EVALUATION OF MULTILEVEL CLOUD PARAMETERS WITH CLOUD PROFILING RADAR

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1. INTRODUCTION

Recent progress in the development of an assimilation method satellite data to Numerical Weather Prediction (NWP) model has given impetus to continued investigation of both assimilation method and characterization of satellite data. By and large, progress has been realized by the use of radiance data in the variational method (Eyre et al., 1993). Further improvement toward successful assimilation depends on features such as improved forward model, bias correction, cloud clearing method. Most attempts were applied to a global NWP model, but the regional scale NWP model has to deal with extracting cloud information from satellite data. Uttal et al. (1995) reported that among cloud boundaries collected during November and December 1991, single layer cloud occurred only 40%. Such statistics attest that the regional scale NWP model assimilation system must include vertically distributed clouds, i.e., multilevel cloud information.

Kim and Chou (1995) presented a simple algorithm to extract multilevel cloud information by combining Advanced Very High Resolution Radiometer (AVHRR) image data and High resolution Infrared Radiometer Sounder (HIRS) data. The initial guess of the multilevel cloud parameters determined from AVHRR pixel values (either counts or brightness temperatures) under the HIRS field of view (fov) is weakly constrained in minimizing the difference between measured HIRS Channel 7 and 8 radiances and computed ones from forecast profiles from the Mesoscale Analysis and Prediction System (MAPS, Benjamin et al., 1995). Thus, AVHRR data are being used to complement cloud-affected sounder data.

In order to validate and evaluate our algorithm for the extraction of the multilevel cloud parameters, we compare our results with observations made by new 35-GHz cloud-profiling radar (Post and Moran, 1996). The cloud-profiling radar is designed by NOAA’s Environmental Technology Laboratory (ETL) to support the Department of Energy’s (DOE) Atmospheric Radiation Measurement (ARM) program by continuously monitoring cloud profiles. The horizontal resolution of the radar beam, about 50 m at a height of 10 km, is much smaller than the AVHRR pixel size (1.1 km). Therefore, subpixel clouds undetected by the full resolution AVHRR image can be easily observed by the cloud-profiling radar.
In this paper improvement of previous algorithm (Kim and Chou, 1995) is briefly discussed as well as some results from the simulated data from well-defined multilevel cloud cases. On 2011 UTC 23 November 1996 TIROS passed over the central United States including the cloud-profiling radar site in northern Oklahoma. We discuss comparisons during this time. This case is of particular interest because it include a frontal system in which several layers of cloud were present.

2. METHODOLOGY

Since five-channels AVHRR data and 19-channels HIRS data are contained in the High Resolution Picture Transmission (HRPT) data stream broadcasted by polar orbit TIROS, there is no delay in combining two data for the real-time processing. As soon as navigation and calibration of sounder data are completed, all AVHRR Channel 4 pixel values that fall within HIRS fov are collected. The steps involved here include 1) to derive initial guess of the cloud fraction and its representative values that are independent of the NWP forecast profiles, and 2) to use constrained minimization to estimate cloud top height for each cloud fraction. In this way, the output after first step can be used in any NWP assimilation system.

2.1 Derivation of initial guess

The mapping of AVHRR pixel values relative to each HIRS fov adopt the method of Aoki (1985) using the geometry of relative scan positions of two instruments. All AVHRR pixel values within a HIRS fov are rearranged as relative frequency of 8 bits count values, whose sum is the unity. This normalized frequency is called the empirical density function. If the number of pixels are less than 100, it is considered of bad quality and set the number of cloud fraction be zero. Since the empirical density function is subject to noise, a triangular smoothing kernel function is repeatedly applied until two conditions are met:

- a maximum number of cloud fractions be 6
- two neighboring peaks must be separated by more than 7 in count value, which is approximately 5 deg K.

