on the $N^*$ approach developed by Smith (1963). The radiative transfer equation for a partly cloudy spot can be written as

$$I_v = (1 - \alpha \epsilon) \left( B_{vs} \tau_{vs} + \int B_v d\tau_v \right) + \alpha \epsilon \left( B_{vc} \tau_{vc} + \int B_v d\tau_v \right)$$

where $I_v$ is the measured radiance at wavenumber $v$, $\alpha$ is the cloud amount, $\epsilon$ is the cloud emissivity, $B_{vs}$ is the radiance emitted by a blackbody at the temperature of the surface, $\tau_{vs}$ is the transmittance between the surface and the satellite, $B_v$ is the radiance emitted by a blackbody at the temperature of the atmospheric layer, $d\tau_v$ is the change in transmittance over the layer, $B_{vc}$ is the radiance emitted by a blackbody at the temperature of the cloud, and $\tau_{vc}$ is the transmittance between the cloud and the satellite. For cloud clearing, it is convenient to write Eq. 1 as

$$I_v = (1 - \alpha \epsilon) I_{vc} + \alpha \epsilon I_{vo}$$

where $I_{vc}$ denotes the clear radiance and $I_{vo}$ denotes the overcast radiance. Equation 2 can be written for two adjacent spots as

$$I_{v1} = (1 - \alpha_1 \epsilon) I_{vc} + \alpha_1 \epsilon I_{vo}$$

$$I_{v2} = (1 - \alpha_2 \epsilon) I_{vc} + \alpha_2 \epsilon I_{vo}$$

where the subscripts 1 and 2 denote the spot. Since the emissivities for the two spots are equal in Eqs. (3 and 4), the quantity $\epsilon (I_{vo} - I_{vc})$ can be eliminated from both equations to give
McMILLIN, L.M. A NEW CLOUD CLEARING APPROACH FOR NESDIS

\[ I_{v_c} = \left[ I_{v_1} - (\alpha_1/\alpha_2) I_{v_2} \right]/\left[ 1 - \alpha_1/\alpha_2 \right]. \quad (5) \]

Defining \( \alpha_1/\alpha_2 \) as \( N^* \) gives the usual \( N^* \) equation,

\[ I_c = \left[ I_1 - N^* I_2 \right]/\left[ 1 - N^* \right]. \quad (6) \]

For a physical interpretation, it is easier to follow the approach used by McMillin (1971) for a similar equation and write Eq. (5) as

\[ I_c = I_1 + \left[ \alpha_1/ \left( \alpha_2 - \alpha_1 \right) \right] \left[ I_1 - I_2 \right] \quad (7) \]

since the second term on the right hand side is simply the correction to be added to \( I_1 \). It is important to note that since the emissivity has been assumed to be equal for both spots, there has been no need to require that emissivity be independent of wavelength. Requiring the emissivity to be equal for both spots is not very restrictive because the \( N^* \) approach requires that the two spots have the same cloud height. The procedures that select two spots with the same cloud top height select spots with equal base heights if the clouds are not opaque, and if the clouds are opaque, the emissivities are equal by definition.

When the \( N^* \) equation is used, a clear radiance is determined for one of the channels affected by clouds. This provides the information needed to determine the value of \( N^* \). Then the value of \( N^* \) is assumed to be constant and used to determine the value of \( I_c \) for the remaining channels.

3. FEATURES OF THE NEW APPROACH
The RTOVS approach differs from the current approach in several ways. First, as mentioned in the previous section, measurements will not be adjusted to nadir before the angle correction. Instead, spots in a 5 by 5 array will be adjusted to the viewing angle of the center spot. Then the spots will be examined to determine which of the surrounding eight spots has the same cloud height as the center spot. Next, the two spots will be used to
McMILLIN, L.M. A NEW CLOUD CLEARING APPROACH FOR NESDIS

derive a clear radiance at the common viewing angle. Finally, if angle adjusted radiances are desired, the clear radiances will be adjusted to nadir. In the past, angle adjustments have been based on simulated radiances, but the new technique will use corrections based on measured radiances using a technique developed by Wark (1983).

