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A SINGLE FIELD OF VIEW METHOD FOR RETRIEVING TROPOSPHERIC TEMPERATURE PROFILES FROM CLOUD-CONTAMINATED RADIANCE DATA

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16. ABSTRACT

A method is presented to retrieve single field of view (FOV) tropospheric temperature profiles directly from cloud-contaminated radiance data through the use of auxiliary data such as observed shelter temperature and estimated cloud-top height. The iterative technique utilized is an extension of the work of Chahine as modified by Smith and Duncan. It is shown that a well-defined temperature profile may be calculated from the radiative transfer equation (RTE) for a partly cloudy atmosphere when the average fractional cloud amount and cloud-top height for the FOV are known. A cloud model is formulated to calculate the fractional cloud amount from an estimated cloud-top height.

The method is then examined through use of simulated radiance data calculated through vertical integration of the RTE for a partly cloudy atmosphere using known values of cloud-top height(s) and fractional cloud amount(s). Temperature profiles are retrieved from the simulated data assuming various errors in the cloud parameters.

Temperature profiles are retrieved from NOAA-4 satellite-measured radiance data obtained over an area dominated by an active cold front and with considerable cloud cover. Excellent radiosonde data for 11 stations participating in the Atmospheric Variability Experiment (AVE III) available for the area are used for comparison with temperature profiles retrieved from the NOAA-4 data. The effects of using various guessed profiles and the number of iterations are considered.

The results of the investigation indicate:

(1) The single FOV method presented improves the accuracy of guessed profiles when retrievals from cloud-contaminated radiance data are attempted. It is significant that in the method presented, improvement in the guessed temperature profile was noted under the cloud layer where retrievals using other single FOV techniques tend to deteriorate.

(2) Through proper choice of a guessed profile, it appears possible to improve many profiles independent of the cloud amount present.

(3) Use of the method presented should provide useful data for mesometeorological research in the form of an accurate temperature profile representative of a relatively small horizontal area, or many temperature profiles to show the pattern of temperature change over a larger area. However, the absolute accuracy of the retrieved profile is also a function of the a priori knowledge of the state of the atmosphere possessed by the researcher.

(4) It is possible to make an accurate estimate of the average tops of a thick overcast layer through use of the cloud model when there are no thick clouds present above the overcast layer.

(5) Observed cloud parameters do not possess sufficient precision for use directly in the RTE to retrieve temperature profiles.

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a	used to denote the power to which weighting function raised
A	effective cloud amount ($A=N\varepsilon$)
A_L	effective cloud amount for the lower of two layers
A_u	effective cloud amount for the upper of two layers
A*	a function of A_L and A_u
A_{Total}	sum of effective cloud layers
B	Planck function (radiance)
B_r	Planck radiance at frequency r
CO_2	carbon dioxide
C	a numerical correction
$\hat{C}$	a computed estimate of C
c_1, c_2	constants used in computing temperature
G	the quantitative difference between the average radiances arising from the clear and cloudy portions of a field of view (FOV)
H_2O	water vapor
I	clear column radiance
$\tilde{I}$	measured radiance for a cloudless atmosphere
$\tilde{I}^*$	measured cloud-contaminated radiance
I*	a computed estimate of $\tilde{I}^*$
I_{MEAS}	measured radiance
I_{CD}	average radiance arising from the cloudy portion of the FOV
I_{CLR}	average radiance arising from the clear portion of the FOV (equivlanet clear column radiance when obtained by filtering cloud effects)
$\bar{I}$	clear column radiance averaged over many FOVs

LIST OF SYMBOLS AND ACRONYMS (continued)

$\hat{I}$	a calculated estimate of clear column radiance
I^{max}_{CLR}, I^{min}_{CLR}	maximum and minimum possible values of clear column radiance
I_b	radiance arising from a black-body cloud
i, j	subscripts
k	the number of effective cloud layers
l	the number of FOV combinations used to calculate average clear column radiance
m	the number of frequencies employed to calculate temperature
n	superscript used to denote iteration number
N	fractional cloud amount
N*	ratio of fractional cloud cover in two FOVs
O_3	ozone
P	pressure
P_o	surface pressure
P_c	pressure at cloud-top level
P_L	pressure at the top of the lower of two cloud layers
P_u	pressure at the top of the upper of two cloud layers
R	residual; error
r	a nominal frequency near the center of the CO_2 band
T	temperature
T_o	surface temperature
T_c	cloud-top temperature
W	weighting function
ω	window channel frequency
ω_s	a short-wave window channel frequency

ω_L	a long-wave window channel frequency
X, Y	functions of cloud-contaminated radiance used to obtain equivalent clear column radiances from measured values
x	a function of pressure ($x = P^{2/7}$)
x_o	value of x at the surface
x_{P_c}	value of x at cloud top level
ΔB	change in the Planck function
$\overline{\Delta B}$	weighted average of changes in the Planck function
ε	emissivity
ε_c	cloud emissivity
η	a function of the fractional cloud amount in the two fields of view
μ	mass of absorbing gas above a given level
ν	frequency
$\bar{\nu}$	average frequency in a small interval
τ	transmissivity
τ_{CO_2}	transmissivity of carbon dioxide
τ_{H_2O}	transmissivity of water vapor
τ_{O_3}	transmissivity of ozone
AGL	above ground level
AVE	Atmospheric Variability Experiment
FOV	field of view
HIRS	High Resolution Infrared Sounder
ITPR	Infrared Temperature Radiometer
JPS	Joint Planning Staff
MSFC	Marshall Space Flight Center

LIST OF SYMBOLS AND ACRONYMS (continued)

NASA	National Aeronautical and Space Administration
NOAA	National Oceanic and Atmospheric Administration
RMS	root mean square
RTE	radiative transfer equation
VTPR	Vertical Temperature Profile Radiometer

I. INTRODUCTION

a. Statement of the problem

Over the past decade, a number of studies have dealt with various aspects of the problem of retrieving temperature profiles from satellite-measured radiances in the infrared region of the electromagnetic spectrum. Much of the research in this area has had the ultimate purpose of providing profiles that are suitable for use as input to numerical forecast models.

Comparatively little attention has been given to the possibility of using satellite-derived profiles for mesometeorological research. Originally, this was probably because of the poor spatial resolution of the radiance measurements of the early satellites. As satellite technology has advanced, the spatial resolution for a single FOV has improved. However, the most accurate temperature profiles retrieved from cloud-contaminated radiance data have generally been achieved through use of a multiple FOV method in which cloud filtered and clear radiance data obtained for many FOVs are averaged.

Through use of a multiple field of view cloud model (the term "cloud model" will be used to represent techniques of filtering or otherwise accounting for clouds in the RTE) an average profile generally representative of a large horizontal area is retrieved. For the High Resolution Infrared Sounder (HIRS) of the Nimbus 6 satellite a resolution of 200 km is obtained (Smith *et al*. 1975).

Recently, good results also have been obtained through use of measurements in the microwave region which are relatively unaffected by cloud contamination. For the Nimbus 5 satellite, average kinetic temperatures were obtained for layers of approximately 10 km thickness centered near 4, 11, and 18 km (Staelin, 1974). Temperatures at discrete levels are then obtained through use of the correlation between these temperatures and the temperature over the weighting function layer (Waters et al. 1975). The Nimbus 6 satellite contains a microwave sensor with a resolution of 145 to 330 km from nadir to scan limit that will have a maximum cloud-caused error of 2K over water and 1K over land (Staelin et al. 1975). The implementation of microwave techniques and improvements of multiple FOV cloud models have not altered the fact that the cloud problem remains the most serious obstacle in the retrieval of temperature profiles for mesometeorological research.

In the present investigation an attempt is made to provide useful retrievals for this purpose by improving the spatial resolution of the temperature profile through use of a single FOV cloud model based on observed cloud and temperature data. The cloud and temperature data are used in conjunction with real and simulated radiance data from the NOAA series of satellites that are currently used for operational retrievals over ocean areas where cloud amounts are not too great to retrieve significant information. Previous single FOV models have been based on climatology (Rodgers, 1970) or, as in the Smith et al. (1970) model, have been found most useful in reducing the influence of clouds on the solution profile above cloud-top level (Fritz et al. 1972).

Routinely observed cloud amounts and heights have not been used as input to the cloud models used in temperature retrieval work. The unknown emissivity of the observed clouds and the uncertainty of cloud-top heights, fractional amounts, and number of cloud layers are some of the reasons why these data have not been utilized. Fritz et al. (1972) pointed out some of the difficulties involved in using auxiliary cloud data to assist in determining the effective cloud cover ($N\varepsilon$), height, and amount, but conceded "...this has not been tried yet, so it is not known what effect such a procedure would have on the accuracy of temperature retrievals." For most models in current use the cloud-contaminated data are filtered to obtain an "equivalent clear column radiance" prior to solving the radiative transfer equation (RTE) to retrieve the temperature profile.

This research represents an extension of previous research in that a method is devised to use auxiliary cloud information to obtain an improved single FOV temperature profile directly from the RTE for a cloudy atmosphere. Also, in order to implement the proposed method a cloud model is devised to obtain the fractional cloud amount at an estimated cloud-top height through use of a search among radiance values which are calculated at a single frequency for various cloud amounts. A single FOV method provides much better spatial resolution than a multiple FOV method, and the method presented in this research has yielded improved temperature profiles below cloud layers. This is the region in which retrievals from other single FOV techniques tend to deteriorate.

b. Objectives

The objectives of this research were to:

(1) Develop a theoretical model to retrieve single FOV temperature profiles from cloud-contaminated radiance data;

(2) Examine the model through use of a parametric study utilizing simulated radiance data computed from a known temperature profile to investigate the errors in retrieved profiles caused by errors in cloud amounts, cloud heights, and other parameters; and

(3) Compare the profiles retrieved through use of the model against radiosonde profiles obtained during the Atmospheric Variability Experiment (AVE III).

The procedures used to achieve the above objectives will be fully explained in the sections that follow.

2. THEORETICAL DEVELOPMENT

a. The Radiative Transfer Equation for a clear atmosphere

Over the past decade attempts to determine atmospheric temperature profiles have concentrated on the 15-μm carbon dioxide band of the electromagnetic spectrum. To retrieve temperature profiles the RTE may be solved numerically for frequencies in this band. Later in this section methods for solving the RTE will be discussed. However, the following fundamental assumptions are required in all methods of determining temperature profiles from carbon dioxide band data (JPS, 1973):

(1) The mixing ratio of CO_2 is constant below 30 km.

(2) The atmosphere below 50 km is in local thermodynamic equilibrium (i.e. Planck's function and Kirchoff's Law may be used).

(3) Scattering by aerosols is negligible.

As a practical matter it is also necessary to assume that $\nu \cong \bar{\nu}$ (defined below) in the small spectral interval of each channel.

Using the above assumptions, the RTE for a plane parallel, cloudless, and non-scattering atmosphere may be expressed as

$$I(\nu) = B[\nu,T(P_o)]\cdot\tau[\nu,\mu(P_o)] - \int_o^{P_o} B[\nu,T(P)]\,\frac{\partial\tau[\nu,\mu(P)]}{\partial P}dP \qquad (1)$$

where $I(\nu)$ is the radiance (intensity), $B[\nu,T(P)]$ is the Planck radiance, and $\tau[\nu,\mu(P)]$ is the transmittance at frequency ν of the mass of absorbing gas μ above pressure P, and the partial derivative $\frac{\partial\tau[\nu,\mu(P)]}{\partial P}$ is a weighting function giving the relative atmospheric contributions to $I(\nu)$. A set of integral equations which is used to calculate radiances at the various frequencies of the 15-μm band may thus be obtained from a known temperature profile when $\tau[\nu,\mu(P)]$ and thus $\frac{\partial\tau[\nu,\mu(P)]}{\partial P}$ can be calculated.

There are several methods of calculating values of $\tau[\nu,\mu(P)]$ used to evaluate the weighting functions. In this research the computer program used in the calculations is the same as that used for the NOAA series of satellites. A general discussion of the procedure used for each gas with references to original sources is given by

McMillin et al. (1973). Transmittances for carbon dioxide (τ_{CO_2}), ozone (τ_{O_3}), and water vapor (τ_{H_2O}) were calculated by use of the following equation

$$\tau[\nu,\mu(P)] = \tau_{CO_2}[\nu,\mu(P)]\cdot\tau_{O_3}[\nu,\mu(P)]\cdot\tau_{H_2O}[\nu,\mu(P)] \tag{2}$$

to obtain the total transmittance above a given pressure level. The ozone transmittance is a relatively minor correction to the total transmittance at a given level. However, as the distribution of moisture is highly variable it is necessary to use a guessed moisture profile as input to the computer program. The mixing ratio of carbon dioxide is relatively constant with height, and thus estimates of the variation of transmittance with pressure have been determined.

Transmittance and weighting function curves for the 15-μm channels of a Vertical Temperature Profile Radiometer (VTPR) instrument (McMillin et al. 1973) are shown in Fig. 1.

For each channel (labeled 1-6 in Fig. 1a) the values of transmittance above a given atmospheric level increase as lower values of pressure are used to indicate the atmospheric level until they approach 1.0 asymptotically at the top of the atmosphere. This result should be anticipated. As the mass of CO_2 present at an atmospheric level decreases with an increase in height above Earth's surface, the transmittance of radiation emitted at a given level must increase with height above the surface.

As transmittance increases with increasing height above the surface, the change of transmittance with height (i.e. the weighting function) increases to a maximum value and then decreases until the value 0.0 is approached at the top of the atmosphere (Fig. 1b). Thus for a given channel the contribution to the measured radiance according to (1) from a given level will increase with altitude until the peak on the weighting function is reached and then decreases above. The height at which the weighting function peaks for a particular frequency is dependent on the location of the frequency with respect to the center of the 15-μm band. At frequencies close to the centers of absorbing bands a small amount

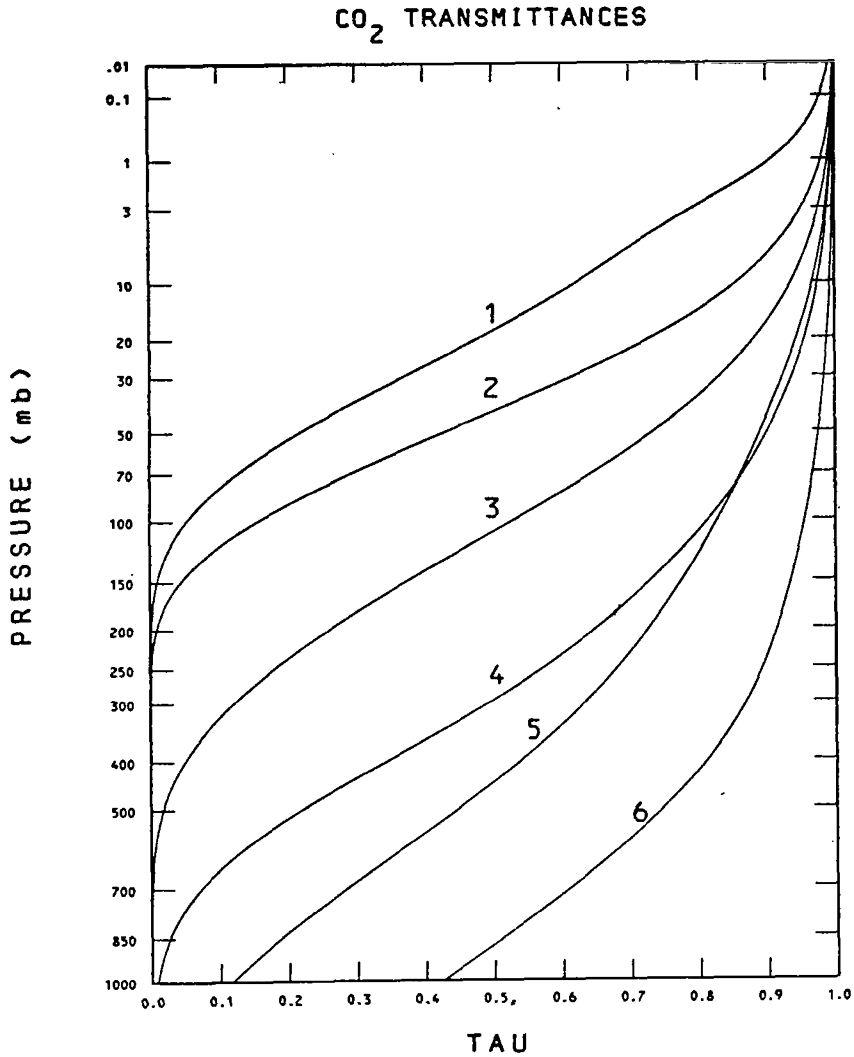

Fig. 1(a). VTPR Transmittance Curves (McMillin *et al*. 1973).

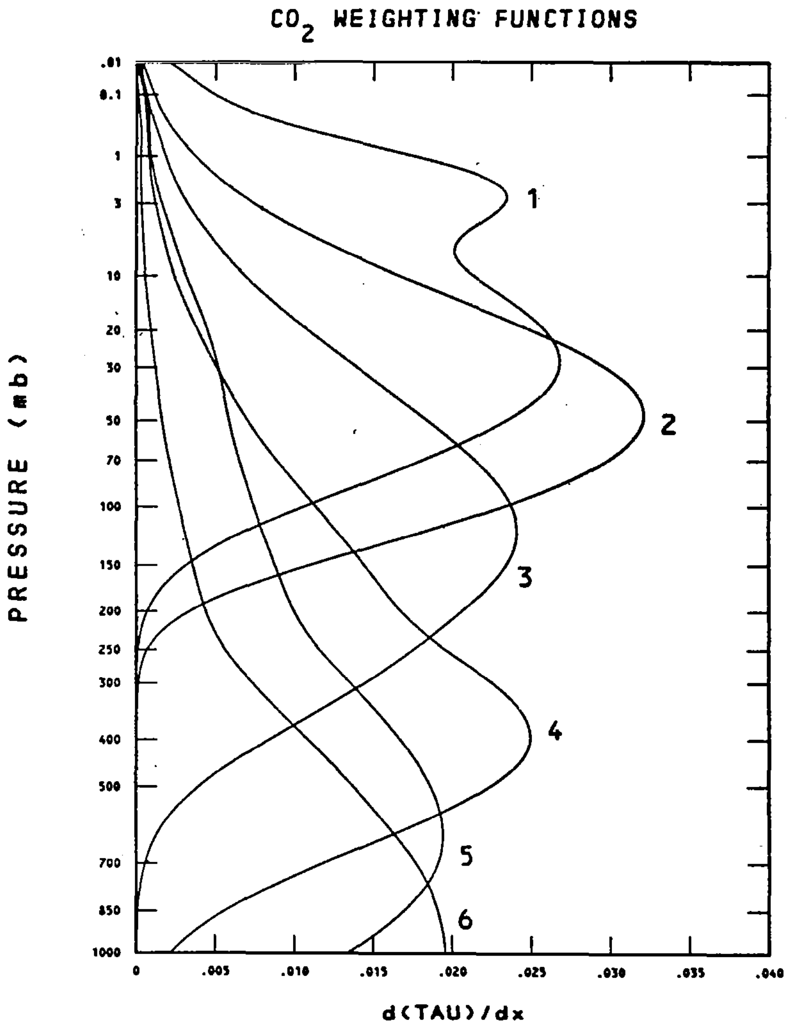

Fig. 1(b). VTPR Weighting Functions (McMillin et al. 1973).

of the absorbing gas will attenuate much of the transmitted radiation and, therefore, most of the outgoing radiation near the centers of absorbing bands arises from the upper levels of the atmosphere (JPS, 1973). At frequencies far from the centers of absorbing bands it takes a large amount of gas to attenuate much of the transmitted radiation; thus, most of the outgoing radiation away from the centers of absorbing bands originated in the lower levels of the atmosphere.

Due to an overlap in the weighting function curves (Fig. 1b) the amount of independent information about temperature that can be obtained from radiance measurements is limited. After a certain number, providing additional radiance measurements for more channels in the 15-μm band will be redundant in the sense that the integral equations will no longer be independent. Seven degrees of freedom is considered a limit. Also, because of the shape of the weighting function curves, small variations in measured data caused by instrument error may lead to large errors in the final solutions of the set of equations and, therefore, to an unrealistic temperature distribution (JPS, 1973).

Measured radiances are dependent on air temperature, instrument characteristics, and atmospheric transmittance. The distribution of CO_2 in the atmosphere is assumed constant and this does not introduce serious errors. However, water-vapor content and the distribution of some gases other than CO_2 is quite variable and atmospheric transmittance can be significantly affected (Fritz et al. 1972).

Early studies by Kaplan (1959) and Yamamoto (1961) revealed the necessity of a special stabilizing technique in the computation of the temperature profile. Wark and Fleming (1966) suggested a practical method of overcoming the instability problem, based on the expansion of the deviation of temperature from standard or mean values in terms of orthogonal functions. A regression method based on the statistical relationship of the distribution of temperature and radiance measurements was successfully derived for operational use by Smith et al. (1970).

Iterative methods have also been developed. Iterative methods work well when there is a reasonable guessed profile (Allison et al. 1975). Significant changes in the retrieved profile compared with the guessed profile identify a poor guess. The "minimum information" iterative method (Smith et al. 1972) is currently used to retrieve temperature profiles from the Infrared Temperature Profile Radiometer (ITPR) of each Nimbus series satellite, and until March 13, 1975 (Werbowetzki, 1975) was used to retrieve temperature profiles from the Vertical Temperature Profile Radiometer (VTPR) of each NOAA series satellite.

An iterative method of retrieving temperature profiles was formulated by Chahine (1968, 1970). Upon using the mean value theorem and the fact that the Planck function has a stronger dependence on temperature than the weighting function, the relaxation formula

$$B[\nu_i, T^{(n+1)}(P)] = \frac{\tilde{I}(\nu_i)}{I^{(n)}(\nu_i)} B[\nu_i, T^{(n)}(P)] \tag{3}$$

is derived from the RTE. In the above formulation, $\tilde{I}(\nu_i)$ is measured radiance and $T^{(n)}$ is the temperature obtained on the nth iteration. A temperature profile is retrieved through use of (3) as follows. First, an initial guessed profile of temperatures corresponding to the approximate peaks of weighting functions is devised. Then, employing the guessed profile, numerical integration of the RTE is accomplished and a radiance value is calculated for each of the sounding frequencies. If the residuals

$$R^{(n)}(\nu) = \frac{|\tilde{I}(\nu) - I(\nu)|}{\tilde{I}(\nu)} \tag{4}$$

approach zero for the individual frequencies then the guessed temperature profile is a solution. When convergence is not obtained, a new guess for the temperature values corresponding to each of the i sounding frequencies (one temperature per frequency), $T^{(n+1)}(P_i)$, is required. A combination of the relaxation equation above with the mathematical expression for Planck's Law for the given frequencies leads to

$$T_i^{(n+1)}(P_i) = c_2\nu_i/\ln\left\{1-[1-\exp(c_2\nu_i/T_i^{(n)}(P_i))]\ (I_i^{(n)}/\tilde{I}_i)\right\}. \qquad (5)$$

Numerical integration is again accomplished with subsequent iteration until convergence is obtained. Chahine's method is non-linear and should converge for a wide spectrum of guessed profiles. However, as pointed out by Barcilon (1975), Chahine's method is only valid for a square matrix of frequencies and levels. Consequently, only a limited number of solution points (for temperature) may be retrieved through use of this method.