Let \( f_n \) be the fractional empirical density function defined on disjoint domain \( \Omega_n \), such that \( \int_{\Omega_n} f_n(x)dx \) is the \( n^{th} \) cloud fraction \( (\alpha_n) \) out of maximum six. Therefore, the sum of the fractional empirical density function is 1, and the expected value of the \( n^{th} \) fraction is \( \int_{\Omega_n} xf_n(x)dx \), which we will consider as the representative value of the \( n^{th} \) cloud fraction. The domain \( \Omega \) spans between 0 and 255, but in general it is between 80 and 230. The computations of smoothing and grouping are carried out with count values. This has two advantages: first, the class interval in the histogram does not use fractions; second, calibration is applied only to the representative values, so that there are at most 6 times of calibrations. Figure 1 is an example of the product. A value of 1 implies the homogeneous fraction (either overcast or clear) and is not plotted.
2.2 Derivation of cloud top heights

The derivation of cloud top heights requires a forward model. We use RTTOV (Eyre, 1991), which conveniently computes overcast radiances at prespecified radiative transfer (RT) levels given a temperature and humidity profile. The profile is a 3-h forecast from MAPS. Assume that the computed radiance is,

\[
R_j^\text{com} = [1 - \sum_k \alpha_k] R_j^\text{clr} + \sum_k \alpha_k R_j^\text{ovc}
= R_j^\text{clr} + \sum_k \alpha_k (R_j^\text{ovc} - R_j^\text{clr}),
\]  

(1)

where the superscript com means computed, clr means clear, ovc means overcast and \( j \) is channel, \( k \) is the index of the lower 16 of 40 RT pressure levels, namely, 250, 300, 350, 400, 430, 475, 500, 570, 620, 670, 700, 780, 850, 920, 950 and 1000 hPa, respectively, and \( \alpha_k \) is the cloud fraction at \( k \)th level. The cloud fractions are obtained when the function \( J = \sum_j (R_j^{\text{meas}} - R_j^{\text{com}})^2 \) is minimal. The superscript meas means measured.

We reformulate this into a linear regression problem,

\[
y = X\beta + \epsilon,
\]

(2)
where $y$ is a vector whose elements are $R^{\text{mod}}_{j,k} - R^{\text{str}}_{j,k}$, $X$ is a matrix whose elements are $R^{\text{mod}}_{j,k} - R^{\text{str}}_{j,k}$, and $\mathbf{b}$ is a column vector of cloud fraction $\alpha_k$, and $\mathbf{e}$ is error. Therefore, the minimization of the sum of the squares of the residuals is identical to the minimization of $(y - X\mathbf{b})'(y - X\mathbf{b})$. The imposition of the constraint that blends with prior information becomes a minimization of

$$J = (y - X\mathbf{b})'(y - X\mathbf{b}) + \lambda \mathbf{b}'\Sigma^{-1}\mathbf{b},$$

whose solution will be a constrained least squares estimator given by

$$\mathbf{b} = (X'X + \lambda \Sigma^{-1})^{-1} X'y,$$

where $\lambda$ is the tuning parameter, and $\Sigma$ is a diagonal matrix whose elements are empirical weighting values.

If the $\mathbf{b}$ is defined as a multivariate random variable with a known distribution, then $\Sigma$ is a covariance of $\mathbf{b}$. The diagonality of $\Sigma$ requires no vertical error correlation in the cloud parameters derived from the AVHRR image. The requirement is reasonably satisfied by the imposed conditions of a distinctive cloud mass. In practice, the radiance value for each representative cloud group is compared to the computed overcast radiance of the HIRS Channel 8, i.e., $R^{\text{mod}}_{j,k}$, $j = 8$, and linearly interpolated to prespecified RT model levels. For example, two cloud groups at 740 hPa with 0.5 fraction and 685 hPa with 0.5 fraction would be entered 0.25 at 780 hPa, 0.5 at 700 hPa, and 0.25 at 670 hPa. In order to compute an element of $\Sigma^{-1/2}$, a temporary matrix $F$ whose element $F_{in}$, $i = 1, \ldots, 16, n = 1, \ldots, 6$ is used. The column number corresponds to the number of the cloud group, the row number corresponds with the vertical levels. The column-wise sum, $\sum_i F_{in}$ is the same as $\int_{\Omega} f_n(x)dx$. Therefore, $\sum_i F_{in}$ is the $i^{th}$ element of $\Sigma^{-1/2}$.

The first term in the right-hand side of Eq. (3) is to make $R^{\text{mod}}$ close to $R^{\text{str}}$, while the second term exerts a penalty if the solution deviates from the first guess. Hence, the purpose of the parameter $\lambda$ is to balance those two terms. We choose a value of one for $\lambda$. At the level of no cloud, we assign a very small value 0.001 to the corresponding element in $\Sigma^{-1/2}$ to avoid numerical problems. Equation (4) is solved by the least squares solver from the linear algebra package (Anderson et al., 1992).