Many of the tests and procedures will be those included in the current method (McMillin and Dean 1982). However, some of the test for clear spots will be modified according to the recommendations of Wahiche et al. (1986) and Chedin et al. (1986). Preliminary versions of the tests and the new limits are being evaluated. They will be published when the evaluation is complete. The most significant change is the inclusion of AVHRR data in the TOVS processing. For a given HIRS spot, data for 17 AVHRR spots will be available. The 17 are all but eight of the 25 for a 5 by 5 array centered on the center of the HIRS. The eight spots that are omitted are those on the perimeter of the 5 by 5 that are not at the corner or the center of a side. These measurements will be used in the following manner:

1. If a HIRS spot is determined to be clear by the HIRS tests, the associated AVHRR spots are examined to assure that they are uniform. One spot with a lower temperature will cause rejection.

2. The AVHRR spots in the area covered by a given HIRS spot are passed through a set of AVHRR cloud tests. If any AVHRR spot fails the clear tests, it follows that the HIRS spot that covers the same area is also cloudy.

3. If any of the AVHRR spots are determined to be clear, a clear value can be derived for the HIRS window channel. This clear value can then be used in the N' procedure to produce the clear value for one channel in the same way that the microwave measurements are being used now.

301
McMILLIN, L.M. A NEW CLOUD CLEARING APPROACH FOR NESDIS

4. The $N^*$ procedure requires that the two spots that are used have the same cloud top temperature. If this is the case, then the 34 AVHRR measurements contained in the two HIRS spots must all lie on a straight line when the measurements for AVHRR channel 3 are plotted against those for AVHRR channel 5.

The NOAA-NASA investigation is an attempt to combine the best features of both systems. The NASA system already has the local angle adjustment while the NESDIS system has extensive screening procedures to assure that adjacent spots meet the required conditions before they are used. In addition, the NASA approach uses the forecast for cloud clearing. While this can improve the accuracy, the resulting model dependence can be a problem for some uses of the data. Ways to decrease the model dependency are being investigated.

The spot selection algorithm can have an important effect on the accuracy of the clear radiances. The $N^*$ approach requires two spots that have different amounts of cloud at the same cloud height. This is a rather rare occurrence because clouds that are bigger are frequently both higher and wider, and the center of a cloud is frequently higher than the edge. Thus a spot with more cloud is also likely to have a higher average cloud height than one that has less cloud because a spot with more cloud is filled with a larger cloud or more of the center of small cloud. The error is serious because it is a bias.

The importance of the spot selection is illustrated in Figs. 1-3. These figures show brightness temperatures for channels 6 and 7 for typical 5 by 5 arrays of spots. Although the cloud clearing should be done in radiances, not temperatures, the effects are illustrated by the figures. Fig. 1 shows the pattern that is observed when most of the spots are from an area covered by clouds at a single height. The 25 measurements mostly fall on a single straight line. Fig. 2 shows a different pattern. The spots in lower left hand corner are from a single high cloud since they have the same brightness temperature at both channels.
Figure 1. Brightness temperatures for a 5 by 5 array.

Figure 2. Brightness temperatures for a 5 by 5 array.
and are tightly grouped. The points in the upper right hand corner are scattered and come from spots with different cloud heights. It is obvious that a clear radiance derived from a pair of spots containing one of these would be highly dependent on the spots selected. Of the spots in the upper right-hand corner, those to the lower right of the cluster are most likely to be from high clouds. However, it would be difficult to obtain a reliable clear radiance from this situation. Fig. 3 shows a typical pattern for mixed clouds. It is clear that there are at least two cloud levels. In a mixed cloud situation, the cloud that is most easily identified is the highest one. Spots from a single cloud form a straight line that, for the highest cloud, form the lower edge of the cluster. This edge can be easily identified in the figure and a clear radiance can be obtained. At the same time, it is clear that picking any two points at random could produce a clear radiance with a large error.