Smith (1970) subtracts the iterative form of the RTE

$$I^{(n)}(\nu_i) = B[\nu_i,T^{(n)}(P_o)]\ \tau(\nu_i,P_o) + \int_{P_o}^{o} B[\nu_i,T^{(n)}(P)]\frac{\partial \tau(\nu_i,P)}{\partial P}\,dP \qquad (6)$$

from (1) and through use of the assumption that $B[\nu_i,T^{(n+1)}(P)] - B[\nu_i,T^{(n)}(P)]$ is independent of pressure over the sensed atmospheric layer obtains the iterative equation

$$B[\nu_i,T^{(n+1)}(P)] = B[\nu_i,T^{(n)}(P)] + [\tilde{I}(\nu_i) - I^{(n)}(\nu_i)]\ . \qquad (7)$$

Here, the radiance values are computed by numerical integration from guessed temperature values that are not restricted to the number of the sounding frequencies employed. When convergence of measured and calculated radiances is not obtained the equation

$$T^{(n+1)}(\nu_i,P) = c_2\nu_i/\ln\frac{c_1\nu^3 + B[\nu_i,T^{(n+1)}(P)]}{B[\nu_i,T^{(n)}(P)]} \qquad (8)$$

is then used to calculate independent estimates of the entire temperature profile for each frequency. To obtain the best estimate of temperature at each level, $T^{(n+1)}(P)$, from the independent temperature estimates for each frequency, the weighted average

$$T^{(n+1)}(P) = \sum_{i=1}^{m} T^{(n+1)}(\nu_i,P)W(\nu_i,P) / \sum_{i=1}^{m} W(\nu_i,P) \tag{9}$$

where $\quad W(\nu_i,P) = d\tau(\nu_i,P) \quad \text{if } P \neq P_o$

and $\quad W(\nu_i,P_o) = \tau(\nu_i,P_o)$

(i.e. the W values for each frequency are the weighting functions used to compute radiance from the RTE) is computed for the m frequencies.

Duncan (1974a) observes that substitution of (3) into (6) is equivalent to multiplying the iterative form of the RTE by $\tilde{I}(\nu_i)/I^{(n)}(\nu_i)$ and hence the computed Planck function satisfies the RTE exactly.

He then uses Chahine's relaxation formula to implement Smith's concept of obtaining an independent temperature profile estimate from each radiance measurement. Upon scaling pressure values by $x = P^{2/7}$ [following Smith et al. (1972)] for pressure levels from 1000 mb to 0.01 mb (for accuracy in applying the trapezoidal rule to the RTE) and substituting (3) into (8), independent estimates of temperature are given by

$$T^{(n+1)}(\nu_i,x) = c_2\nu_i/\ln \frac{c_1\nu_i^{\,3} I^{(n)}(\nu_i)/\tilde{I}(\nu_i) + B[\nu_i,T^{(n)}(x)]}{B[\nu_i,T^{(n)}(x)]} \tag{10}$$

for each frequency at each of 100 pressure levels. A weighted average temperature similar to that obtained from (9) may then be computed.

A comparison of various aspects of the minimum information, Smith, and Duncan methods, is given by Alexander (1974.)

Chow (1975) demonstrates that use of the weights of (9), which are the weights of the integral form of the RTE, makes it impossible to determine any of the fine structure of the atmosphere that is not present in the initial guessed profile. Furthermore, the retrieved profile must retain a shape similar to the guessed profile unless the weights are raised to some power, a. He concludes that increasing the value of a not only increases vertical resolution, but also increases the rate of convergence. However, these results are achieved at the expense of a significant increase in the effects of radiance measurement errors on the retrieved profile (i.e. computational instability). Chow, therefore, concludes that a small value of a should be used in determining profiles for Earth's atmosphere since climatological and forecast profiles are available for use as guessed profiles.

b. Related cloud models

The presence of clouds causes serious complication and results in errors in retrieved temperature profiles. In order to demonstrate this fact, simulated measured radiance data (radiances calculated through vertical integration of the RTE from a known temperature profile) were calculated for various cloud amounts and tops. Retrievals were then attempted from this data using Duncan's method. No attempt was made to modify the procedures used for a clear atmosphere through use of a cloud model. Examples of results will be shown later. Attempts to account for the effects of clouds have results in models proposed by Smith et al. (1970), Rodgers (1970), Chahine (1970), and Jastrow and Halem (1973), among others. The Rodgers' model is based on the correlation between temperatures above and below clouds. The others are based on the equation

$$I_{MEAS} = NI_{CD} + (1 - N)I_{CLR} \tag{11}$$

where I_{MEAS} is the measured radiance, I_{CD} and I_{CLR} are the average radiances arising from the cloudy and clear portions of the FOV, and N is the amount of cloud cover. Through use of radiance measurements in a cloud-dependent channel, two or more channels and/or FOVs, (11) may be transformed to a set of simultaneous equations and solved for N. The known N is then used in (11) to obtain I_{CLR} which is then used as the measured radiance in the temperature retrieval. With improved resolution of radiance elements a multiple FOV technique of eliminating cloud cover has proven successful in improving the accuracy of retrieved profiles for use in numerical weather prediction. In general, however, satellite-derived temperature profiles have not provided a significant input to mesometeorological research and the accuracy of profiles derived from any model yet formulated tends to decrease with increasing cloud cover.

Below are outlined some of the important models that have been developed to filter cloud-contamination effects from the measured radiance data.

(1) Smith (1968) Model. It is assumed that average radiance arising from two resolution elements (radiance spot measurements) is the same; thus implying that cloud heights are the same if the clouds are black-bodies. The FOV of the sensing system must be as small as practicable to insure no radical difference in cloud heights between elements. It is also assumed that angular resolution is sufficiently high that each of the resolution elements encloses an area much smaller than the area for which the average temperature is desired.

Measured radiance for frequency ν_i is given by (11). For two different elements, subscripts 1 and 2, (11) may be rewritten

$$I_{MEAS_1}(\nu_i) = N_1 I_{CD_1}(\nu_i) + (1 - N_1) I_{CLR_1}(\nu_i) \qquad (12)$$

and

$$I_{MEAS_2}(\nu_i) = N_2 I_{CD_2} + (1 - N_2) I_{CLR_2}(\nu_i) \ . \qquad (13)$$

If $N_1 \neq N_2$, these equations can be solved for average clear column radiance. If $I_{MEAS_1} \neq I_{MEAS_2}$ for the window channel (in this channel transmittance is nearly 1.0 for atmospheric gases, but not for cloud), then cloud cover for the two elements is not the same. For small and adjacent elements it is assumed that

$$I_{CD_2}(\nu_i) = I_{CD_1}(\nu_i) \qquad (14)$$

and

$$I_{CLR}(\nu_i) = I_{CLR_1}(\nu_i) = I_{CLR_2}(\nu_i) \ . \qquad (15)$$

With the above assumptions in mind, (12) and (13) are solved for $I_{CLR}(\nu_i)$ to give

$$I_{CLR}(\nu_i) = [I_{MEAS_1}(\nu_i) - N^* I_{MEAS_2}(\nu_i)]/(1 - N^*) \tag{16}$$

where

$$N^* = N_1/N_2 \ . \tag{17}$$

When N_1 is not equal to N_2, and I_{MEAS_1} is not equal to I_{MEAS_2} (i.e. only differences in fractional cloud cover cause variations in measured radiance), N^* can be obtained from two simultaneous measurements of radiance in the window (ω) region through use of (12) and (13). Clear-column radiance may then be calculated through use of (16). If instead it was desired to calculate N^* from clear column radiance obtained from a surface temperature observation or measured directly by a high angular resolution window radiometer, the following equation was used:

$$N^* = [I_{MEAS_2}(\omega) - I_{CLR}(\omega)]/[I_{MEAS_1}(\omega) - I_{CLR}(\omega)] \ . \tag{18}$$

In any case, if the field of view of the sensing element is small, average clear column radiance may be calculated over a large geographic area from the equation

$$\bar{I}_{CLR}(\nu_i) = \sum_{j=1}^{\ell} W_j I_{CLR,j} \Big/ \sum_{j=1}^{\ell} W_j \tag{19}$$

where W_j are the weights $(1-N_j^*)$. These weights are used because the observations tend to be inflated by $\frac{1}{(1-N^*)}$ [Ref. (16)]. For the 342 different combinations of adjacent elements in a 10 x 10 matrix of spatially independent observations originally used with this model (i.e. ℓ=342), the effects of random observational errors and differences in cloud heights were assumed to be reduced to insignificance.

(2) Smith et al. (1970) Model. A first guess of the temperature profile is made in order to compute corrections to the observed radi-

ances. Then using radiance measurements in two spectral intervals sensitive to clouds, a system of two equations in two unknowns is formulated and solved for the equivalent clear column radiance. The equivalent clear column radiance is then used to make a next guess temperature profile. The iteration is continued until convergence is obtained. In this method the temperatures above clouds may be improved, but temperatures below are highly dependent on the first guess (Fritz et al. 1972).

This is a two level model. It is based on the "...common atmospheric situation..." where a semitransparent layer of cirrus exists over opaque middle clouds. It can be shown that the following equation describes the effect of cloud cover for an atmosphere containing no more than two layers of cloud:

$$I_{CLR}(\nu) = I_{MEAS}(\nu) + A_u X[\nu, P_u, P_L, T(P)] + A^* Y[\nu, P_L, T(P)] \tag{20}$$

where $I_{CLR}(\nu)$ is the radiance that would be measured in channel (ν) under clear conditions ("the equivalent clear column radiance"), $I_{MEAS}(\nu)$ is the measured radiance in channel (ν), and A_u, called the fractional radiative cloud amount (effective cloud cover) for the upper cloud layer, is the product of the fractional cloud amount and the fractional cloud transmittance for the upper layer. Also

$$A^* = A_L(1-A_u) \tag{21}$$

where A_L is the fractional radiative cloud amount for the lower cloud layer. Further, the parameters X and Y are given by

$$X = B[\nu, T(P_s)]\,\tau(\nu, P_s) - B[\nu, T(P_u)]\,\tau(\nu, P_u) - \int_{P_u}^{P_L} B[\nu, T(P)]\,d\tau(\nu, P) \tag{22a}$$

and

$$Y = B[\nu,T(P_s)]\tau(\nu,P_s) - B[\nu,T(P_L)]\tau(\nu,P_L) - \int_{P_L}^{P_s} B[\nu,T(P)]d\tau(\nu,P) \ , \tag{22b}$$

respectively. The essence of (20) is that a correction

$$C(\nu) = A_u X + A^* Y \tag{23}$$

must be computed and added to the measured radiance to get the equivalent clear column radiance. In computing $C(\nu)$, clouds are allowed to exist at any two "standard" pressure levels below 150 mb. An estimate of equivalent clear column radiance from the radiative transfer equation is first computed from a guessed temperature profile. This was done for each of the channels most sensitive to clouds for Nimbus 3. An estimate of $C(\nu)$ is therefore

$$\hat{C}(\nu) = \hat{I}_{CLR}(\nu) - I_{MEAS}(\nu) \tag{24}$$

for ν=714, 750, and 899 cm^{-1} (window), and where $\hat{I}_{CLR}(\nu)$ is the estimated clear column radiance calculated from a guessed temperature profile. Next, the X and Y terms of (22) are specified from the guessed profile for all standard pressure-level combinations. Substituting $\hat{C}(\nu)$ of (24) for $C(\nu)$ in (23), A_u and A^* are calculated for all possible standard pressure-level combinations for 714 cm^{-1} and 899 cm^{-1} channels by solving the simultaneous equations generated by the substitutions. Using the various pressure-level combinations, different values of A_u and A^* (and thereby A_L) are used to calculate $C(\nu)$ from (23) for the 750 cm^{-1} channel. The value of $\hat{C}(\nu)$ is then calculated from (24) using 750 cm^{-1}. The most probable cloud cover is specified as that for which

$$|C(\nu) - \hat{C}(\nu)| = \text{Min} \ , \tag{25}$$

where ν is 750 cm^{-1}. As new temperature profiles are calculated, the cloud cover computations are repeated until the cloud correction ceases to change from one iteration to the next. It should be noted that in this model the surface temperature is specified in the guessed profiles to prevent them from becoming unrealistically cold (corrections are always from cold to warm). Also, this method is generally useful only in determining temperature profiles down to cloud-top level, and profiles below clouds were predominantly calculated from statistical relationships between the temperatures above the cloud layer and those below. A variation of the above method has been recently formulated by Cooper (1975)[1], but as yet satisfactory results have not been obtained.

(3) Rodgers (1970). In this method Rodgers uses the high correlation with temperatures above cloud level to obtain temperatures below. He also suggests that the accuracy of this method can be improved by using other data sources such as surface temperature, cloud picture data, and forecast profiles. The basic approach is to obtain a maximum probability estimator of the atmospheric state (Fritz et al. 1972).

(4) Smith et al. (1974) Multiple FOV Approach. This is the method used by NOAA to filter ITPR (Nimbus 5) data. Two geographically independent observations are required. But the observations must be close as it is assumed that temperature profiles and, therefore, equivalent clear column radiances are the same for both observations. Error is introduced if measured radiance variations are caused by anything but variation in cloud amounts. A good estimate of surface temperature is also required in this method as is a high resolution measuring device (Fritz et al. 1972). When variation of radiance from one FOV to another is due to variation in cloud amount only and surface temperature is known, then clear column radiances may be computed from two sets of independent data.

It is first necessary to determine if cloud properties (height, opacity, etc.) in the FOVs chosen are similar. It should be noted that the Nimbus 5 ITPR has window channels at both 3.7 μm and 11 μm.

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[1] Cooper, M., 1975: Personal communication.

The same brightness temperature would be observed for both channels for a uniform and opaque scene (e.g. Earth's surface), but brightness temperatures would differ significantly for the two channels under broken cloud conditions because of the different dependence of the two channels on temperature. Where clouds are present their properties are considered the same for the two FOVs if

$$I_{CLR}^{min}(\omega_s) - \frac{2\sigma\varepsilon}{1-N^*} \le I_{CLR,i,j}(\omega_s) \le I_{CLR}^{max}(\omega_s) + \frac{2\sigma\varepsilon}{1-N^*} , \quad (26)$$

where I_{CLR}^{min} and I_{CLR}^{max} are the minimum and maximum possible clear column radiance values [Ref. Smith et al. (1974) for the necessary procedures to determine I_{CLR}^{min} and I_{CLR}^{max}], ω_s refers to the short wave (3.7 μm) window channel and the term added to (subtracted from) I_{CLR}^{max} (I_{CLR}^{min}) is the expected error of $I_{CLR,i,j}(\omega_s)$, the clear column radiance for the two FOVs. Also,

$$N^*_{i,j} = \frac{N_i}{N_j} = [I_{MEAS,i}(\omega_L) - I_{CLR,i,j}(\omega_L)] \,/\, [I_{MEAS,j}(\omega_L) - I_{CLR,i,j}(\omega_L)] \quad (27)$$

where ω_L is the long wave window channel. The clear column radiance is computed from the equation

$$I_{CLR,i,j}(\nu) = [I_{MEAS,i}(\nu) - N^*_{i,j} I_{MEAS,j}(\nu)]/(1 - N^*_{i,j}) \quad (28)$$

which naturally follows from (27) once $N^*_{i,j}$ is defined. In this method specific criteria are used to determine if FOVs are overcast, affected by broken clouds, or unaffected by clouds. No clear column computations are used for the overcast condition. Where cloud corrections are made as above (and in clear areas) an average value is obtained for the sub-grid area involved.

(5) Chahine (1970) One-Layer Cloud Model. Assuming a single layer of clouds behaving as a black-body in equilibrium with the local ambient temperature, then cloud effects can be filtered from

the measured radiance if P_c (pressure at cloud top) and N (fraction of the FOV affected by clouds) can be specified. It can be shown that

$$I_{MEAS}(\nu,\overline{P}) = I_{CLR}(\nu,\overline{P}) - NG(\nu,P_c) \tag{29}$$

where

$$G = I_{CLR} - I_{CD} \quad . \tag{30}$$

The pressure at cloud-top height (P_c) may be obtained from one set of radiance measurements if the cloud-top temperature is known or from two sets of measurements made over adjacent areas with different cloud cover. Based on experimental evidence using simulated data, two different sets of radiance data may be used to determine P_c as profiles obtained from the two sets of data should coincide from P_c to the top of the atmosphere (this concept is also basic to the Jastrow-Halem procedure that follows). However, the equation

$$N = (I_{CLR} - I_{MEAS})/G \quad , \tag{31}$$

a functional transform of the unknown temperature profile, should not then be used for some cloud-dependent frequency to obtain N from (31). If this result is used in the RTE for a partly cloudy atmosphere [Ref. (39)] by substituting N for A, then the corresponding residuals

$$R(\nu) = |I_{MEAS}(\nu) - I(\nu)| \;/\; I_{MEAS}(\nu) \tag{32}$$

are small for all cloud-dependent frequencies for any temperature profile below clouds. Therefore, an extra parameter such as surface temperature is necessary to obtain N. Chahine concludes that any one of the combinations (P_c,N), (P_c,T_o), (T_c,N), or (T_c,T_o) will suffice to allow determination of the temperature profile. Then assuming the combination (T_c,T_o) is known, (31) is used for a cloud-dependent frequency to calculate N and thus retrieve a new temperature profile from the RTE for a partly cloudy atmosphere. Using the retrieved profile a new value of N is obtained from (31) and the process is repeated until convergence is obtained. A more detailed discussion of the RTE for a partly cloudy atmosphere will be presented in Section 3.

(6) Jastrow and Halem (1973). This procedure is a modification of Chahine's cloud model. Cloud height is first computed by determining the initial near approach value (Ref. Chahine (1970) model) of the profiles obtained from sets of radiance observations obtained over partly cloudy areas but calculated assuming no clouds. Next, the radiance emitted over the cloudy portion of the ares is calculated (computed from top of atmosphere to cloud-top height). Then this computed radiance, $I_{CD}(\nu)$, is used in the equation

$$I_{MEAS}(\nu) = (1 - N)\ I_{CLR}(\nu) + NI_{CD}(\nu) \tag{33}$$

to calculate the equivalent clear column radiance, $I_{CLR}(\nu)$, for several values of N between zero and one. By interpolation, the value of N is selected that produces the clear column radiance used to calculate the temperature profile whose surface temperature is closest to an observed surface temperature value.

(7) Chahine (1974). Assuming two FOVs with different amounts of cloud at the same height, clear column radiance values are computed from a guessed temperature profile for all frequencies used. Next, the clear column value for a "cloud dependent" window channel, ω, is used in the equation

$$\eta = [I(\omega) - I_{MEAS_1}(\omega)] \ / \ [I_{MEAS_1}(\omega) - I_{MEAS_2}(\omega)] \ . \tag{34}$$

In this equation the subscripts denote the two FOVs and η is related to the fractional cloud cover by

$$\eta = N_1 \ / \ (N_2 - N_1) \quad . \tag{35}$$

Clear column radiance is then constructed from the expression

$$I_{CLR}(\nu) = I_{MEAS_1}(\nu) + \eta[I_{MEAS_1}(\nu) - I_{MEAS_2}(\nu)] > 0 \quad . \tag{36}$$

A temperature profile is retrieved through use of this clear column radiance. All steps are then repeated to determine new values of computed clear column radiance, $I(\omega)$, constructed clear column radiance (i.e. equivalent clear column radiance), and the temperature profile. The iteration is continued until convergence of the clear column radiance values is attained. Chahine points out that as $I_{CLR}(\nu)$ is dependent on the temperature profile the problems of determining the cloud coefficient and the temperature profile are "...inseparable and should be carried out simultaneously." Other variations of the method presented above are given in the same reference, including a single FOV, dual-frequency approach. The methods have been tested with simulated data and are based, as the 1970 model, on Chahine's relaxation scheme using the frequency set ν_j to recover temperatures at solution points $T(P_j)$, and a cloud frequency (or frequencies for single FOV) to determine N.

(8) Chahine (1975). This model is unique in that temperature profiles are retrieved without calculating the clear column radiance. A single layer of black-body clouds is assumed, and an analytical transformation is derived to relate the temperature profile that would be derived from clear column radiance values directly to the apparent temperature profile. The apparent temperature profile is defined as the profile obtained from the measured radiance data without accounting for cloud effects. Illustrations are provided for simulated observations in the 15-μm band. For the single FOV, profiles showed good agreement with the two FOV solutions obtained and the exact profile when the fractional cloud cover is less than five tenths, but not as good for increased amounts of cloud cover.

3. A NEW METHOD FOR RETRIEVING TEMPERATURE PROFILES FROM THE RADIATIVE TRANSFER EQUATION FOR A PARTLY CLOUDY ATMOSPHERE

a. General

In previous sections, methods for retrieving temperature profiles from the RTE for a clear atmosphere have been discussed. In the method of Chahine (1968, 1970) a given frequency and a pressure level are paired to retrieve temperature solution points at the specified pressure levels. Smith (1970) presented an iterative equation in which there "...is no limiting assumption made about the analytical form of the profile imposed by the number of radiance observations available." Duncan (1974a) demonstrated that Chahine's relaxation formula could also be used with no limiting assumption imposed by the number of sounding frequencies utilized. He then used Smith's method of calculating temperature values at each atmospheric level from a weighted average of the temperature values calculated for each frequency.