3. A SIMULATION STUDY

The method presented in the previous section was tested with a simulated dataset (Kim, 1996). Since the purpose of the simulation study is to compare the result of a constrained minimization with a single level cloud parameter estimation (Eyre and Menzel, 1989), the specified cloud levels are made to coincide with RT model levels to eliminate vertical interpolation error. The HIRS clear and overcast (black cloud) brightness temperatures at the given 15 RT model levels (up to 300 hPa) are computed using the RTTOV forward model from the standard atmosphere profile. Ten configurations of the vertical cloud distribution are considered. The prespecified cloud levels at 300, 500, 700 hPa have a cloud fraction of 0, 1/3, 2/3, 1, and the number of AVHRR pixels are proportioned accordingly out of a total of 370 pixels. True HIRS data are linear combinations of overcast with known cloud fractions. Thereafter, a set of Gaussian errors of standard deviation 5.0 deg K is added to the overcast brightness temperature of the cloud level to simulate realistic
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AVHRR data and cloudy HIRS data. The simulated HIRS Channel 8 data are obtained by averaging all of the simulated AVHRR pixels after adding the random errors. The difference between simulated data and the truth in Channel 8 is added to Channel 7 truth to create a consistent measurement error.

The result showed that a multilevel model is necessary when there are multilevel clouds in the HIRS fov. The single level method, using HIRS channels 7 and 8, can mislead retrieved parameters. As long as AVHRR data are available, estimating multilevel cloud parameters by merging HIRS and AVHRR data is a desirable choice.

4. A CASE STUDY

We chose a case from 2011 UTC 23 November 1996 that TIROS (NOAA-14) passed over the cloud-profiling radar site near Lamont, Oklahoma. Figure 2 is a subset of AVHRR image that contains 4 x 4 HIRS fov. Count value of each AVHRR pixel has been converted to brightness temperature. The radar site is near the northeastern edge of the HIRS footprint at the 28th scan line and the 35th scan element. The approximate scan time of the image is 2014 UTC. We note that cloud system in this area has homogeneous boundary layer clouds (pale green area) and higher level clouds above the boundary layer clouds (dark blue and grey area).

![Figure 2](image.jpg)

Fig. 2. Brightness temperature of an AVHRR Channel 4 image. Dotted circles are boundaries of the HIRS fov. Ten fovs out of 16 fov are recognized as single level implying that the cloud tops are almost homogeneous. These single level cloud fov's correspond to postfrontal situation, and multilevel cases correspond to prefrontal situations. The numbers on the right are scan lines of HIRS in ascending mode, and the numbers at the top show each scan element. Color scale of green-blue-grey represents warm to cold brightness temperatures, implying low to high level cloud.
Fig. 3. The number of cloud masses as identified by the method in section 2.1 are shown in Fig. 3a, top. Each ellipse corresponds to the HIRS footprint in Fig. 2. Multilevel cloud parameters at the corresponding HIRS fov of Fig. 2 are shown in Fig 3b, middle. The numbers above represent cloud top pressure in hPa (NCL), and below represent the fractional coverage (FCL). When it is a single level, the cloud top pressure level is estimated from the RT model level. Fig. 3c, bottom, is the same as Fig. 3b except assuming only one cloud layer.
The three panels in Figure 3 show the cloud parameters. Figure 3a is the initial guess of number of cloud layers using the AVHRR Channel 4 data alone. This can be visually confirmed qualitatively by comparing with Fig. 2. Cloud distributions are more complex within the bottom and lower-right side of the HIRS fov. Figure 3b is the solution of Eq. (4). If any HIRS fov is identified as single, then the cloud top pressure is estimated from neighboring levels, for example, the top-left fov in Fig. 3b has a solution with 86% of a fraction at 700 hPa and 14% of a fraction at 780 hPa so that the a final result is the overcast at 711 hPa. At the same fov, the single layer solution in Fig. 3c results in 49% of fractional cloud at 570 hPa and remaining (51%) as clear. In comparison with the AVHRR Channel 4 image, there is no indication of a clear fraction. Thus, the clear fraction in the single layer solution is due to an inadequate cost function. A small error in the surface temperature could generate an erroneous cloud-parameter when we use a single layer model (McNally, 1990).