**Figure 3.** Brightness temperatures for a 5 by 5 array.
As illustrated by the three figures, it is necessary to find a subset of points with the same cloud height and the points for the highest cloud in the array fall on a sharp border that forms the lower right-hand edge of the cluster of points. This edge can be easily identified. The current technique consists of the following steps.

1. A point is selected and the 25 points in a 5 by 5 array centered on the point are identified.
2. All radiances are adjusted to the viewing angle of the center point.
3. The warmest and coldest points for HIRS channel 7 are identified and connected with a straight line.
4. The perpendicular distances from all points to the straight line are determined.
5. The point with the largest departure in the direction of the high clouds is identified.
6. The slopes of the lines connecting the selected point to the remaining 24 are determined.
7. For the points that are warmer than the selected point, the points with the minimum slopes are selected. For colder points, the points with the maximum slopes are selected. Slopes for points too close to the selected point are unreliable and are not used.
8. The selected points are used to derive the cloud correction using the N* procedure.

Once the points with the same cloud height have been selected, the next step is to derive the clear column radiance. The key to the N* procedure is the determination of a clear radiance for one of the channels. For TOVS, the clear estimate is derived from the microwave measurement. However, the relationship between the microwave and infrared measurements is not simple.

In the NASA algorithm, the brightness temperature of HIRS channel 13 or 14 is assumed to approximate that of MSU2. This is a rather crude approximation, but the difference is determined by
using a forecast. The forecast is used to calculate radiances and determine the difference between HIRS channel 13 (or 14) and MSU2. The forecast can be used in the same way in the new procedure, but it is correcting the difference that is about 1.0K not 10K, a typical difference between MSU2 and channel 13 or 14. Thus the dependence on the forecast is reduced. In addition, it may be better to avoid the forecast and any hint of model dependence.

As an alternative, one could predict the HIRS measurements from the microwave values. This produces an estimate, but one that has a large uncertainty. The uncertainty is due to the fact that there are fewer microwave measurements than HIRS measurements. As a result, the microwave measurements are widely spaced in the vertical. In addition, only microwave channel two overlaps with those HIRS channels that are affected by clouds. As a result, the prediction accuracy for the HIRS channels affected by clouds is poor.

The best alternative is to predict microwave channel 2 from the HIRS channels. Because the HIRS channels are more closely spaced, this provides a more accurate relationship between the two wavelength regions. However, it is also complicated. When the microwave channels are used as predictors, the regression can be done in terms of brightness temperatures because the microwave radiance does not depend on the cloud amount. Since, the HIRS radiances are cloud contaminated, the HIRS radiances must be used as predictors. Recall that the N^2 relationship works because the radiance for each channel is a linear function of cloud amount. To preserve this relationship, the regression must use radiances as predictors. To do so, the microwave radiance is converted to an equivalent radiance at the frequency of the HIRS channel 6. Then a regression relationship using coefficients derived from clear conditions is used to predict this value from HIRS radiances from channels 5, 6 and 7. This procedure results in a virtual channel that satisfies the requirements of a linear relationship with cloud amount and an accurate relationship.
McMILLIN, L.M. A NEW CLOUD CLEARING APPROACH FOR NESDIS

between infrared and microwave measurements. When HIRS channels 5, 6, and 7 are used to predict MSU channel 2, the error in the prediction is slightly over 1.0 K.

3.2 Summary

The cloud clearing techniques being used at NESDIS are being modified. A new technique has shown improvements in several areas. The initial angle correction of cloud contaminated radiances to nadir is being removed, the AVHRR data will be used for cloud detection and correction, and better spot selection techniques are being employed. These changes will result in improved accuracy for the cloud clearing process and any retrieval products derived from the resulting radiances.

3.3 References


TECHNICAL PROCEEDINGS OF
THE SEVENTH INTERNATIONAL TOVS STUDY CONFERENCE

Igls, Austria

10-16 February 1993

Edited by

J R Eyre

European Centre for Medium-range Weather Forecasts
Shinfield Park, Reading, RG2 9AX, U.K.

July 1993