In the discussion of cloud models used in profile retrievals it was mentioned that Chahine (1970) used the calculated cloud parameters with the RTE for a partly cloudy atmosphere to retrieve temperature profiles. This method was based, as Chahine's subsequent work, on the pairing of frequency with pressure level mentioned previously in order to achieve convergence over the widest possible spectrum of guessed temperature profiles. Now, a method will be presented which extends Duncan's procedures to an RTE for a partly cloudy atmosphere, and a new cloud model will be devised to accommodate observed cloud parameter(s) in this method.

b. The method

A solution to the problem of obtaining temperature profiles directly from cloud-attenuated radiance measurements would have to account for the heights, amounts, and opacities of the clouds that appear in the FOV. For a single layer of clouds assuming zero cloud reflectivity, Fritz *et al.* (1972) presented the equation

$$I_{CD}(\nu) = \varepsilon_c(\nu) I_b(\nu) + [1 - \varepsilon_c(\nu)] I_{CLR}(\nu) \tag{37}$$

where ε_c is cloud emissivity and $I_b(\nu)$ is the radiance associated with black-body cloud conditions. By substitution of (37) into (33), the equation

$$I_{MEAS}(\nu) = A I_b(\nu) + (1 - A) I_{CLR}(\nu) \tag{38}$$

where $A = N\varepsilon$ was obtained (assumes clouds are gray bodies).

We consequently write the RTE for a partly cloudy atmosphere as

$$\begin{aligned} I(\nu) &= A\, B[\nu, T(x_{P_c})] \cdot \tau[\nu, \mu(x_{P_c})] - \int_0^{x_{P_c}} B[\nu, T(x)] \frac{\partial \tau[\nu, \mu(x)]}{\partial x} dx \\ &+ (1 - A)\, B[\nu, T(x_o)] \cdot \tau[\nu, \mu(x_o)] - \int_0^{x_o} B[\nu, T(x)] \frac{\partial \tau[\nu, \mu(x)]}{\partial x} dx \end{aligned} \tag{39}$$

where P_c is the cloud-top pressure. In an analogous manner to the clear case we may then define an expression

$$B[\nu_i, T^{(n+i)}(x)] = \frac{\tilde{I}^*(\nu_i)}{I^*(\nu_i)} B[\nu_i, T^{(n)}(x)] \tag{40}$$

where $\tilde{I}^*(\nu_i)$ is the measured cloud-contaminated radiance, and $I^*(\nu_i)$ is the computed estimate of this unfiltered radiance. As the Planck function values are constant for a given frequency and level even though appearing under the integral sign, (40) will satisfy the RTE, and if the residuals

$$R^{(n)}(\nu_i) = |\tilde{I}^*(\nu_i) - I^*(\nu_i)| \tag{41}$$

are sufficiently small then the guessed temperature profile is a solution to the RTE. If the guessed temperature profile is not a solution, $T^{(n+1)}(\nu_i, P)$ may then be computed theoretically as in the cloudless case from the weighted average

$$T^{(n+1)}(x) = \sum_{i=1}^{N} T^{(n+1)}(\nu_i,x)W(\nu_i,x) \Big/ \sum_{i=1}^{N} W(\nu_i,x) \ , \tag{42}$$

where

$$W(\nu_i,x) = d\hat{\tau}(\nu_i,x) \quad \text{if} \quad x \neq x_o \text{ or } x_{p_c} \tag{43}$$

$$W(\nu_i,x_o) = \hat{\tau}(\nu_i,x_o) \tag{44}$$

and

$$W(\nu_i,x_{p_c}) = A\hat{\tau}(\nu_i,x_{p_c}) + (1 - A)d\hat{\tau}(\nu_i,x_{p_c}) \ . \tag{45}$$

Here the W values for each frequency are also the weighting functions used to compute radiance from the RTE for a partly cloudy atmosphere. However, Duncan (1974b) has demonstrated that for the atmospheric temperature range the Planck function can be approximated with sufficient accuracy by a Taylor's series expansion about a guessed temperature through the first derivative term. Although independent estimates of temperature for each frequency are not obtained, the approximations

$$T^{(n+1)}(x) = T^{(n)}(x) + \overline{\Delta B}[T^{(n+1)}(x)]/(.01T^{(n)}(x) - 1.3) \tag{46}$$

where $\overline{\Delta B}[T^{(n+1)}(x)]$ is the weighted [weights are given in (43) - (45)] average of $\Delta B[\nu_i,T^{(n+1)}(x)]$, and

$$B[\nu_i,T^{(n+1)}(x)] = B[\nu_i,T^{(n+1)}(x)] + \overline{\Delta B}[T^{(n+1)}(x)] \tag{47}$$

save significant machine computational time with no noticeable loss of accuracy. They have, therefore, been used throughout this research.

In using (40) as a basis for calculating subsequent temperature values, the equation becomes less valid below clouds unless it is assumed that the ratio of the measured-to-calculated radiance values is approximately equal to the ratio of calculated clear column radiance to the radiance that would have been measured in a clear situation [Ref. (3)].

The assumption is required because the amount of measured radiance arising from below cloud level decreases as the amount of cloud cover increases. Therefore, as cloud cover increases, calculated temperatures below the cloud layer are increasingly based on radiances arising from cloud-top level. The assumption is also required because in calculating a weighted average [Ref. (42)], significant weight will frequently be given to channels that peak below cloud-top level. If a correct combination of cloud amount and height were used and the guessed and true profiles were equivalent in temperature at every level, then the assumption would be completely valid. As long as errors in the guessed profile do not get too big, errors in the retrieved profile should remain small even though cloud cover increases. If the assumption is generally valid, the degree of cloud contamination should not significantly affect temperature calculations below cloud level. Furthermore, if the ratio of measured to calculated radiance is greater (less) than one it can be seen from (40) that the temperature at each level of the guessed profile must increase (decrease) in order to provide a better estimate of measured radiance. Therefore, as cloud cover increases the importance of choosing an initial guessed profile that is in error in the same direction (with respect to sign) both above and below clouds assumes greater importance. As the shape of the guessed profile should not change significantly with successive iterations (Chow, 1975), a smooth guessed profile beginning with a known surface temperature should generally produce a temperature profile that is more accurate that the guessed profile even below clouds.

c. <u>The cloud model</u>

A temperature profile may therefore be retrieved through use of (39) and (40) if accurate values of effective cloud cover and cloud-top height can be obtained. For multiple observed cloud layers, the equation

$$\tilde{I}^*(\nu_i) = \sum_{j=1}^{k} A_j(I_b(\nu_i)_j) + (1 - A_{Total})I_{CLR}(\nu_i) \tag{48}$$

where k is the number of cloud levels, can be used. But these are black-body clouds (A=N) with the A values as would be observed from the top of the atmosphere looking down. It will be shown later that observed cloud cover is not an effective tool in retrieving temperature profiles. However, an estimate of cloud height alone may be used as a first guess in calculating effective cloud cover for a single layer through use of the procedures described below:

(1) Use the guessed temperature profile and only the window channel to calculate an estimate of the measured radiance for a clear situation from the RTE. Next, subtract the calculated value of clear column radiance in the window channel from the measured value of radiance in the window channel. If the sign of the resultant value is positive, then the radiance calculated assuming no cloud has been found to be less than the measured radiance for a cloudy atmosphere. This result must, of course, be erroneous. The attempt to calculate effective cloud amount must therefore be abandoned or a revised estimate of surface temperature employed in the calculations. However, if the sign of the resultant is negative, we may proceed to the next step.

(2) Calculate radiance in the window channel for an overcast (A=1.0) situation at the estimated level and subtract this calculated value of radiance from the measured radiance in the window channel. If the sign resulting from this subtraction is negative, then the radiance calculated from an overcast atmosphere is greater than the measured radiance. The estimated cloud-top temperature is therefore too warm. If the estimated cloud-top height is known to be accurate, then a revised cloud-top temperature may be used. However, in this research reasonable estimates of the guessed profile are employed while estimated cloud-top height is assumed to be in

error. Therefore, overcast black-body cloud radiance is again calculated and subtracted from the measured radiance at successively higher levels until a positive sign results from the subtraction performed. When a positive sign is obtained, whether it results from calculations using the initially estimated height or from the trial and error method described above, we may proceed to calculate effective cloud cover at the chosen level.

(3) In the present research effective cloud cover was calculated through use of a one dimensional search. The search is performed at the chosen level as follows:

(a) Calculate radiance for the window channel using a value of effective cloud cover that halves the possible choices for a value that will satisfy the RTE (i.e. first use 0.5).

(b) Subtract the value of radiance calculated in (a) from the measured radiance value.

(c) If the sign of the results of the subtraction in (b) is negative, then the value we are seeking must lie between 0.5 and 1.0.

(d) If the sign of the results of the subtraction in (b) is positive, then the value we are seeking lies between 0.0 and 0.5.

(e) Calculate radiance for the window channel using a value of effective cloud cover that halves the possible choices for a value that will satisfy the RTE (i.e. either 0.25 or 0.75). Repeat the procedures discussed above (i.e. halve intervals) until the differences between measured and calculated radiance in the window channel approaches zero.

Smith (1976)[2] has noted the one dimensional search described above is based on the equation

$$\tilde{I}^*(\omega) - A[I_b(\omega)] + (1 - A)I_{CLR}(\omega) = 0 \quad . \tag{49}$$

He therefore suggests that in order to save computer time the equation

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[2]Smith, W. L., 1976: Personal communication.

$$A = \frac{\tilde{I}^*(\omega) - I_{CLR}(\omega)}{I_b(\omega) - I_{CLR}(\omega)} \quad . \tag{50}$$

be used instead of the search.

In any case, computed effective cloud amount is not unique except for a perfect guessed profile (guessed temperature = true value at all levels) when it is calculated at the true cloud level. However, results that will be presented in the next section seem to indicate that if the estimated cloud-top height is not grossly in error, then choosing a cloud amount and height combination that gives the best estimate of measured radiance for the guessed profile will lead to a better retrieval than when one of the cloud parameters is correct but the other is in error. Also, the possibility of using the retrieved profile to calculate an improved value of cloud cover and height and, hence, improve the retrieval will be investigated.

4. PARAMETRIC STUDY

a. Procedures

Prior to using the method described in the previous section with real data it was tested with simulated radiance data (radiances calculated through vertical integration of the RTE from a known temperature profile and known cloud parameters) to determine the effect of errors in observed or calculated parameters on the retrieved temperature profile. The general procedure was to cause an error in one or more of the parameters needed to retrieve the temperature profile while other parameters retained their true values (i.e. the values used to calculate synthetic radiance data). The method outlined in Section 3b is particularly well suited to such an approach as the effects of varying cloud parameters are immediately apparent in the retrieved profile since cloud parameters are not filtered out before commencing the retrieval.

Simulated radiance data were calculated for the channels of the NOAA-2 satellite through use of (39) or (48) and the temperature profiles designated "true" in the figures to follow. The fractional cloud layers and their heights used to calculate the simulated radiances are noted at the top of each figure and also adjacent to the pressure value corresponding to cloud height at the side of each diagram.

In the temperature profile retrieval, the guessed profile used is a version of the 1962 U.S. Standard Atmosphere with 10°C added to the temperature at each level above the surface through 221 mb. The guessed profile is then approximately five degrees cooler than the true profile for most of the troposphere at all levels except the surface. Cloud parameters that are read in are designated "input cloud" at the top of the figure while those that are calculated are designated "calc cld." Profiles are shown up to 250 mb.

As in the Duncan model, numerical integration for the model was accomplished through use of the trapezoidal rule using centered differences for a maximum of 100 pressure levels from 1000 mb to 0.01 mb that are equally spaced in pressure to the two-sevenths power. Where surface pressure falls between two levels the higher level is used as the surface for computational purposes (e.g. surface temperature) except that the centered difference at the bottom of the atmosphere was applied between the surface pressure and the pressure level above the next highest pressure level.

b. Results

In Figs. 2 and 3 the effects of not accounting for clouds in the presence of a poor surface temperature guess are illustrated. As anticipated from the work of Chahine (1970), in each case the apparent temperature profile begins to coincide with the true profiles in the vicinity of the top of the cloud layers. Figures 4 and 5 (same guessed profile and cloud parameters as Figs. 2 and 3, respectively) are illustrations of the improvement made in the retrieved profiles through use of the procedures described in Section 3c to calculate cloud cover when the cloud-top height is known. Surprisingly, improvement was noted even in profiles where very large amounts of cloud cover were present (Fig. 4). This result is probably due to the validity of the assumption discussed in the previous section for the NOAA-2 weighting functions and the guessed profile used. Tests of profiles calculated for several values of fractional cloud cover and height reveal that errors of ±1 level (≅1000 ft in the troposphere) have a relatively insignificant effect on the retrieved profile. This magnitude of error is probably representative of those that would be made in handling actual data for many low cloud situations. The effect of making a larger error in a high cloud situation will be illustrated later in this section.

Profiles were retrieved for several cloud parameter values from guessed profiles exhibiting sharp inversions. Results of a typical retrieval are illustrated in Fig. 6. There is no doubt that the calculated profile takes on the shape of the guessed profile. In the absence of prior knowledge, the necessity of using a smooth guessed profile in connection with this model becomes obvious.

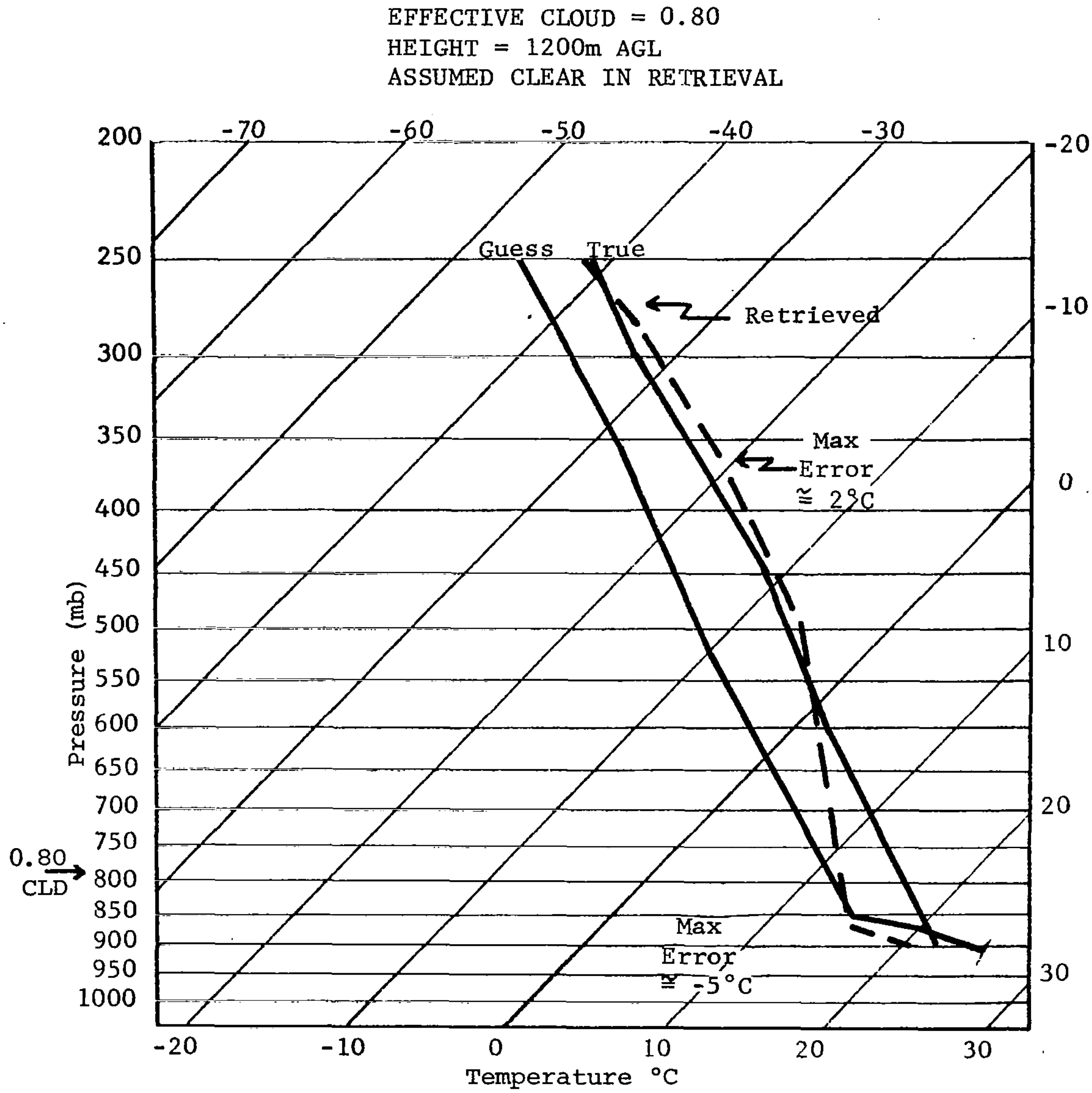

Fig. 2. Temperature sounding retrieved from Duncan's Method for a clear atmosphere using simulated radiance measurements for broken (0.80) low cloud conditions. There is a +5°C error in the guessed surface temperature.

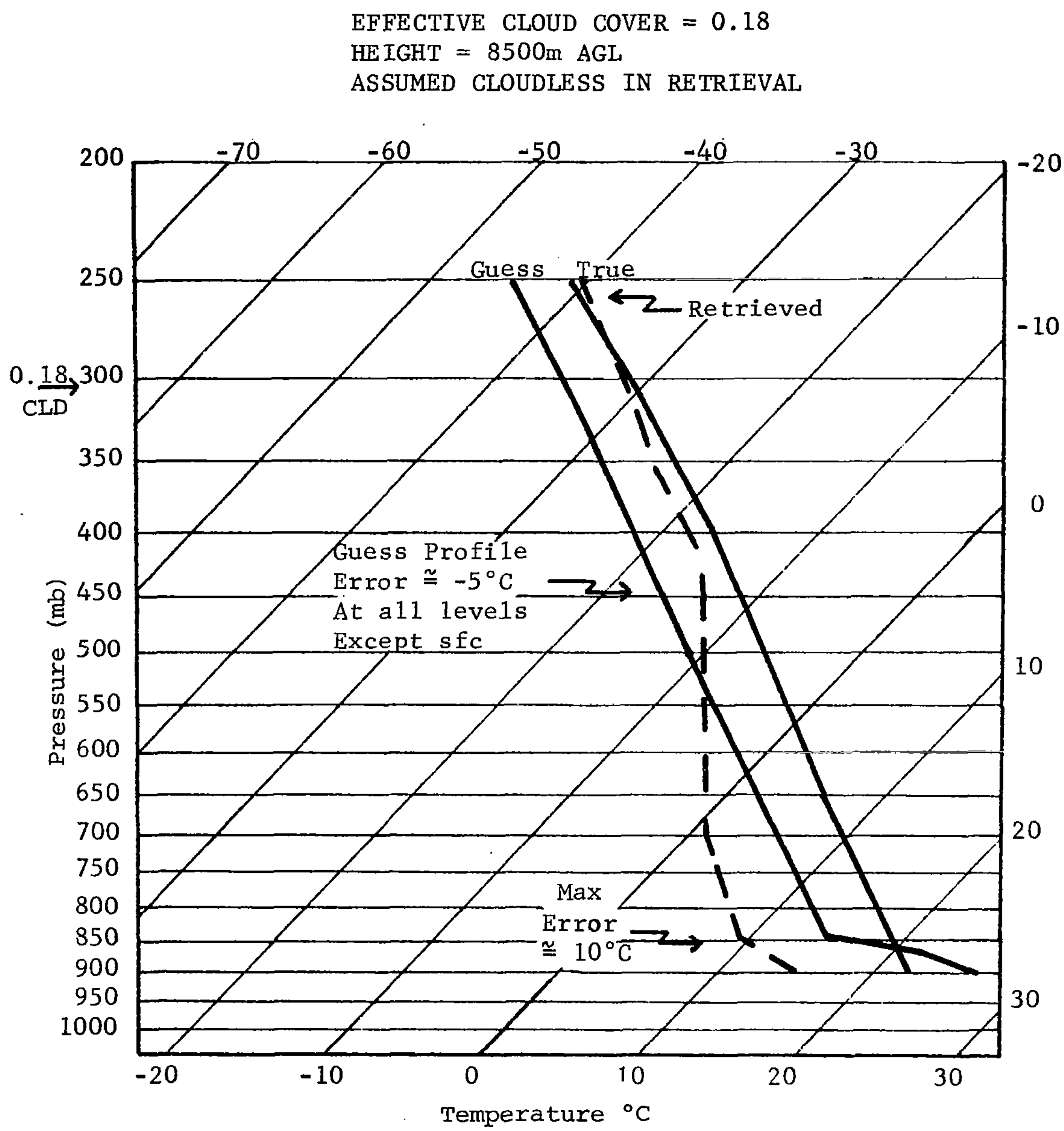

Fig. 3. Temperature sounding retrieved from Duncan's Method for a clear atmosphere using simulated radiance measurements for scattered (0.18) high cloud conditions. There is a +5°C error in the guessed surface temperature.