5. COMPARISON WITH CLOUD PROFILING RADAR

The routine verification of cloud parameters derived from the satellite is important because in situ measurements of cloud parameters often are not available. If exist, they often are expensive aircraft measurements. The DOE sponsors the Atmospheric Radiation Measurement (ARM) program that operates many instruments at its Cloud And Radiation Testbed (CART) sites. In collaboration with DOE, NOAA's Environmental Technology Laboratory (ETL) began to produce 35 GHz Doppler cloud-profiling radars. Data have been produced since 12 November 1996 near Lamont, Oklahoma, one of DOE/ARM's Southern Great Plains sites.

Fig. 4 Time-height cross-section of cloud profiling radar reflectivity at the CART site near Lamont, Oklahoma. The very high temporal (9 sec of dwell time) and spatial (50 m) resolution depicts very fine vertical structures of multilevel clouds.
Such radar data is perhaps the only in situ measurement that can verify satellite-derived cloud parameters routinely. Figure 4 is a time-height radar reflectivity for about 3 hours beginning 2000 UTC 23 November 1996.

A complete TIROS pass within the MAPS domain (see Fig. 1) takes less than 15 min, so the image of Fig. 2 would take less than 30 sec. While this AVHRR image shows a quasi-instantaneous horizontal view, the radar image is a timeseries which includes local temporal change. As both the weather and the cloud systems move nonlinearly, it is almost impossible to collocate an AVHRR image with the cloud-profiling radar. For a qualitative discussion, let us assume the system is frozen. If the system moves with a typical scale of 10 m s$^{-1}$, then the passage of a HIRS footprint would take approximately 30 min. At the TIROS pass on 2014 UTC, the cloud-profiling radar shows the detailed structure of the subpixel variation of the cloud top. The overall feature during the 3-h period is that the boundary layer cloud top slowly increases from 800 hPa to 750 hPa as the sun heats the boundary layer, intermittent midlevel clouds whose tops are about 500 hPa, another layer at 400 hPa, and another at 300 hPa with a strong indication of a cirrus type cloud.

In general, the proposed method agrees quite well with the boundary layer cloud tops which vary between 690 and 765 hPa (see Fig. 3b for fov's with a single cloud mass) while the radar shows about 770 hPa at 2200 UTC (Fig 4). The HIRS fov's which is closest to the radar image is the 28th line and 35th element, but the AVHRR image shows only a fraction (initial guess was 14%, and final result from the constrained minimization was 5%) at 645 hPa. This estimated cloud top is much lower than the radar image between 2015 and 2045 UTC with an approximate height of 400 hPa. This example shows the difficulty in matching the two dataset, thereby posing a danger in interpreting statistics from collocated samples. The cloud-profiling radar is certainly free from inherent problems pertaining to satellite data, that is, an inability to estimate multilevel cloud when upper level clouds are overcast at the HIRS fov. Also, any cloud phase product (e.g., cirrus) can be verified with the cloud radar.

6. SUMMARY AND FUTURE PLANS

The proposed method of multilevel cloud-parameter estimation using AVHRR data to supplement HIRS has shown advantages over the single layer method of Eyre and Menzel (1989) based on two HIRS Channels 7 and 8. The results from both simulated and real data suggest that the AVHRR data can actually be used to complement the sounder radiance by identifying vertical cloud structure, rather than just simply being used to eliminate cloud contaminated HIRS data. This is a desirable direction for the radiance assimilation to regional scale NWP, where prediction of cloud system is very important. Several tasks listed in Kim (1996) have been accomplished, but the treatment of semi-transparent cloud is still under development. A few candidates to help improving the present method include 1) the use of AVHRR channels 3 and 5; 2) the use of high frequency Geostationary Operational Environmental Satellite (GOES) sounder and imager. Fortunately, cloud-profiling radar will easily verify the result of a new algorithm.

Since the AVHRR resolution is about 20 times higher than that of the HIRS sounder (20 km to 1 km), we
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had to adopt a process of smoothing and grouping AVHRR data so that the multilevel cloud information could be used in NWP (the example used in the forward computation is the 60-km version of MAPS). The same practice should be applied in the routine validation and evaluation of cloud parameters by the cloud-profiling radar. The ratio of the resolution of the AVHRR to that of cloud profiling radar is, interestingly, about 20 (1 km to 50 m). To coincide with ETL's plans to install additional radars, FSL also plans the routine validation and evaluation of satellite-derived cloud parameters.

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8. REFERENCES


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