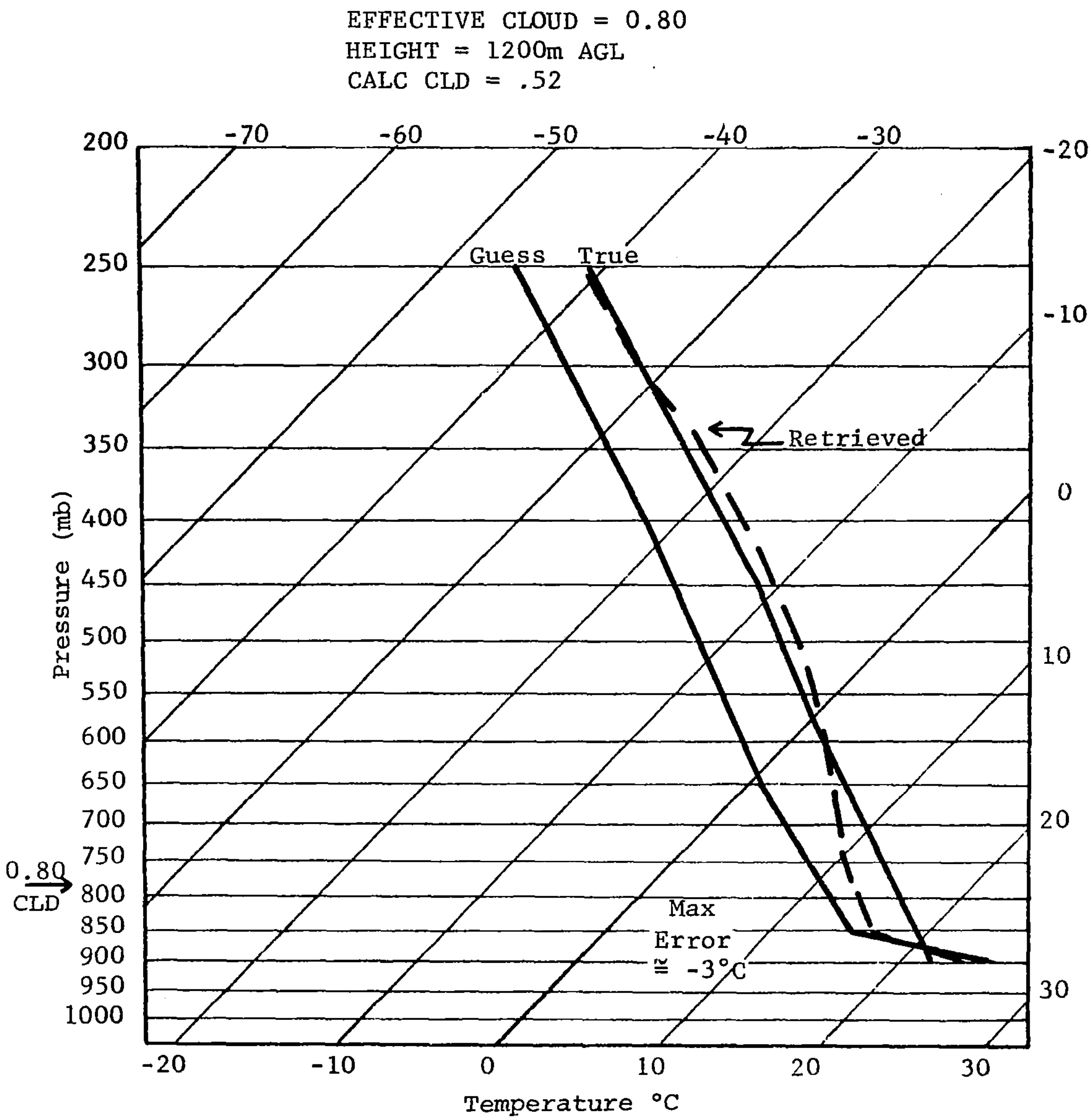

Fig. 4. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere. Simulated radiance measurements were prepared for broken (0.80) low cloud conditions. There is a +5°C error in the guessed surface temperature.

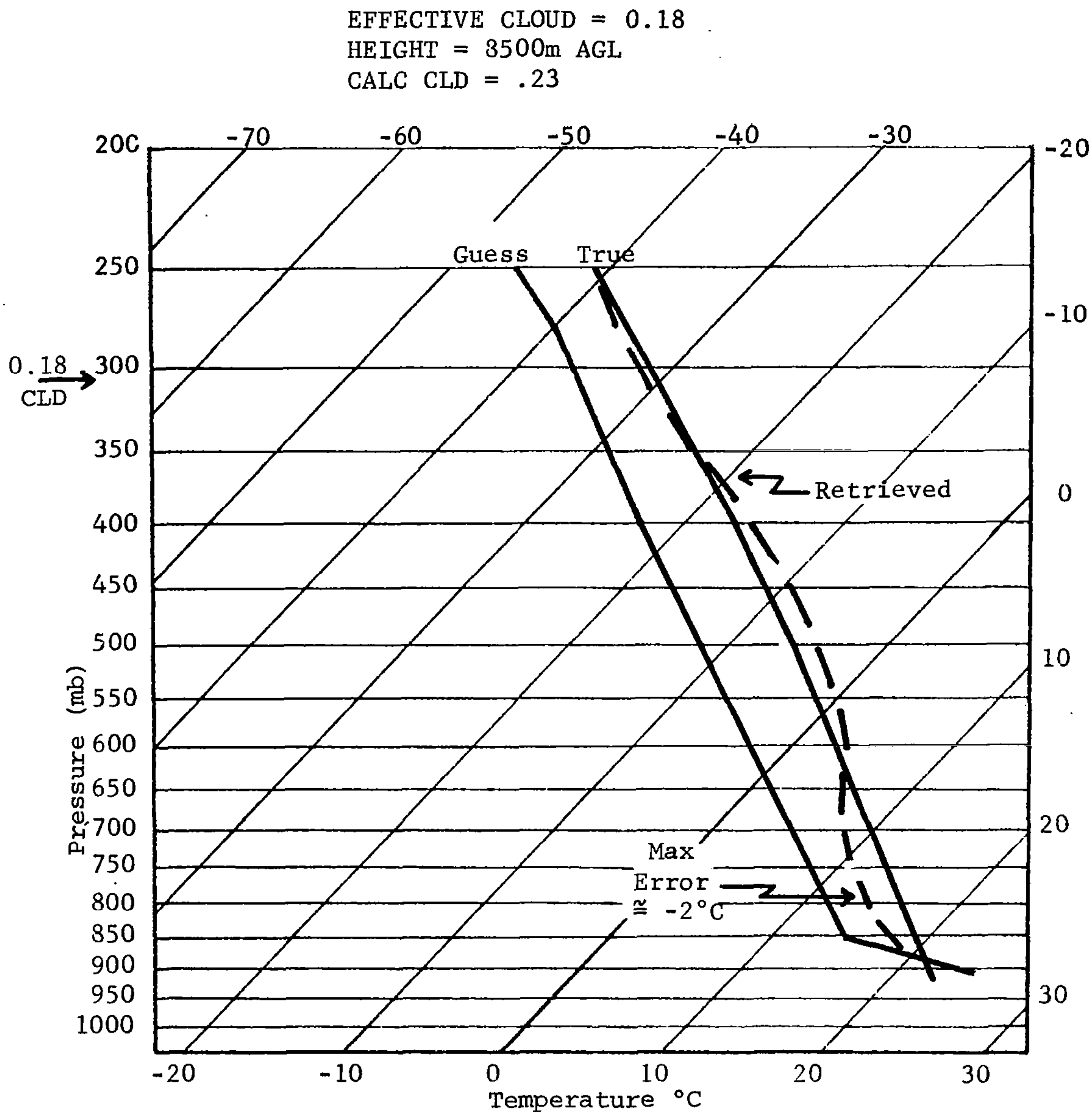

Fig. 5. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere. Simulated radiance measurements were prepared for scattered (0.18) high cloud conditions. There is a +5°C error in the guessed surface temperature.

EFFECTIVE CLOUD = 0.60
HEIGHT = 2200m AGL
CALC CLOUD = 0.69 at 2200m

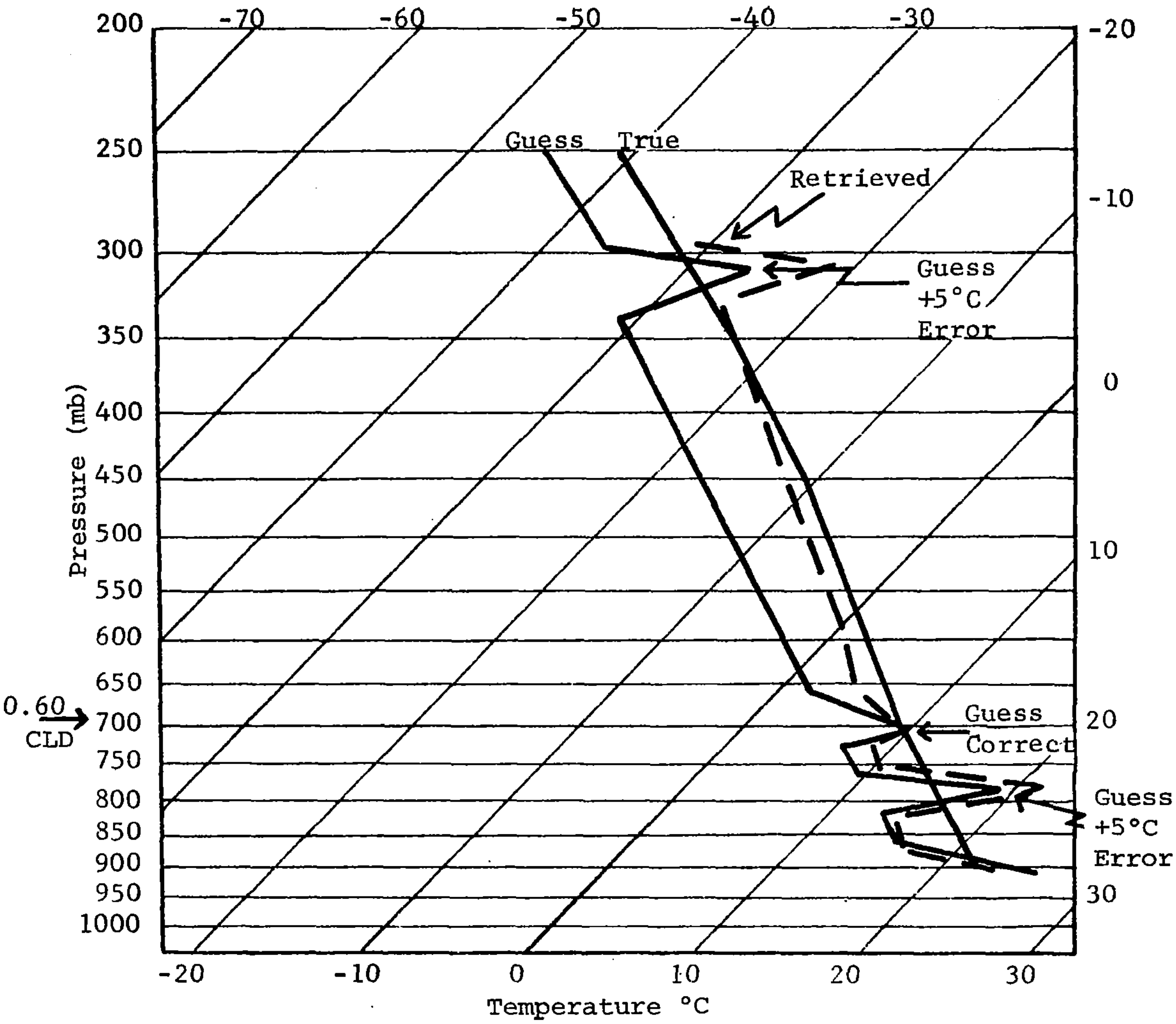

Fig. 6. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere accomplished by employing a guessed profile exhibiting sharp temperature inversions. The simulated radiance measurements were prepared for broken (0.60) middle level cloud conditions using a +5°C error in the guessed surface temperature.

Testing indicates that observed cloud parameters could be used to retrieve profiles even for the two-layer case (Fig. 7) if their values could be specified exactly. However, small errors in these parameters lead to unacceptable retrieval errors (Fig. 8).

An attempt was made to retrieve profiles from simulated data derived from two-layer cloud cases through use of the one-layer cloud model. Here a single cloud layer that returns radiance values that approximate those of the true cloud parameters is sought. Examples of results are shown in Figs. 9 and 10. In these examples the estimated single cloud-layer height was chosen as the highest cloud layer.

The accuracy of retrieved profiles deteriorates when the height of a significantly lower layer is chosen as the estimated height for a single layer. As calculated radiance for the low layer must be larger than the measured radiance, a higher level is sought to calculate the fractional cloud amount [Ref. Paragraph 3c-(2)]. Since this process does not give unique values of fractional cloud amount/height it should be noted that the greatest amount of calculated fractional cloud cover will occur at the lowest possible height. In Fig. 11 an example of the results of choosing a significantly low estimate of average cloud-top height is shown.

An example of a profile retrieved through use of a guess that is significantly too high is given in Fig. 12 where the estimated height is 1900 m higher than the true highest cloud tops. It should be noted that estimating cloud-top heights too high will give radiance values that are lower than comparable measured values. Since calculated clear column radiance values will be higher than the measured radiance, the sign change required by the model is accomplished and it is possible to calculate a radiance that is approximately equal to the true radiance at all levels above the true cloud tops (assuming one-layer cloud cover). For more than one layer an estimated level somewhat higher than the highest average cloud-top layer might be appropriate (Ref. Fig. 10 where calculated cloud amount is greater than the true amount at the highest level).

Finally, numerous attempts were made to improve the accuracy of retrieved profiles by calculating an initial cloud amount from the

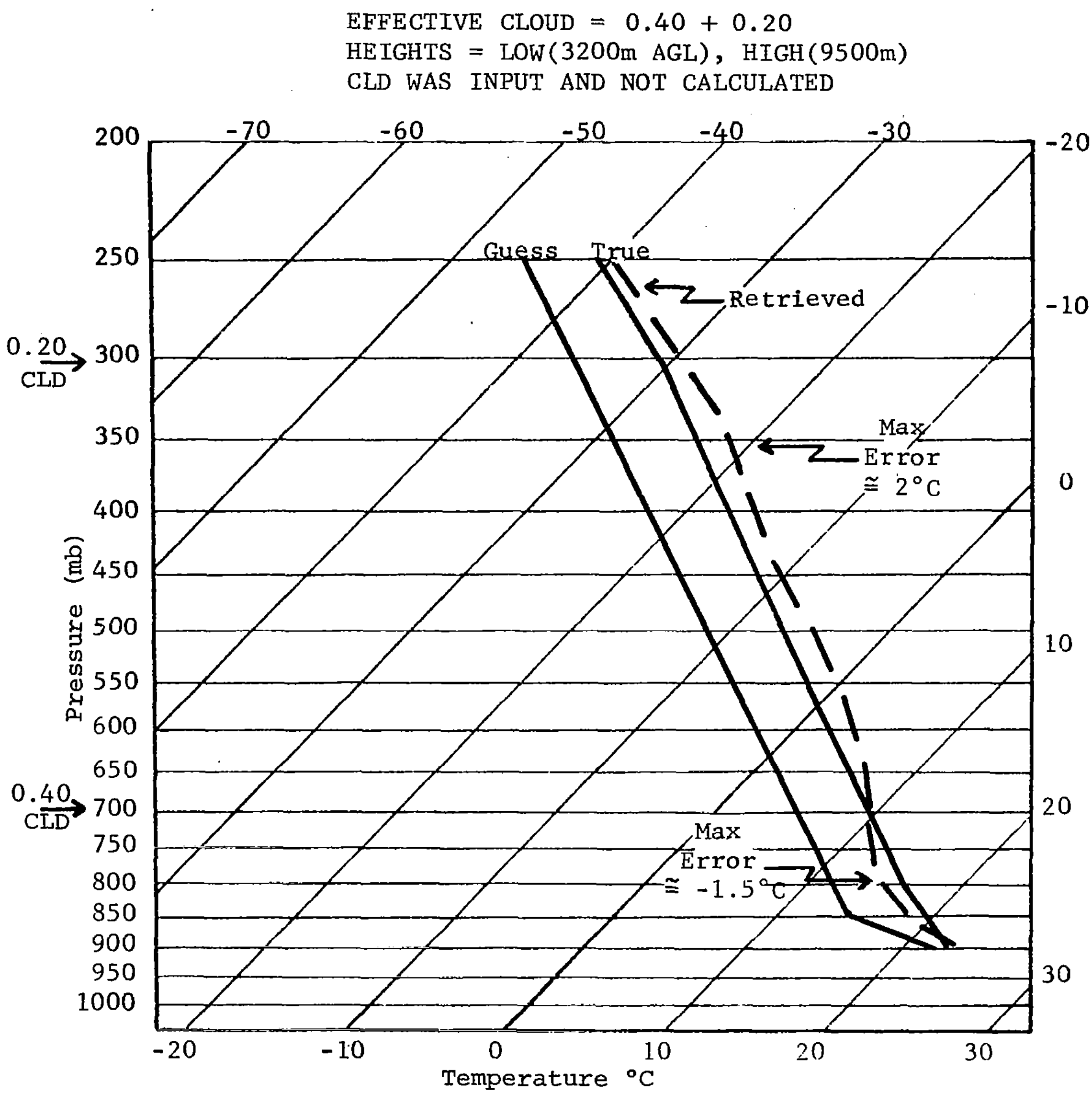

Fig. 7. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere accomplished by employing in the retrieval the same values of the cloud parameters as used to calculate the measured (simulated) radiance values. The simulated radiance measurements were prepared for two layers of clouds with the fractional amount and height values shown above.

EFFECTIVE CLOUD = 0.50 + 0.30
HEIGHTS = LOW(3200m AGL), HIGH(9500m)
INPUT CLOUD = 0.40 at 3200m + 0.20 at 9500m

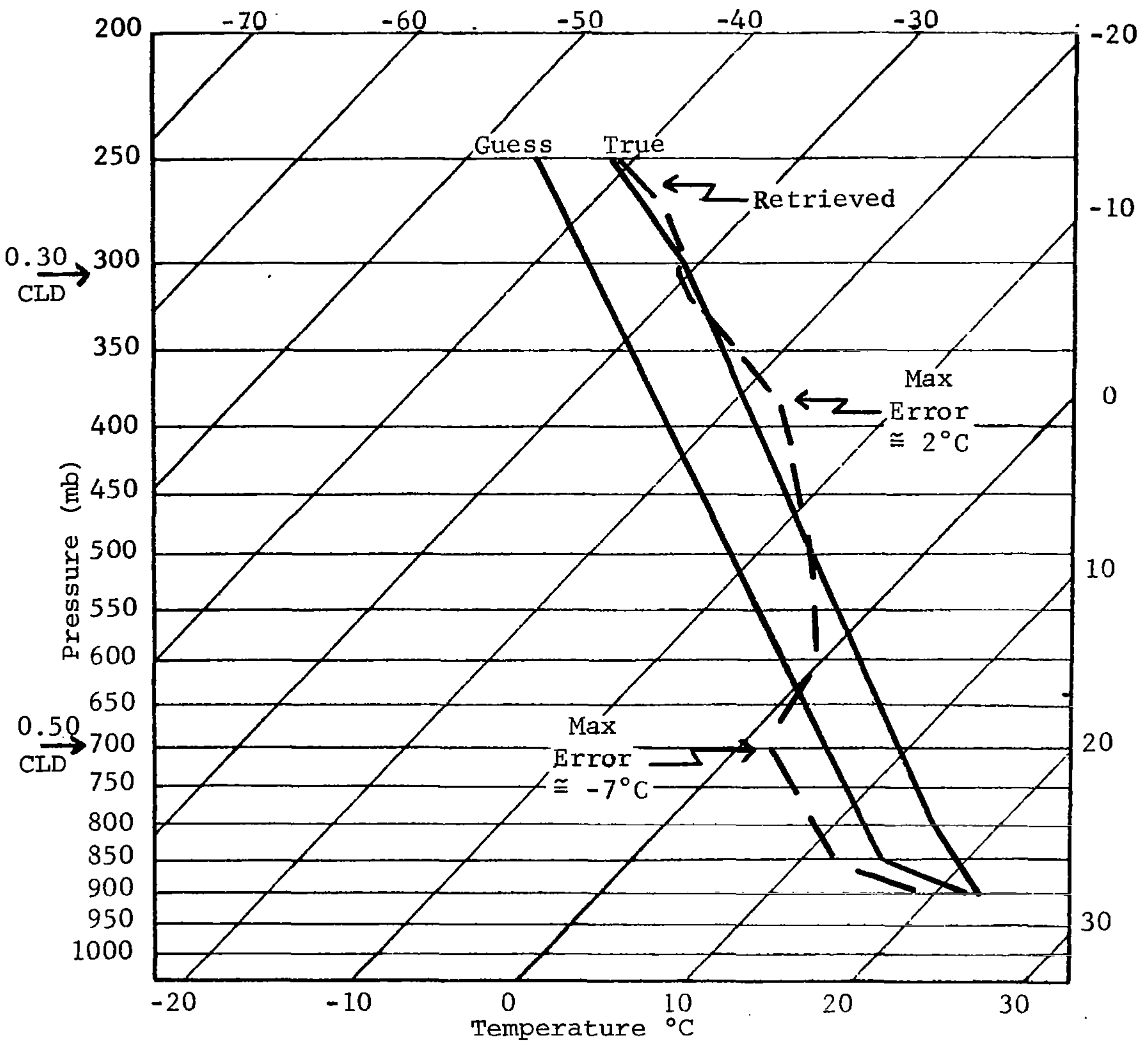

Fig. 8. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere accomplished by employing in the retrieval the same cloud-top heights as used to calculate the measured (simulated) radiance values but fractional cloud amounts that are each 0.1 less than the values used to calculate the simulated radiances. The simulated radiance measurements were prepared for two layers of clouds using the effective cloud amount and height values shown above.

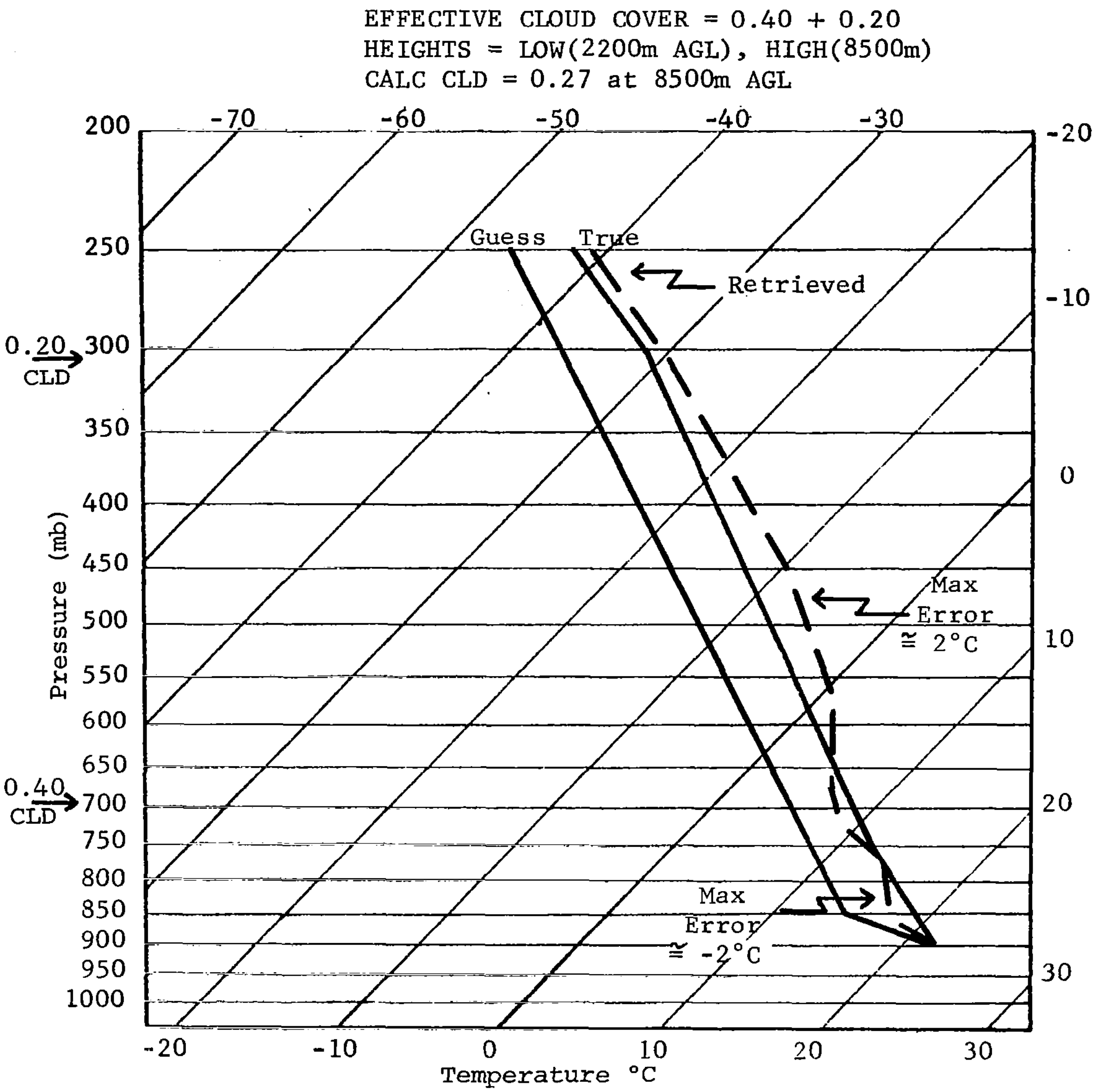

Fig. 9. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere accomplished by employing in the retrieval the highest cloud-top height used to calculate simulated radiance measurements and calculating a one level fractional cloud amount (0.27) at that level. The simulated **radiance** measurements were prepared for two layers of clouds using the effective cloud amount and height values shown above.

EFFECTIVE CLOUD COVER = 0.50 + 0.50
HEIGHTS = LOW(2200m AGL), HIGH(8500m)
CALC CLD = 0.59 at 8500m AGL

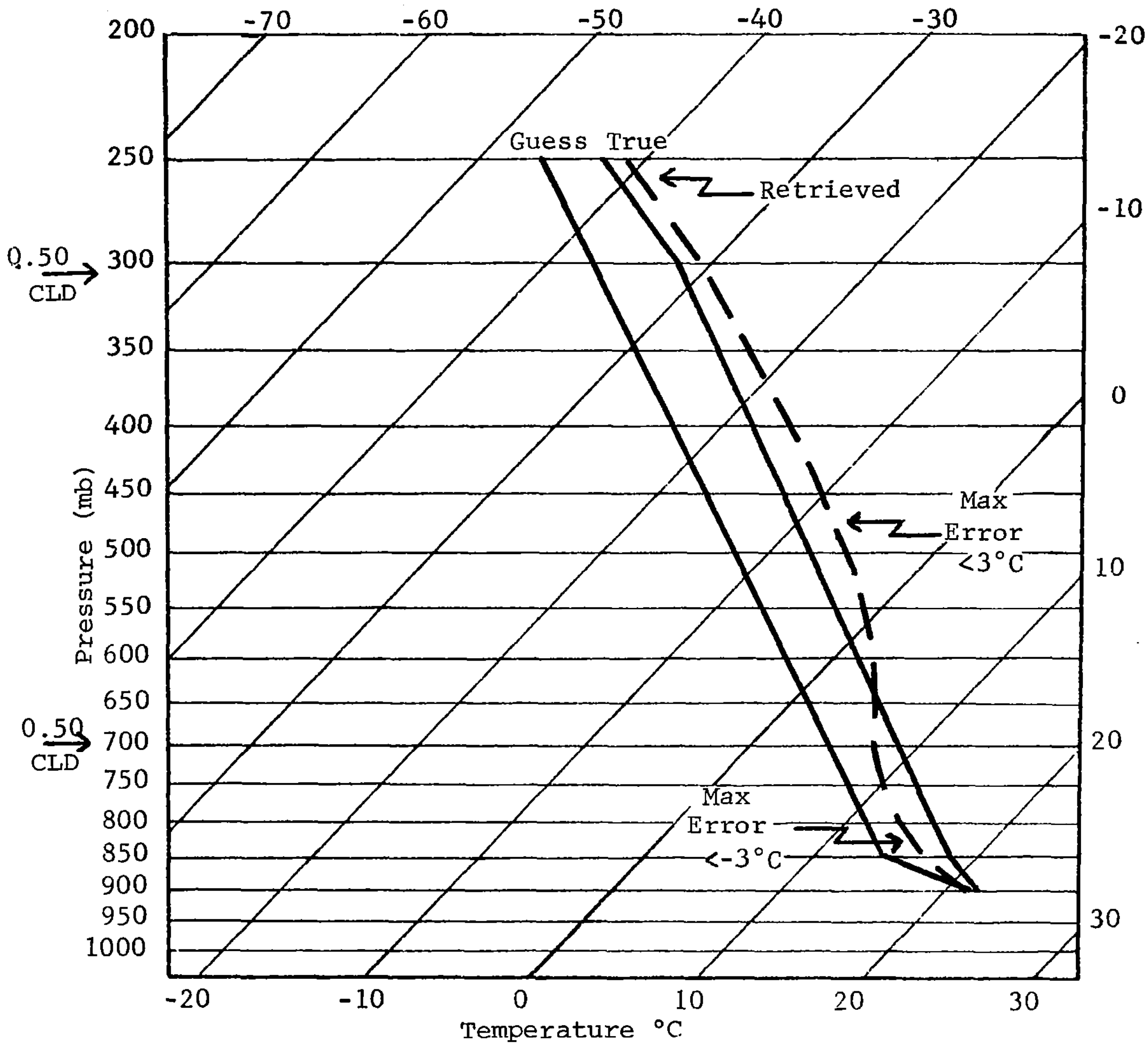

Fig. 10. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere accomplished by employing in the retrieval the highest cloud-top height used to calculate simulated radiance measurements and calculating a one level fractional cloud amount (0.59) at that level. The simulated radiance measurements were prepared for two layers of clouds using the effective cloud amount and height values shown above.

EFFECTIVE CLOUD = 0.50 + 0.50
HEIGHTS = LOW(2200m AGL), HIGH(8500m)
CALC CLD = 0.95 at 5000m

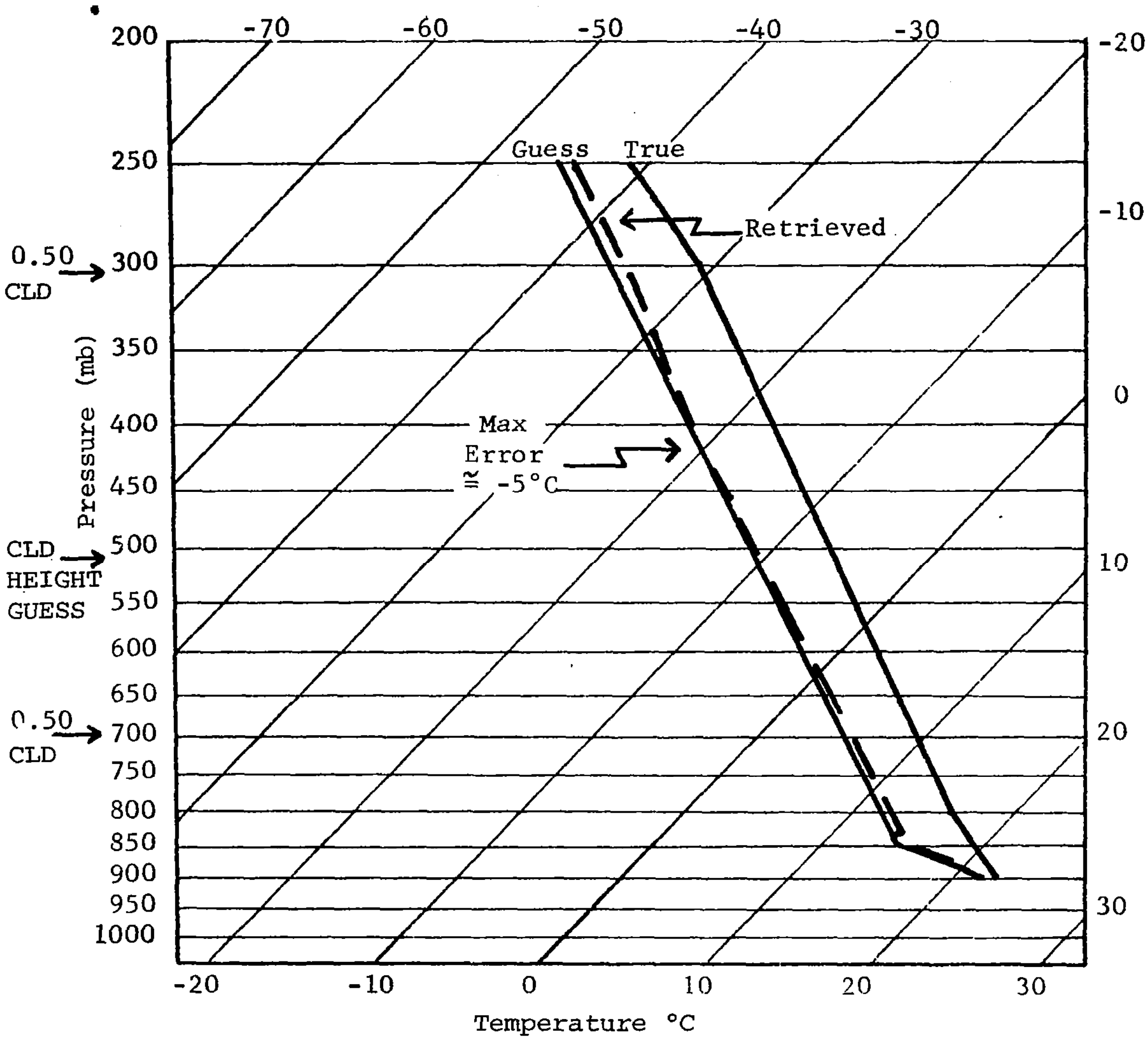

Fig. 11. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere accomplished by employing in the retrieval a cloud height that is significantly lower than the highest cloud-top height used to calculate simulated radiance measurements and calculating a one level fractional cloud amount at the significantly low level. The simulated radiance measurements were prepared for two layers of clouds using the effective cloud amount and height values shown above.

EFFECTIVE CLOUD = 0.40 + 0.20
HEIGHT = LOW(2200m AGL), HIGH(8900m)
ESTIMATED HEIGHT - 10,800m AGL
CALC CLD = 0.18 at 10,800m AGL

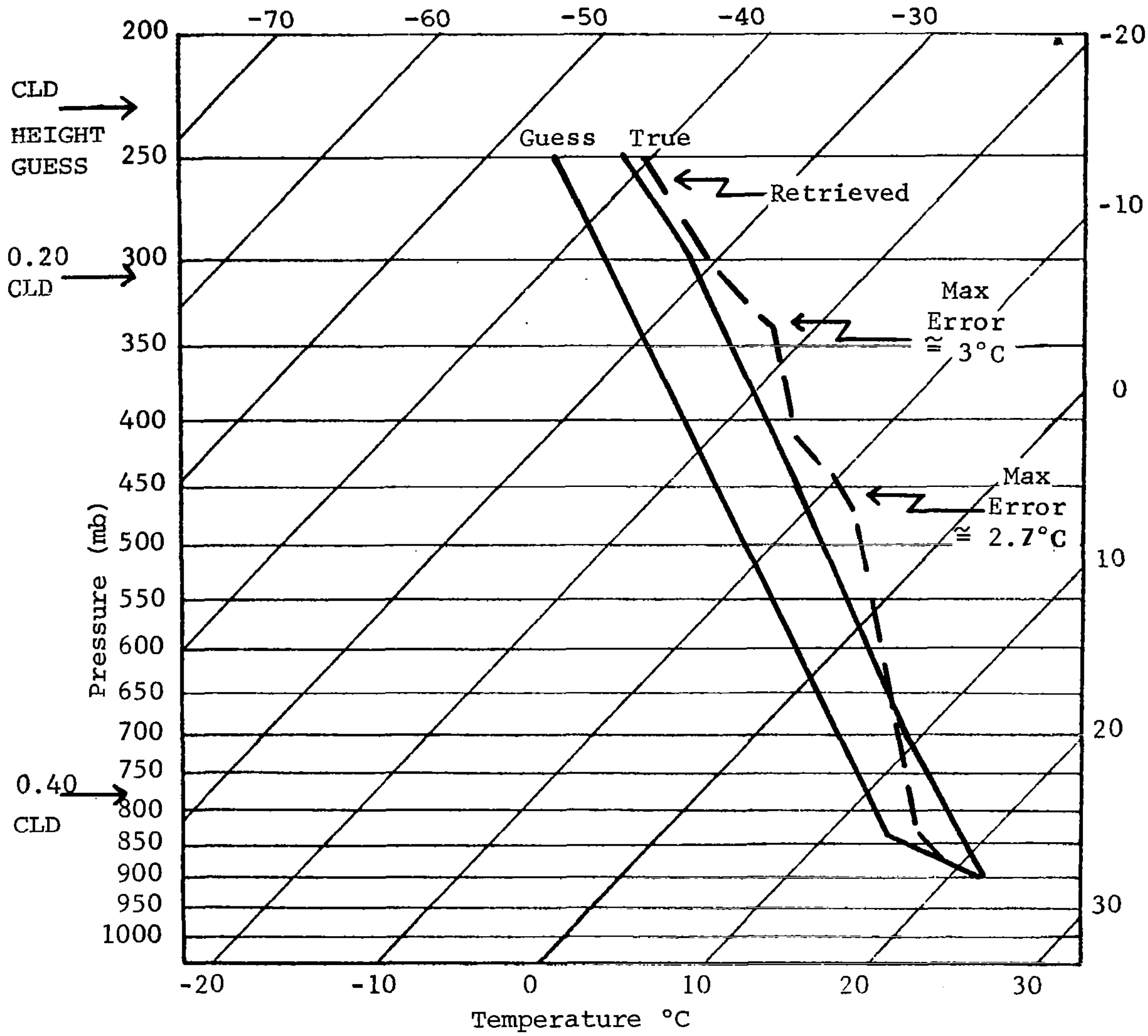

Fig. 12. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere accomplished by employing in the retrieval a cloud-top height that is significantly higher than the highest cloud-top height used to calculate simulated radiance measurements and calculating a one level fractional cloud amount at the significantly high level. The simulated radiance measurements were prepared for two layers of clouds using the effective cloud amount and height values shown above.

guessed profile as previously, but then using the retrieved profile to calculate a new estimate of cloud amount and continuing this iteration until measured and calculated radiance values converged for all channels. These attempts generally resulted in slightly improved profiles. Figure 13 is an example of a profile obtained in this manner. However, this procedure is unsatisfactory when applied directly to real as opposed to simulated data.

EFFECTIVE CLOUD = 0.80
HEIGHT = 2200m AGL
ESTIMATED HEIGHT = 2500m AGL
CALC CLD = 0.25 0.55 (CONV IN 4 ITERATIONS)

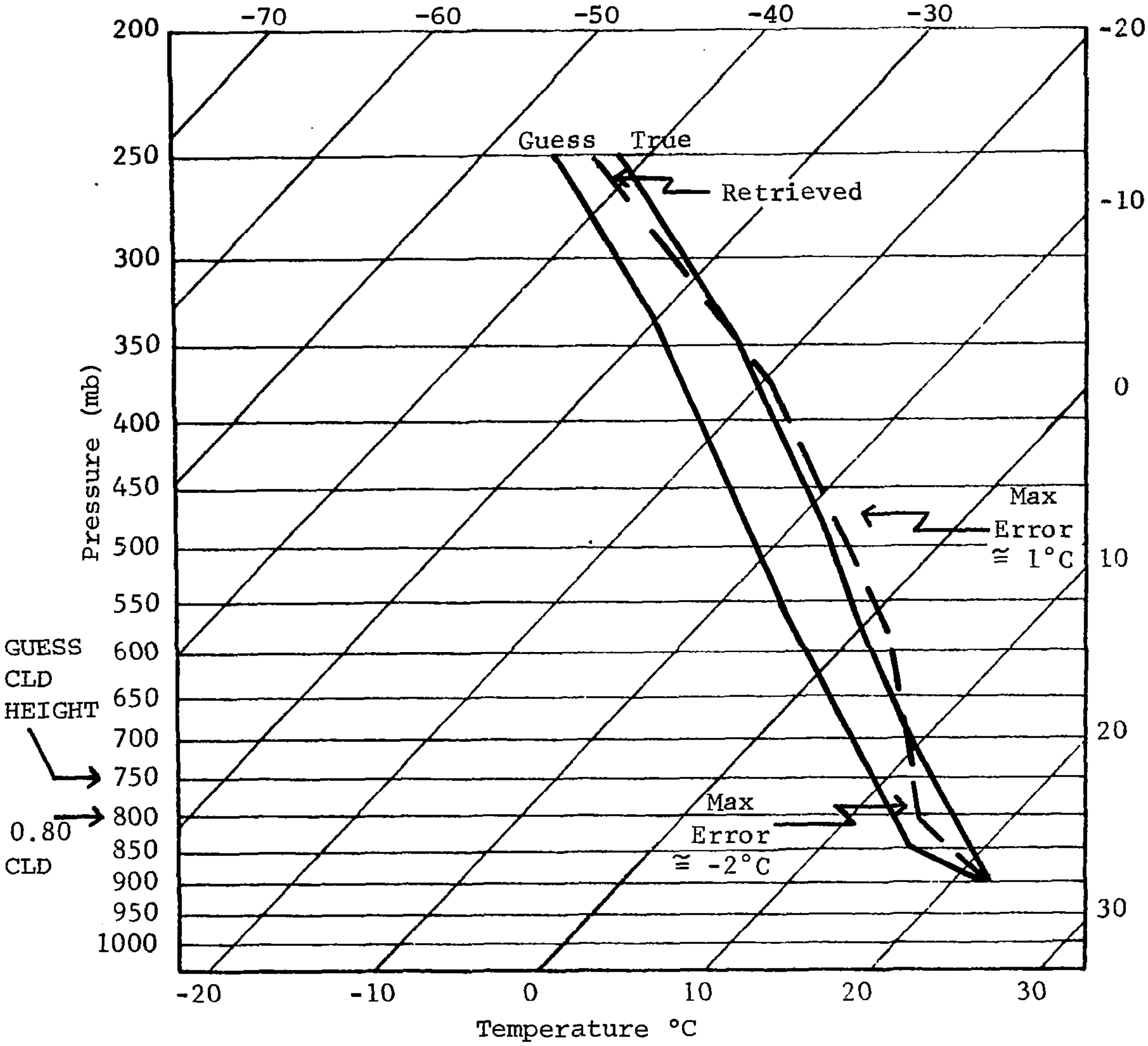

Fig. 13. Temperature sounding retrieved from the RTE for a partly cloudy atmosphere. It was accomplished by calculating a value of fractional cloud amount at an estimated cloud-top height, employing the calculated value to retrieve a temperature profile and then calculating revised values of cloud amount and temperature until calculated radiance values and the simulated measurements converge. The simulated measurements were prepared for two layers of clouds using the effective cloud amount and height values shown above.

5. APPLICATION TO ATMOSPHERIC VARIABILITY EXPERIMENT (AVE III) DATA

a. Procedures

In Section 3 a method was developed to retrieve temperature profiles directly from cloud-contaminated radiance data. In Section 4 the method was examined through use of simulated data. However, these data are easier to handle and less noisy than real data. Furthermore, transmittance errors do not affect simulated data. The feasibility of using the model for a real case was therefore investigated. The general procedure followed was to use NOAA-4 satellite radiance data measured over the area of the AVE III experiment to retrieve temperature profiles, and to compare the retrieved profiles with the excellent radiosonde data obtained during the AVE III experiment for the station nearest the center of the applicable radiance spot (resolution element). Highest cloud-top heights and surface temperature were estimated from the synoptic observations available for the time closest to satellite passage over the area. No attempt was made to refine the cloud-top or temperature data from any other data source or to correct the shelter temperature in any way to give a closer approximation of the true surface value for the area of the radiance spot.

b. Data

A description of the Vertical Temperature Profile Radiometer (VTPR) used on NOAA series satellites and the accuracy and format of retrieved data is given by McMillin *et al*. (1973). The VTPR scans from left to right in 23 discrete steps per scan line. In the 0.5-sec interval allowed for each spot, radiance measurements are obtained in six channels of the CO_2 band, a window channel, and a channel in the water vapor absorption band (not used in this study). Incremental steps of about 2.7° are used, giving 30.3° areal coverage from the nadir direction for each scan line. When viewing in the nadir direction the projection of each scan spot on Earth's surface is approximately a square 55 km on a side, with spot size increasing somewhat with viewing angle. After completing a scan line (12.5 sec of which 11.5 is used to make measurements) the instrument takes an additional second to return to its original position. Scan spots are contiguous along and across the satellite track. The orientation of the eight lines of the radiance data used in this experiment with reference to Earth's surface and AVE III observing stations in the area is shown in Fig. 14. Scanning was initiated at approximately 0233 GMT, 6 February 1975.

AVE III radiosonde data for 6 February 1975 at approximately 0000 GMT were used for comparison with the temperature profiles retrieved from satellite radiance data. The method of collecting and processing the AVE III data was discussed by Fuelberg and Turner (1975). Sounding data were obtained for 51 stations (Fig. 15), 11 in the area of interest of this study, for every pressure contact and interpolated to give values at 25-mb intervals from Earth's surface to 25 mb. RMS errors for computed temperature values are estimated to be $\leq 1°C$. As temperatures are required for approximately 100 intervals from 0.01 mb to the surface in the present study, the necessary values were obtained through linear interpolation of the AVE III temperatures. In like manner dew point values were obtained to 258 mb, the highest level for which these data are used in the program to compute weighting functions. Surface temperatures and dew points were obtained from surface synoptic observations or interpolation from 0000 GMT radiosonde surface values. Temperature and dew point values for Stephenville, Texas, were not available above 375 mb, therefore, measurements in this region of the atmosphere for Shreveport, Louisiana, were substituted for the missing Stephenville data. The substitution was necessary for use in computer programs to compare the AVE III data with the satellite-derived profiles, but the comparisons for Stephenville above 375 mb are, of course, invalid.

The surface weather map for 6 February 1975 at 0000 GMT (after Fuelberg and Turner) is shown in Fig. 16. The data in Table 1 were used to estimate a cloud-top height for each station. These heights were then used as input to the cloud model previously described. Although there is no known way to retrieve the temperature profile under an overcast layer of black-body clouds from the radiation originating from the surface under these clouds, retrievals were attempted for

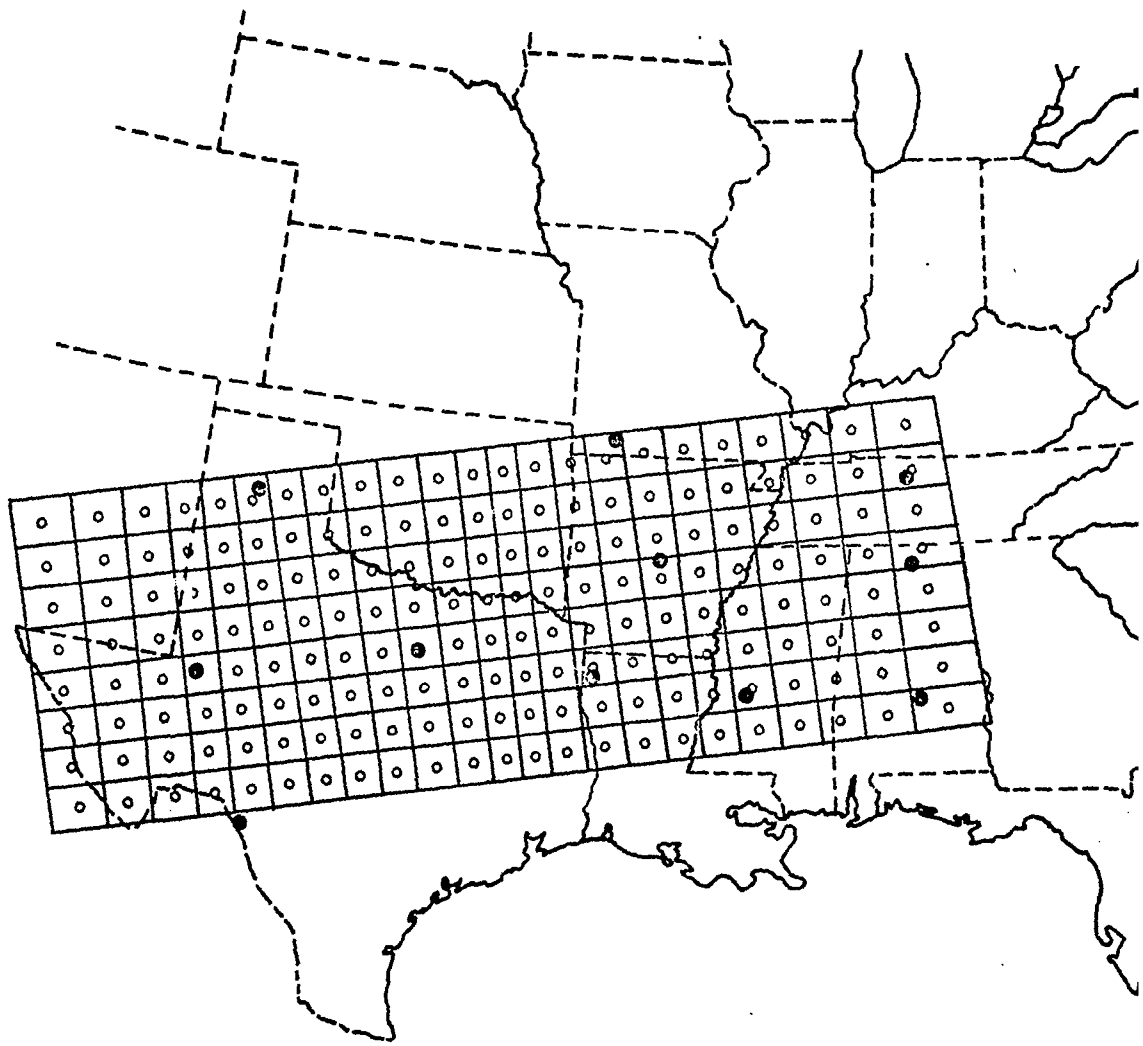

Fig. 14. **Satellite** radiance measurements (o) at 0233 GMT and AVE I radiosonde runs (●) at 0000Z, 6 February 1975.

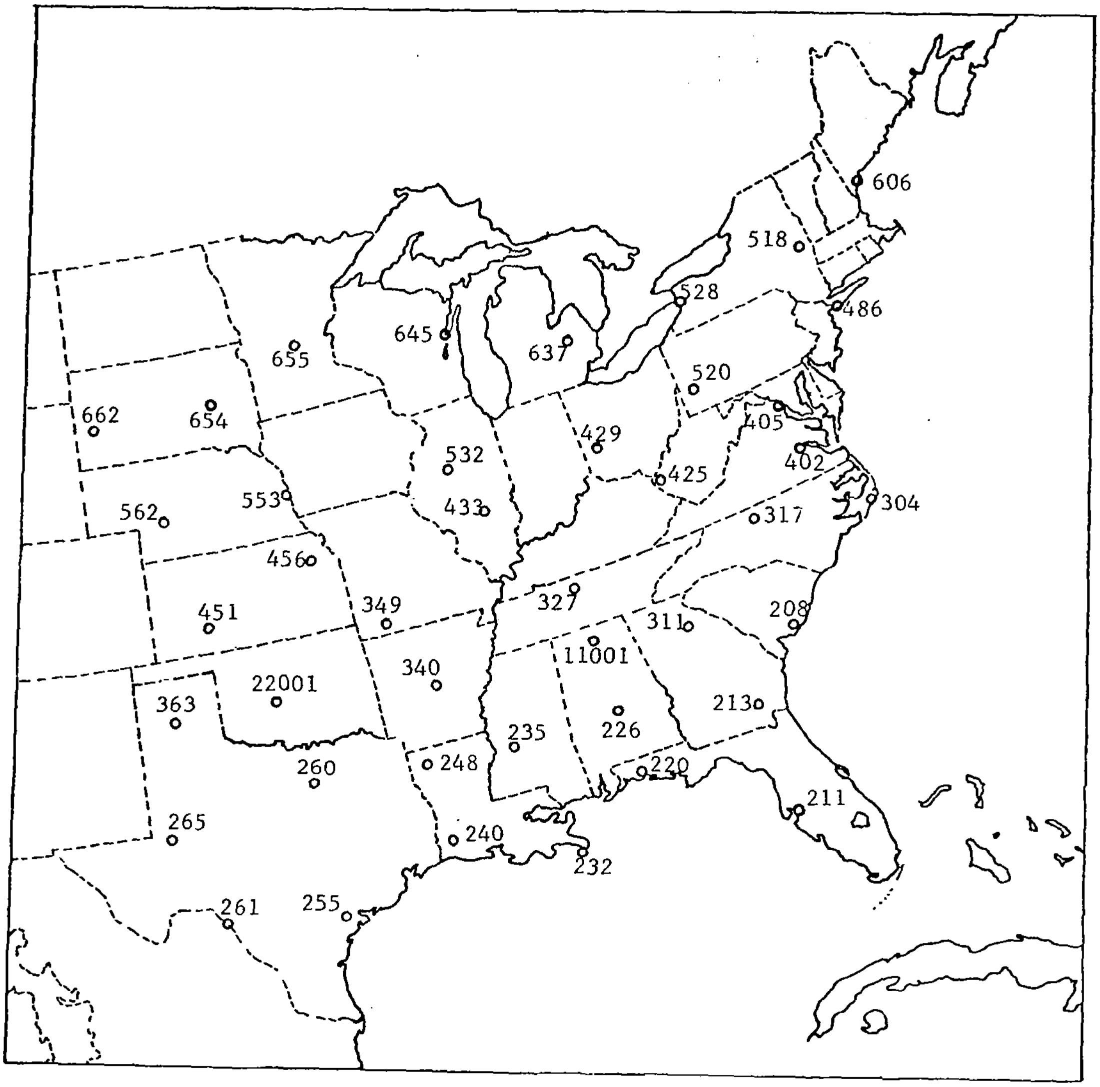

Fig. 15. Rawinsonde stations participating in the AVE III experiment (Fuelberg and Turner, 1975).

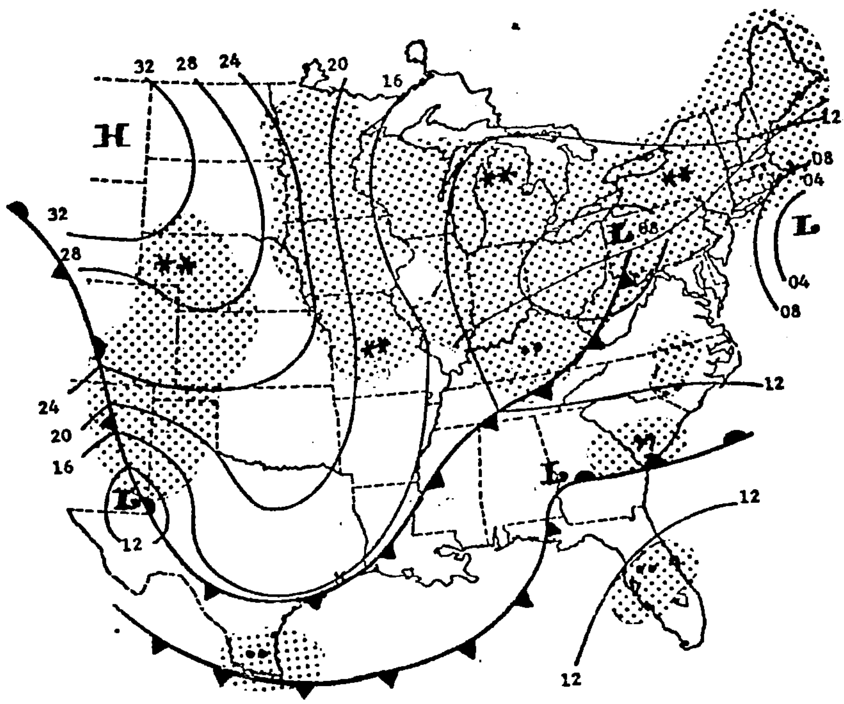

Fig. 16. Surface synoptic chart for 0000 GMT, 6 February 1975 (Fuelberg and Turner, 1975).

Table 1. Estimation of average cloud-top heights.

Station	SFC P (mb) (From AVE III)	Cloud and Visibility Observations 02Z	03Z	Estimated P (mb) at Cloud Top
Centerville, Ala.	996.6	30 ⦶10	30 ⦶10	870
Jackson, Miss.	1003.0	280-⦶20+	280-⦶ 20+	329
Shreveport, La.	1008.5	Not Available		870
Stephenville, Tx.	971.2	M16 ⊕15	M18V ⊕15	870
Del Rio, Tx.	977.7	250-⦶ 20+	250-⦶ 20+	361
Midland, Tx.	913.3	250-⦶ 20+	250 ⦶20	344
Nashville, Tenn.	989.4	M24⦶ 65 ⊕10	24⦶ M35⊕ 10	699
Little Rock, Ark.	1007.1	M22⦶ 12	M22 ⊕12	902
Monette, Mo.	966.1	M11⊕ 10	M11⊕10	810
Amarillo, Tx.	889.3	6⦶M35⊕ 10	10⦶M35⊕12	699
Marshall Space Flight Center, Ala.	991.2	70⦶ 250 ⦶15	250⦶ 15	377

all stations including those where overcast conditions were observed. It was felt that at the overcast stations, as long as a relatively smooth guessed profile was used, the assumption discussed in Section 3c, i.e.

$$\frac{\tilde{I}^*(\nu_i)}{I^*(\nu_i)} \approx \frac{\tilde{I}(\nu_i)}{I(\nu_i)} , \tag{51}$$

would be valid and an improvement of the guessed temperature values below cloud level could be obtained. It is also possible that although a station reports an overcast condition, it may not be a true black-body overcast. The overcast layer may be thin, and may not completely attenuate radiance arising from below the cloud layer. Because of its low emissivity, a reported overcast layer of thin clouds may yield no greater value of effective cloud cover ($A=N\varepsilon$) than a broken or even scattered layer of thick clouds.

c. Results

In order to retrieve an accurate temperature profile through use of the method outlined in this study it is necessary to employ a first guess profile that approximates the true temperature values. Both smooth climatological profiles and numerical forecasts have been used with the "minimum information" method as guessed profiles. The question of the proper guessed profile to choose for a particular retrieval is necessarily dependent on the knowledge of the true profile that is possessed prior to attempting the retrieval. As can be seen from Fig. 6, the shape of an inversion in the guessed profile will be picked up in the retrieved profile and at approximately the same atmospheric pressure. The coincidence of shape thus attained is independent of the validity of the inversion. Thus to attain the most accurate retrieval it would seem best not to include fine detail in the guessed profile. However, if a retrieval is desired for a location at the same latitude and in the same air mass as a station for which a recent radiosonde run is available, it would seem logical to use at least some of the known radiosonde temperatures (with modification in the lower layers and smoothing between radiosonde temperatures as necessary) as the guessed profile in the retrieval. Even so, for situations comparable to the 6 February 1975 situation, where an area is under the direct influence of a strong frontal system, using the radiosonde run of one station as the guessed profile of a nearby station might lead to fictitious features in the retrieved profile. This would also be true if a day old profile for a station were used as the guessed profile. Furthermore, it was desired that guessed profiles for all stations be coincident in temperature above the lower portion of the atmosphere so that changes in similar profiles might be noted for the various stations.

In investigating the 6 February situation several different guessed profiles were tried. Guessed profiles were computed as follows: (1) Temperatures were averaged at each level above the surface to 25 mb for the 51 stations of the AVE III experiment. The profile of temperature above 25 mb was provided by Dr. L. Duncan (1975)[3] and is a standard profile for the White Sands area. (2) Temperatures were averaged as above for the 51 AVE III stations. Next, a constant lapse rate between levels was computed from the surface to level 90 (699 mb) and a new constant lapse rate for each 10 levels thereafter to level 50 (97 mb) was computed. These values were substituted for the previously computed averages below level 50. (3) The same method as in (2) above was employed except averages were computed for only the eleven stations for which radiance data were obtained. It was hoped that this procedure would lead to a smooth profile that incorporated the general shape of the average profile. (4) Temperatures were computed as in (3), but the dew point profile was computed differently. For the three profiles discussed above the 0000 GMT AVE III dew points for each station were employed. In this case dew points were averaged and smoothed in precisely the same manner as the temperature profiles in (2), (3), and (4).

For each of the guessed profiles discussed above retrievals were performed for each of the eleven AVE III stations. The root mean

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[3]Duncan, L. D., 1975: Personal communication.

square errors from the surface to cloud-top level resulting from comparison of the true and retrieved profiles were calculated. Results are shown in Table 2. Chahine (1970) has noted that the effects of clouds on the retrieved profile are almost entirely confined to the region below cloud-top level. This effect may also be noted in Figs. 2 and 3. Comparison of RMS errors in Table 2 for the same stations but different guessed profiles should therefore provide a relative estimate of the usefulness of the various guessed profiles tested. Results shown in Table 2 indicate that in guessed profile (1), a simple average of the true temperature profiles at all AVE III stations, false detail in the guess causes serious errors in the retrieved profiles. Comparing results of profiles (1) and (2), it can be seen that smoothing out the false detail will invariably result in an improved retrieval. Use of the eleven-station average points in profile (3) does not give significantly better results than retrievals obtained using guessed profile (2). Neither does use of an average, but smoothed, dew point profile [profile (4)] significantly improve the below cloud-top level retrieved profiles. All changes in the guessed profile have little effect on the large RMS errors calculated for Stephenville and Midland. The errors are probably the result of a gross error in estimated cloud-top height caused by the presence of clouds that are much higher than estimated. Improvement of retrievals at these stations will be attempted later in this section. From Table 2, guessed profile (4) appears to give the best results and is used for subsequent retrievals unless otherwise indicated.

In the retrievals discussed above a convergence interval of 0.1 mw/m^2 sr cm^{-1} was used for the convergence of computed to measured radiance values for each channel. After the computation of the cloud parameters was achieved a total of fifty iterations was allowed to achieve convergence in the interval prescribed. Both the interval and the maximum number of iterations had been used in computations by Duncan (1975).[4] However, for the 6 February 1975 cases convergence was in no case achieved within 50 iterations for all channels.

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[4] Ibid.

Table 2. RMS errors (°C) below cloud-top level for various guessed profiles.

Station	(1) Retrieved vs True	(2) Retrieved vs True	(3) Retrieved vs True	(4) Retrieved vs True
Centerville	6.8	3.8	2.9	2.3
Jackson	3.2	2.3	2.0	2.0
Shreveport	0.9	1.4	1.3	1.6
Stephenville	*	4.8	5.0	4.7
Del Rio	4.5	2.9	2.7	2.1
Midland	*	4.3	4.2	4.1
Nashville	2.6	1.5	1.6	1.8
Little Rock	1.4	2.0	1.5	1.7
Monette	7.5	3.4	3.5	3.3
Amarillo	3.7	1.7	1.9	2.1
MSFC	*	3.0	2.9	3.0

*Profile not computed.

Increasing the convergence interval beyond the error tolerance allowed in computing cloud cover is impractical as convergence does not occur at the same rate in each channel. As pointed out by Chahine (1970), the relaxation method upon which the present research is based is "...a discrete numerical process in which the concept of formal convergence plays hardly any role..." and the rate of convergence is judged as the rate at which the residuals for each channel reach their "asymptotic" values. For the profiles investigated, decreasing the number of iterations below fifty revealed that differences between measured and computed radiance reached different, but nearly constant values, for the various channels in a fairly rapid manner. A review of results (RMS errors) obtained by comparing AVE III profiles with profiles retrieved using various numbers of iterations (Tables 3 and 4) gives the impression that the degree of accuracy can rarely be improved after approximately ten iterations. This is in agreement with the empirical results found in tests of Chahine's method (Conrath and Revah, 1972). Comparison of RMS errors in the guessed profile with RMS errors in retrieved profiles (Table 4) reveals that accqurate retrievals for ten iterations were generally obtained to tropopause level. With the exception of Marshall Space Flight Center (MSFC), errors greater than those that are present in the guessed profile generally occur only when inversions are present in the guessed or true profiles. At MSFC the guessed profile fits the true atmosphere so well that iteration does not appear to lead to improvement of the guessed profile. However, for ten iterations the maximum RMS error in the results is only 1.0 degree greater than the guessed value (Table 4).

It was assumed that results for some of the overcast and high cloud cases could have been degraded by a gross error in the estimate of the height of the highest cloud layer in the field of view of the radiometer. Therefore, all profiles were recomputed using an estimated cloud-top height of 299 mb. Significant improvement was noted at Stephenville and Midland, and the computed cloud parameters were used therefore in subsequent research. Results for ten and one iterations are shown in Table 4.

Table 3. RMS errors (°C) for retrieved profiles.

Station	SFC to CLD			SFC to 726mb			699 to 489mb			469 to 314mb		
	RMS error (°C) for iterations shown											
	75	50	25	75	50	25	75	50	25	75	50	25
Centerville	2.6	2.3	2.2	2.7	2.1	1.9	2.3	1.7	1.5	4.9	4.1	3.2
Jackson	2.6	2.0	1.5	2.7	2.3	2.1	1.9	1.3	0.9	3.0	2.2	1.2
Shreveport	2.0	1.6	1.5	2.2	1.6	1.4	3.0	2.9	2.9	4.2	3.5	2.6
Stephenville	4.6	4.7	4.7	3.4	3.6	3.9	8.3	7.9	7.0	8.0	7.3	5.9
Del Rio	2.8	2.1	1.6	2.3	1.5	0.8	2.4	1.7	1.5	3.7	2.9	2.2
Midland	4.1	4.1	4.2	2.8	3.0	3.3	4.2	4.5	4.8	4.8	4.3	4.9
Nashville	1.9	1.8	1.8	1.0	1.0	1.0	2.1	2.0	2.3	4.1	3.3	1.9
Little Rock	1.7	1.7	1.6	1.6	1.6	1.6	3.8	3.3	2.3	7.0	6.2	4.9
Monette	3.8	3.3	2.9	3.7	3.0	2.3	3.8	3.1	2.7	1.8	0.7	2.2
Amarillo	2.1	2.1	2.0	1.9	1.9	1.8	1.9	1.7	1.8	4.3	3.7	2.7
MSFC	3.5	3.0	2.4	3.9	3.4	2.8	3.6	3.1	2.6	2.2	1.5	0.8

*True profile for Shreveport used above 375 mb.

Table 4. RMS errors for guessed (G) and retrieved profiles.

Station	RMS Errors (°C) for Iterations Shown															
	SFC to CLD				SFC to 726 mb				699 to 489 mb				469 to 314 mb			
	G	25	10	1	G	25	10	1	G	25	10	1	G	25	10	1
Centerville	3.3	2.2	2.3	2.5	3.5	1.9	2.1	2.5	3.4	1.5	1.8	2.2	2.9	3.2	2.3	2.0
Jackson	3.0	1.5	1.4	1.9	3.3	2.1	2.1	2.4	3.1	0.9	0.9	1.8	2.3	1.2	0.8	1.2
Shreveport	2.0	1.5	1.7	1.9	1.9	1.4	1.6	1.8	2.7	2.9	2.7	2.6	1.4	2.6	1.9	1.4
*Stephenville	3.2	4.7	1.9	1.9	4.0	3.9	2.8	2.7	3.7	7.0	1.4	1.9	**1.3	5.9	0.5	0.5
Del Rio	5.9	1.6	1.6	3.4	5.0	0.8	0.7	2.5	7.0	1.5	1.9	4.2	4.6	2.2	1.8	2.7
*Midland	4.1	4.2	2.8	3.6	4.1	3.3	3.0	3.6	5.1	4.8	3.5	4.6	2.9	4.9	1.9	2.7
Nashville	2.5	1.8	1.9	2.2	1.5	1.0	1.3	1.4	4.6	2.3	3.0	4.2	1.3	1.9	1.0	1.2
Little Rock	1.9	1.6	1.6	1.6	1.2	1.6	1.7	1.6	3.5	2.3	1.4	1.9	0.4	4.9	3.3	1.5
Monette	4.1	2.9	2.9	3.5	2.5	2.3	1.9	2.0	6.5	2.7	3.6	5.6	8.4	2.2	4.9	7.7
Amarillo	3.2	2.0	2.0	2.3	1.4	1.8	1.8	1.6	5.7	1.8	2.6	4.2	3.0	2.7	1.6	2.1
MSFC	1.5	2.4	2.2	1.9	1.7	2.8	2.5	2.2	1.4	2.6	2.4	2.1	0.9	0.8	0.9	0.7

*Stephenville and Midland results for ten and one iterations computed using revised cloud parameters (see discussion in results section).

**True profile for Shreveport used above 375 mb.

In Figs. 17 through 27, the guessed, retrieved (using 10 iterations), and AVE III profiles are shown to 300 mb. It should be noted that in all cases the errors in the surface temperatures were probably greater than computed because the observed shelter temperatures were used as both the true and first guess temperatures. However, errors for the first few levels above the surface would normally be less than shown as the AVE III temperatures at these levels were not modified for the time lag between the times the radiosonde and satellite measurements were taken.

Isotherms were drawn for the nearest level to standard from 850 to 300 mb for the AVE III and retrieved temperature data (Figs. 28-37). Surface frontal positions where shown are from the analysis by Fuelberg and Turner (1975).

Comparison of the analyses shows the most serious error in gradient resulted from the spurious warm ridge of Fig. 31. This feature was caused by the very poor 699-mb temperature at Monette. Thus the primary reason for this occurrence may be traced to the fictitious inversion used in the guessed profile for Monette where the 699-mb surface is at the apex of the inversion. The importance of not introducing fictitious features in the guessed profile (in this case the inversion was created by using average data across a frontal zone) is again emphasized. Analysis of the retrieved isotherms in the lower levels appears consistent with surface frontal positions. In evaluating the retrieved analyses it should be recalled that at all levels above 839 mb guessed temperatures were the same for each station at a particular level. Improvement was thus demonstrated, even in a generally cloudy situation. Greater improvement would be anticipated when account is taken of anticipated profile features for a given air mass or station.

An exact comparison of the results achieved for the cases shown in Table 4 and the isotherm maps with the results of previous investigators is impossible. This is not only because of the different methods of retrieval and different guessed profiles employed, but also the variance in three-dimensional space investigated, the averaging

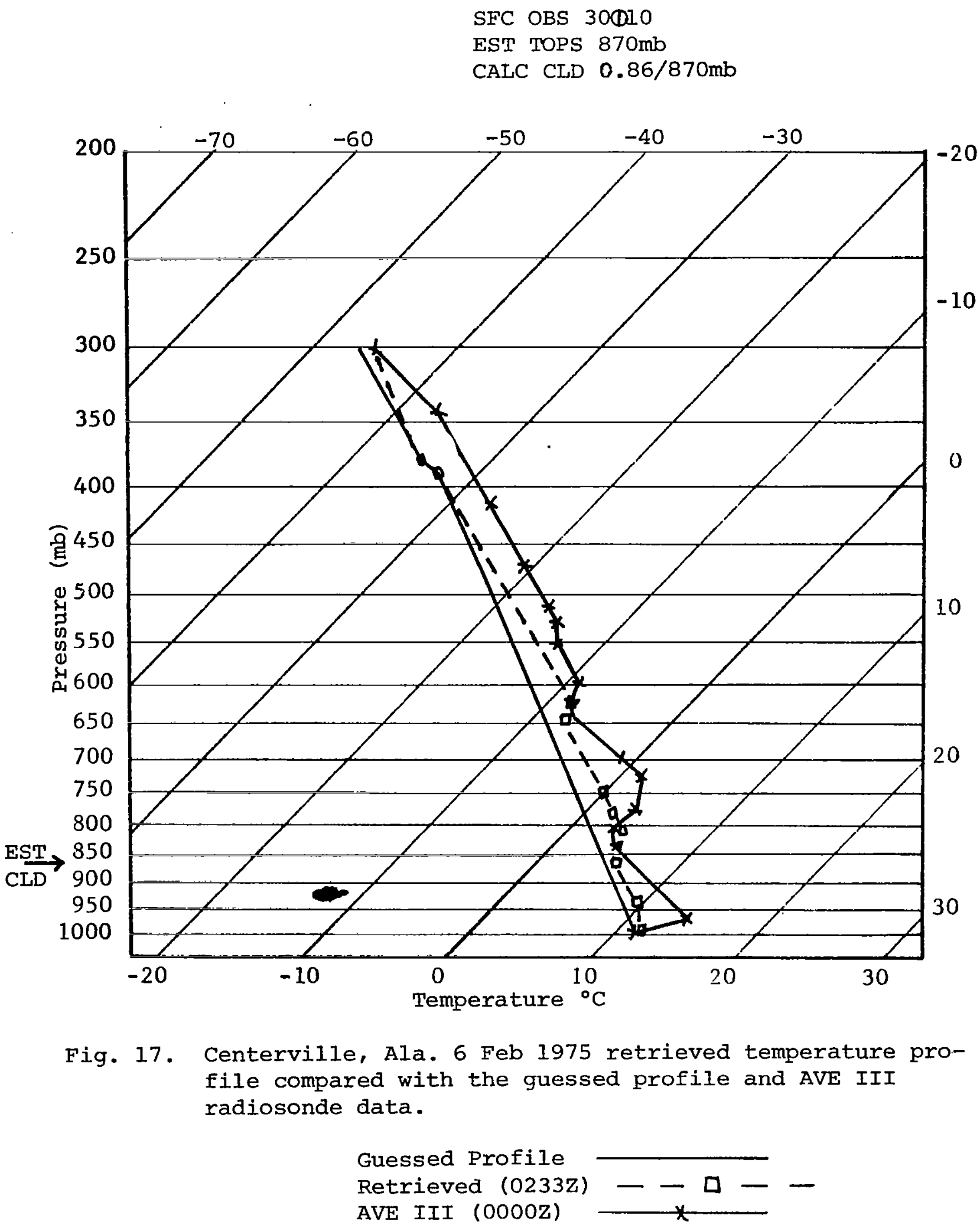


Fig. 17. Centerville, Ala. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

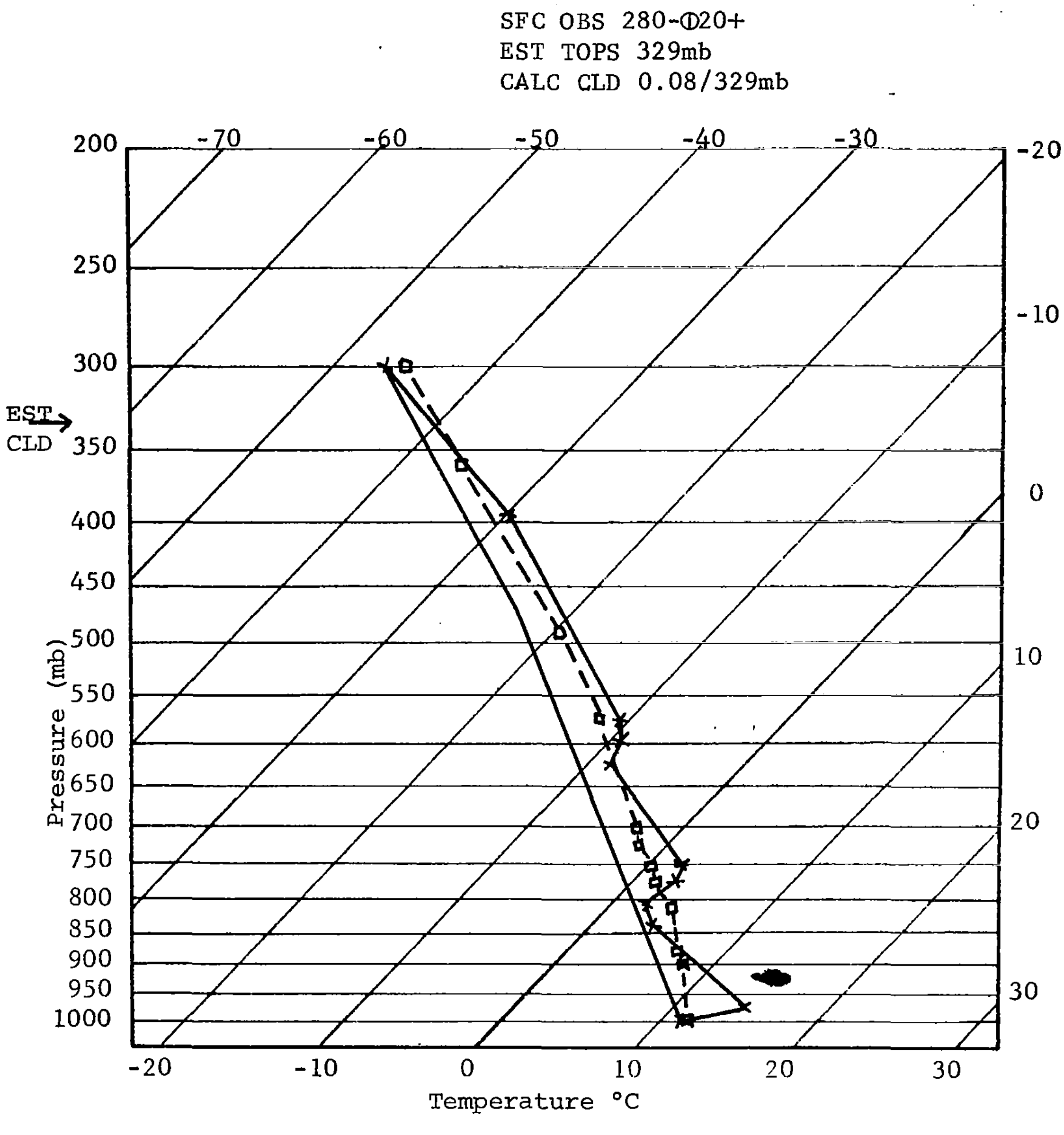


Fig. 18. Jackson, Miss. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile
Retrieved (0233Z)
AVE III (0000Z)

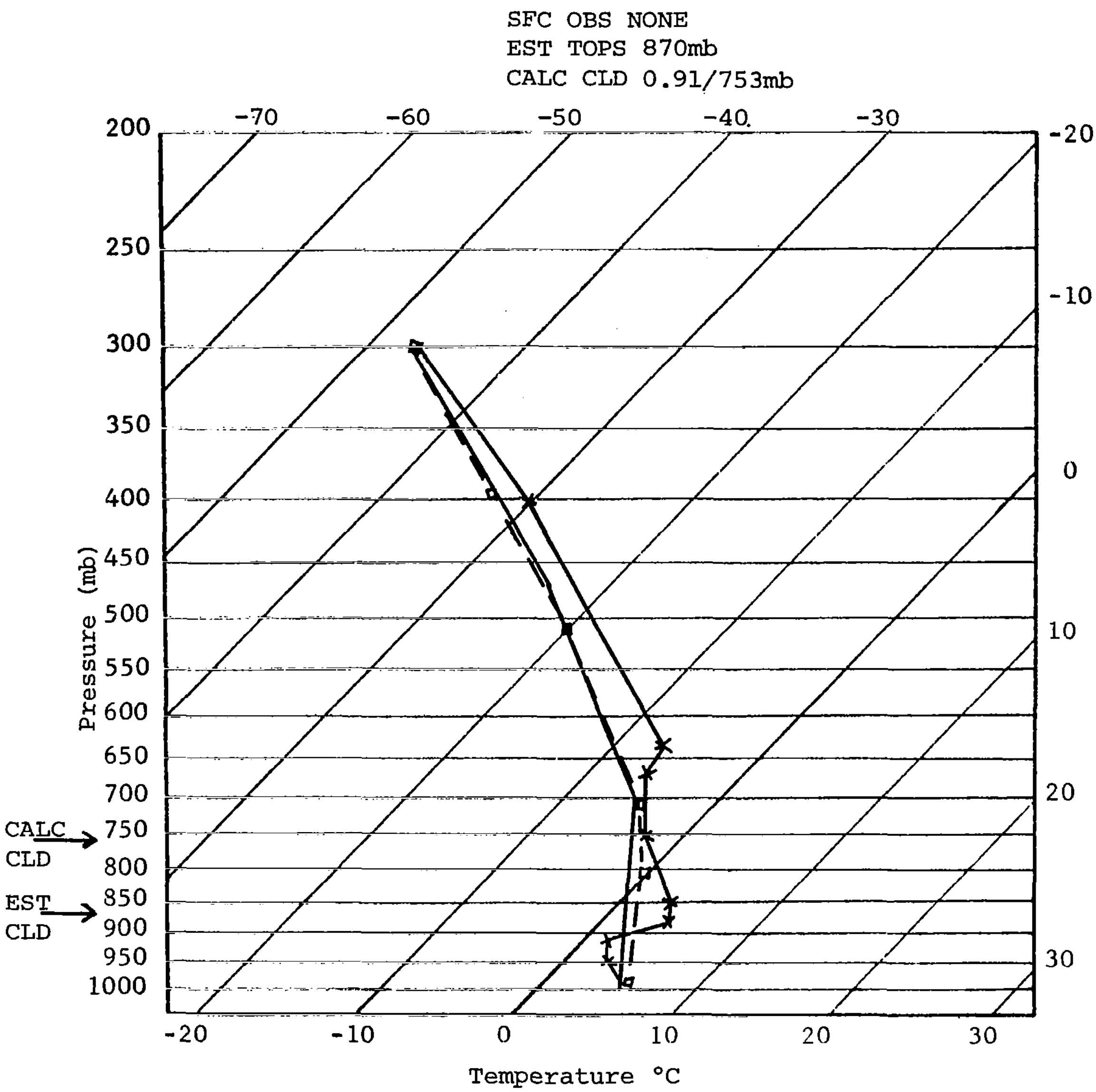


Fig. 19. Shreveport, La. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile
Retrieved (0233Z)
AVE III (0000Z)

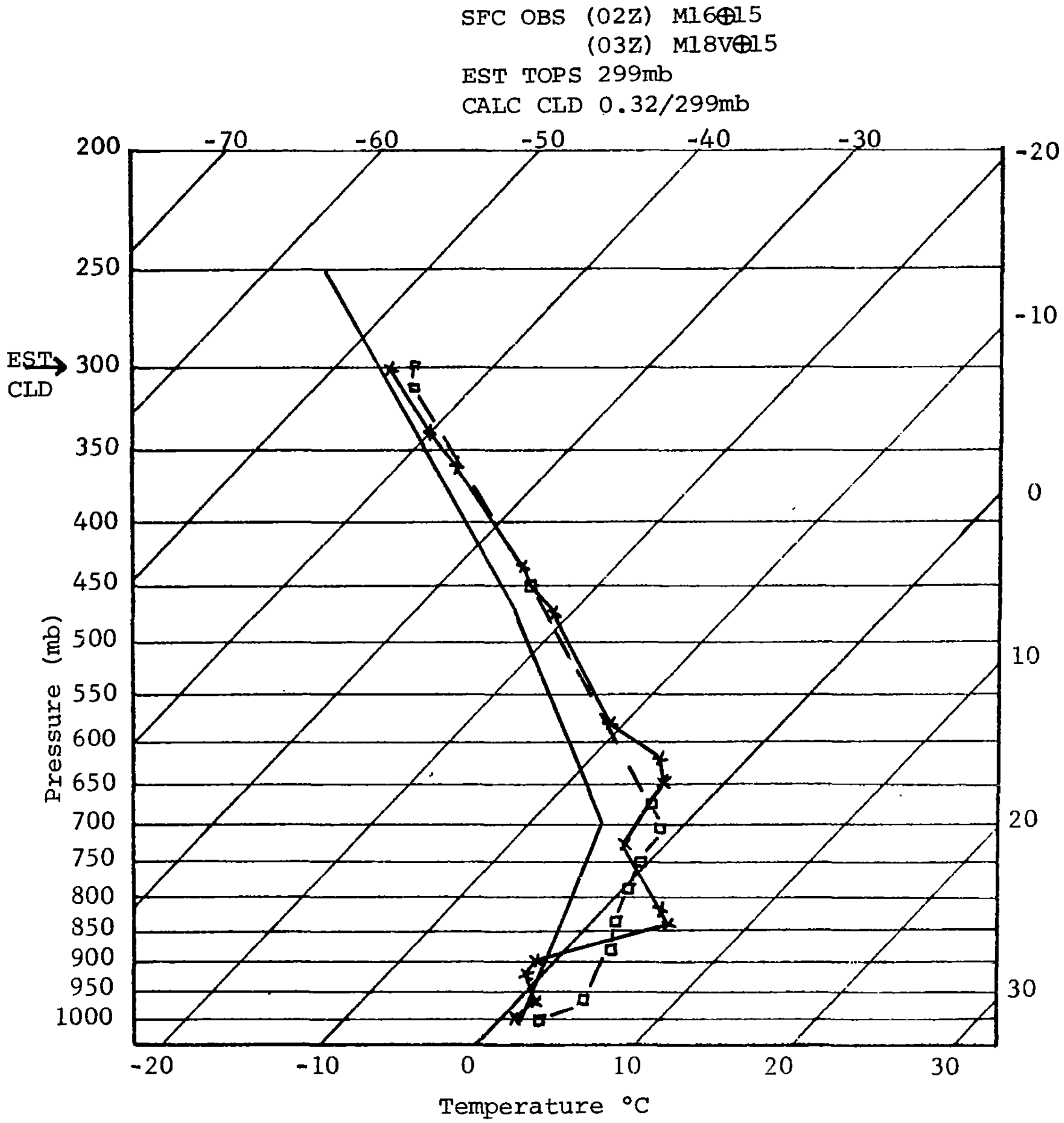


Fig. 20. Stephenville, Tx. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile
Retrieved (0233Z)
AVE III (0000Z)

SFC OBS 250-⊕20+
EST TOPS 361mb
CALC CLD 0.18/361mb

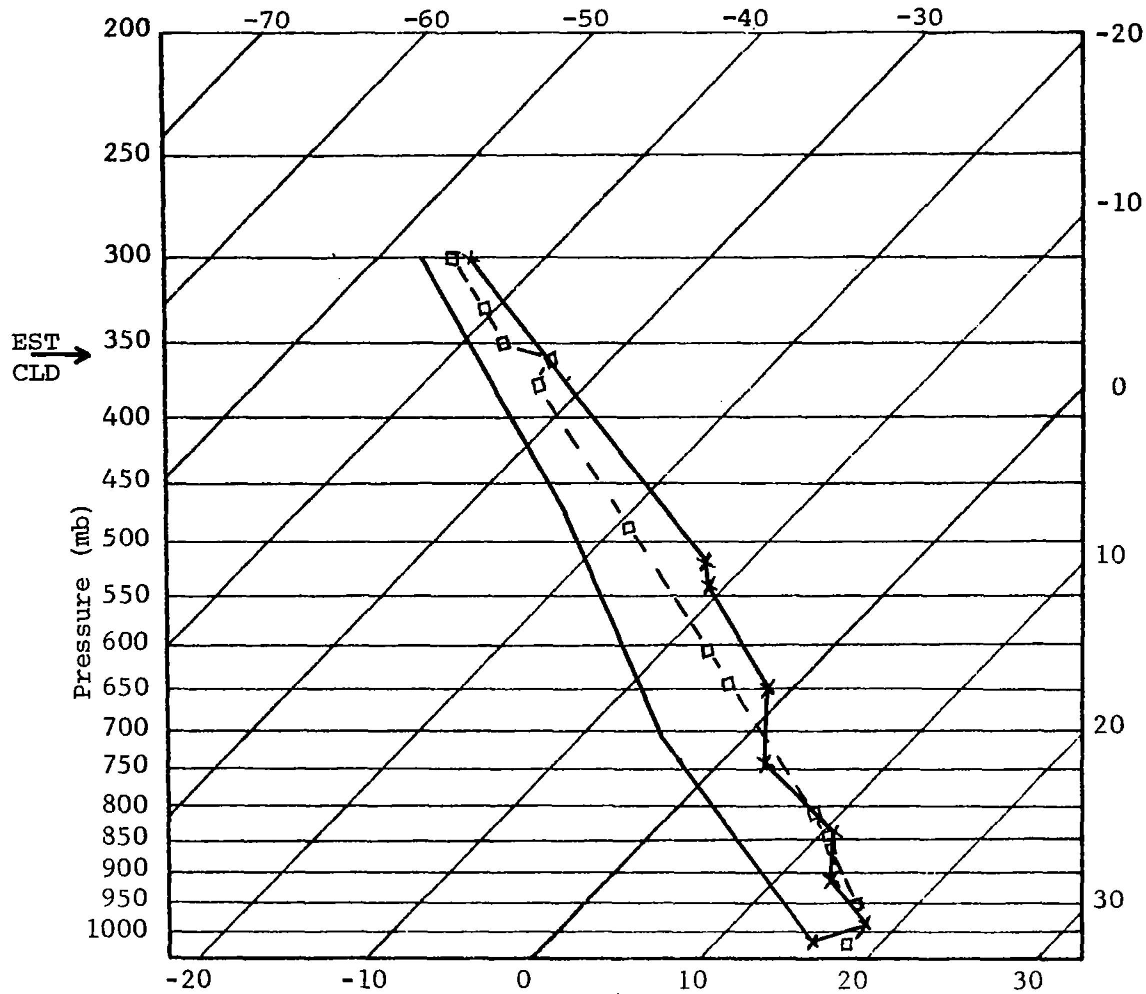


Fig. 21. Del Rio, Tx. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile
Retrieved (0233Z)
AVE III (0000Z)

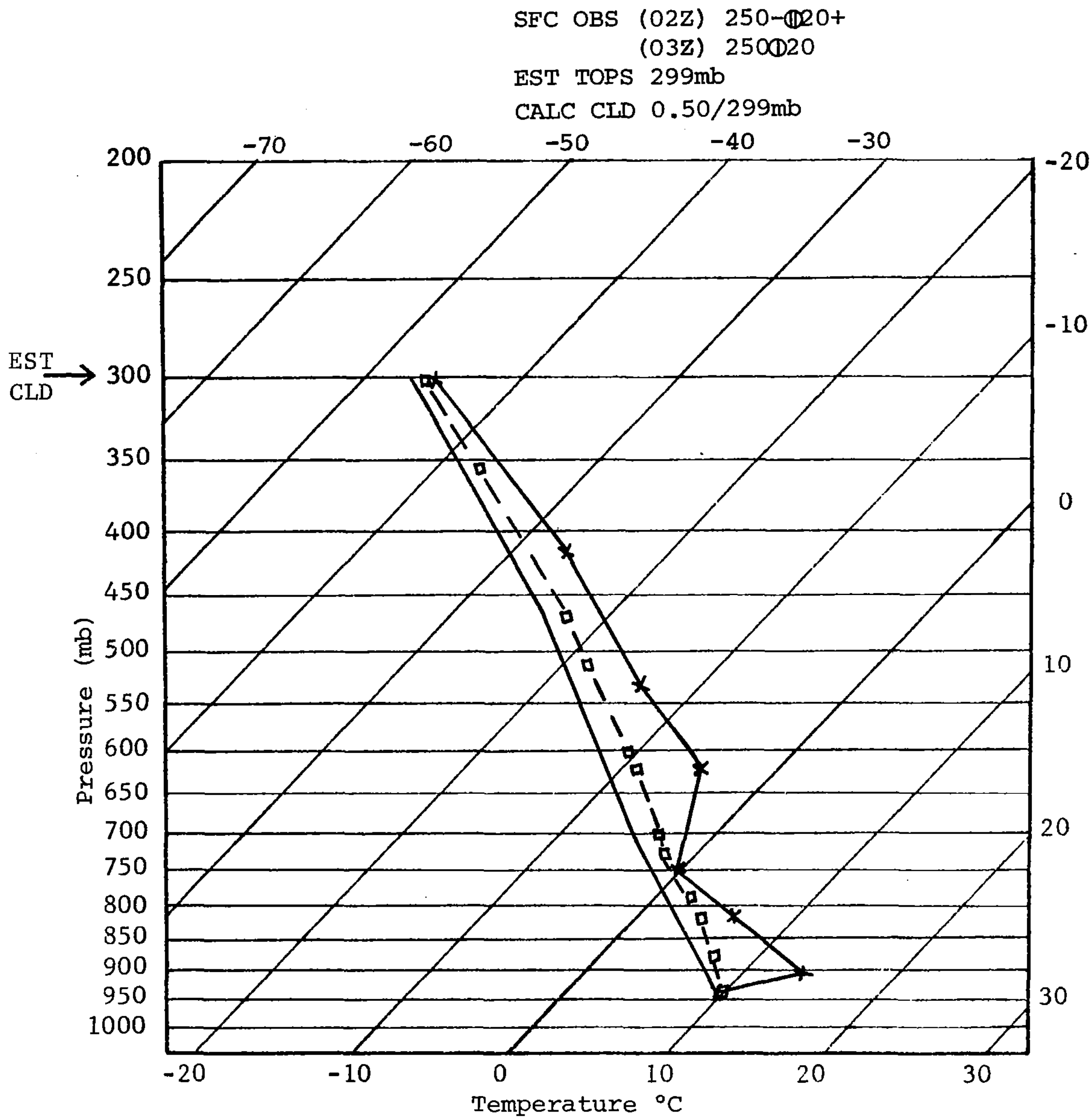


Fig. 22. Midland, Tx. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile ————

Retrieved (0233Z) — — ◻ — —

AVE III (0000Z) ——×——

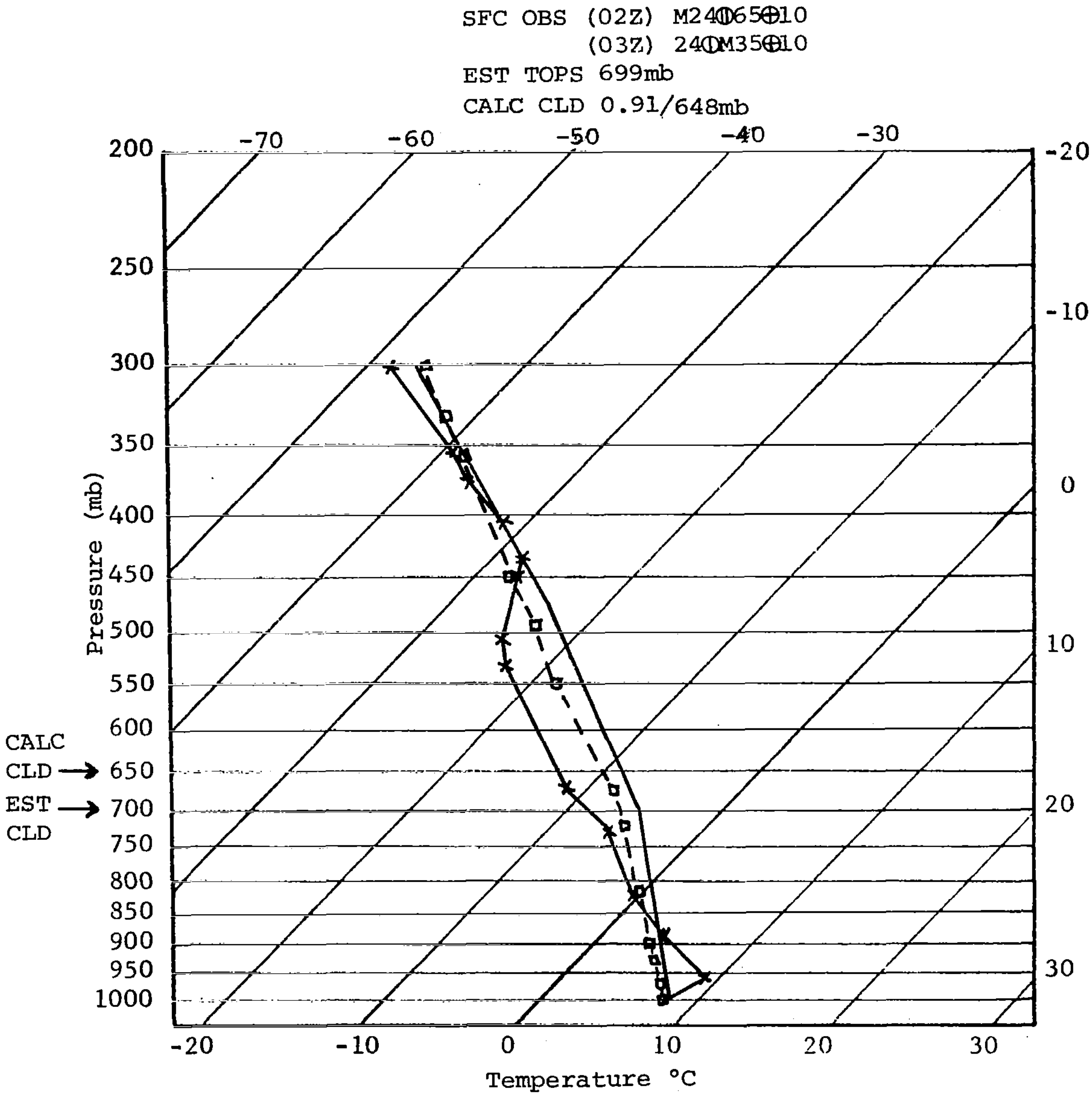


Fig. 23. Nashville, Tenn. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile
Retrieved (0233Z)
AVE III (0000Z)

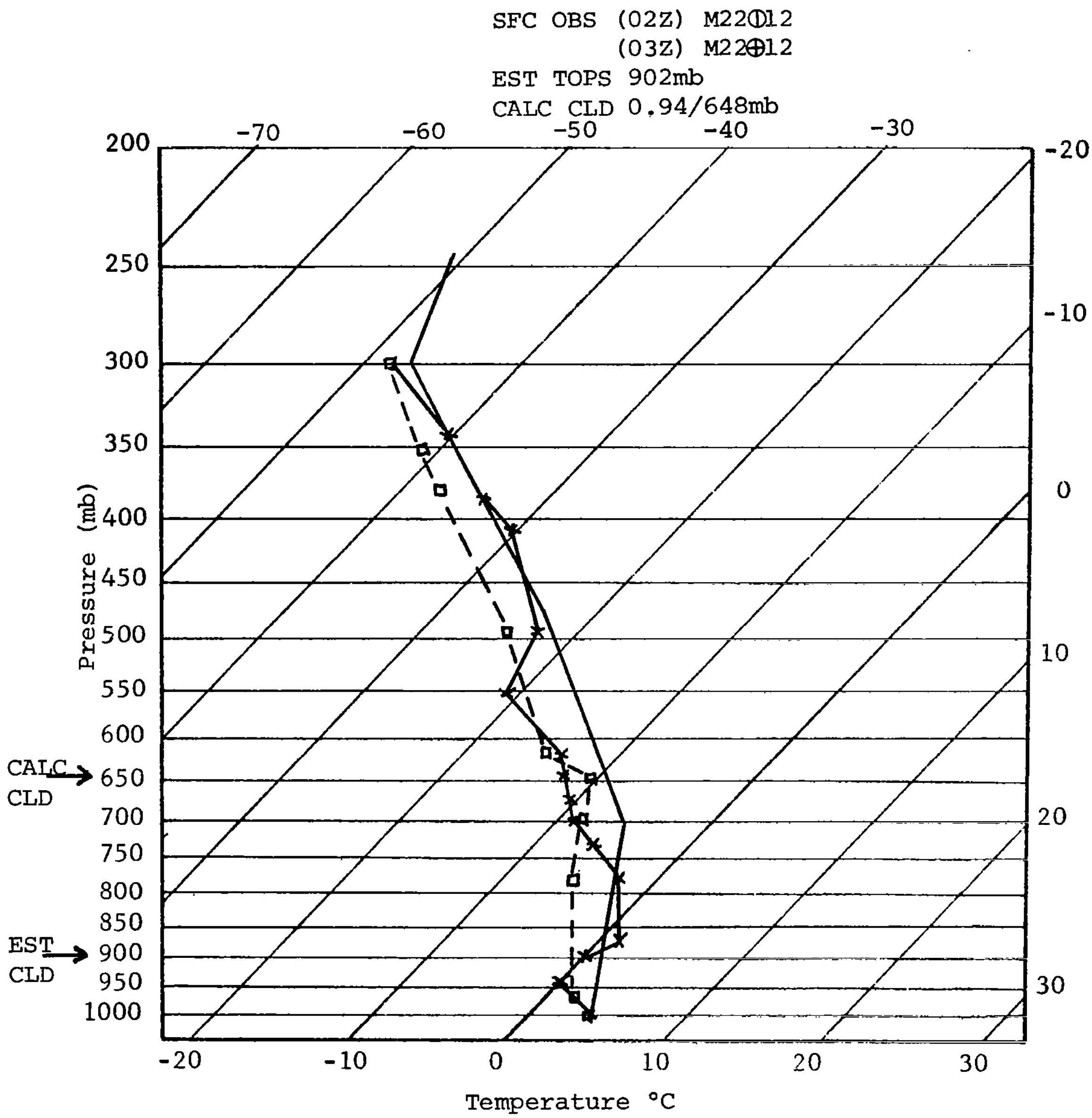


Fig. 24. Little Rock, Ark. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile ————

Retrieved (0233Z) — — ◻ — —

AVE III (0000Z) ——✕——

SFC OBS M11⊕10
EST TOPS 810mb
CALC CLD 0.97/599mb

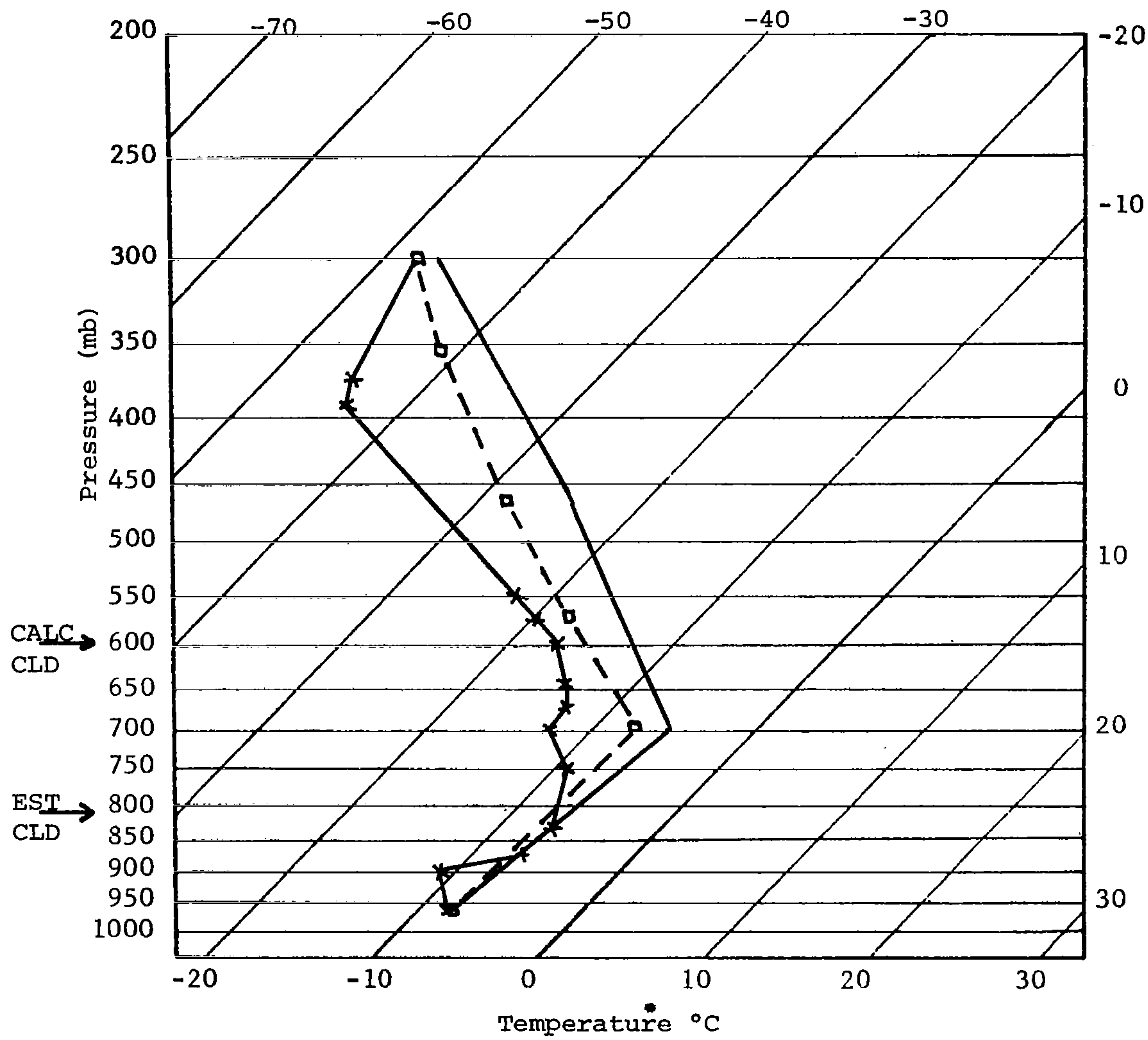


Fig. 25. Monette, Mo. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile ————
Retrieved (0233Z) — — ◻ — —
AVE III (0000Z) ——x——

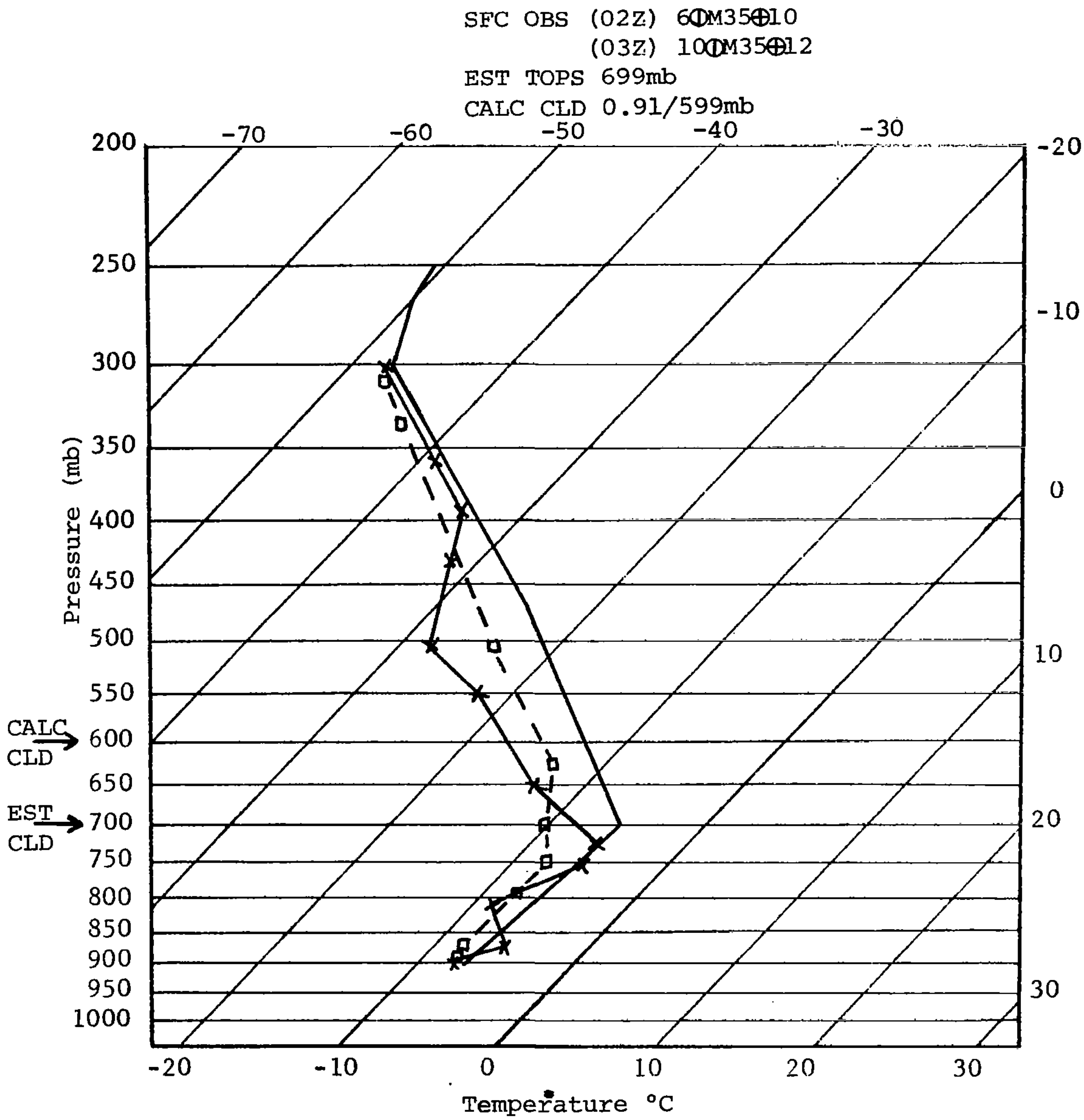


Fig. 26. Amarillo, Tx. 6 Feb 1975 retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile
Retrieved (0233Z)
AVE III (0000Z)

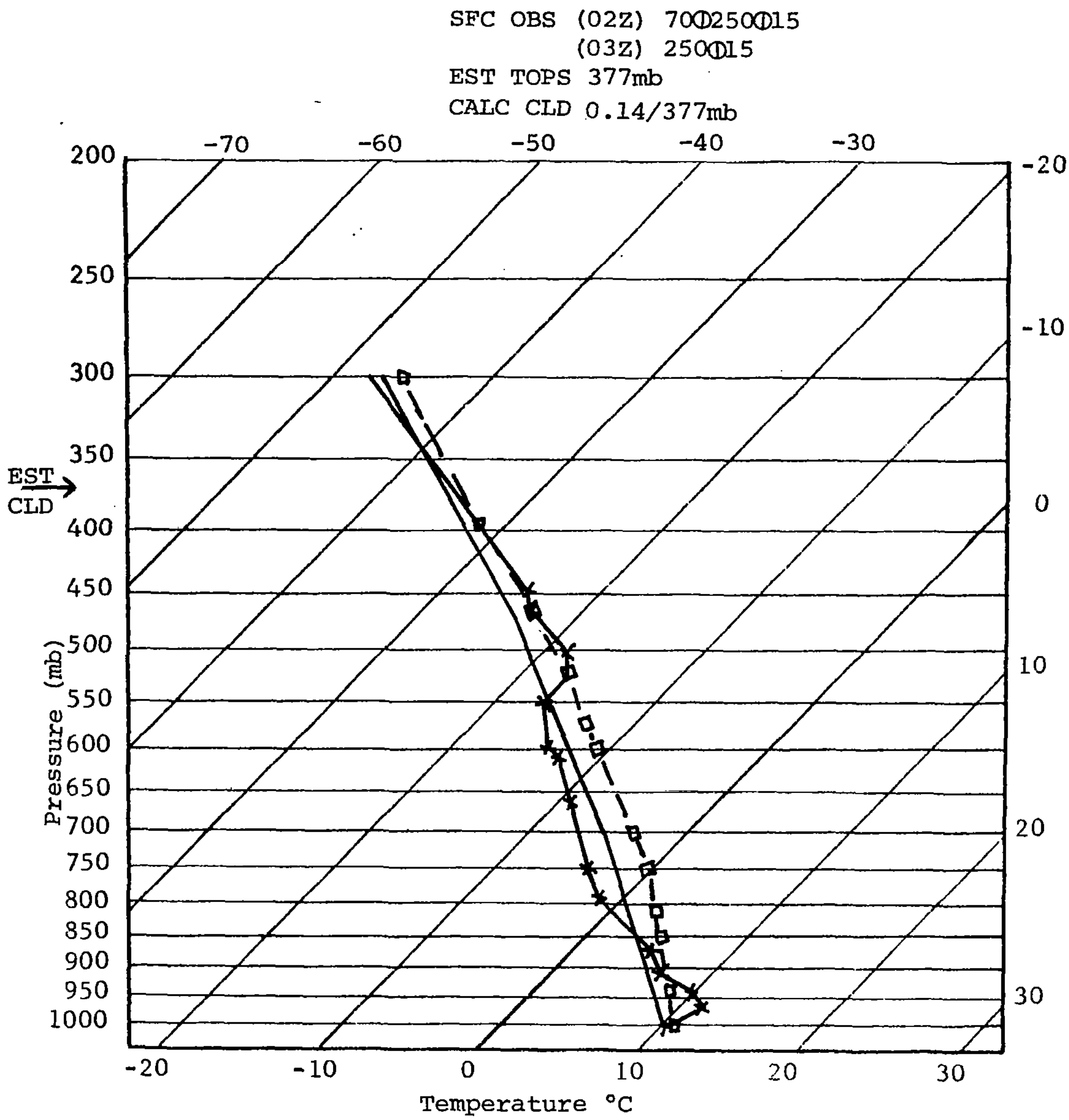


Fig. 27. Marshall Space Flight Center, Ala. retrieved temperature profile compared with the guessed profile and AVE III radiosonde data.

Guessed Profile
Retrieved (0233Z)
AVE III (0000Z)

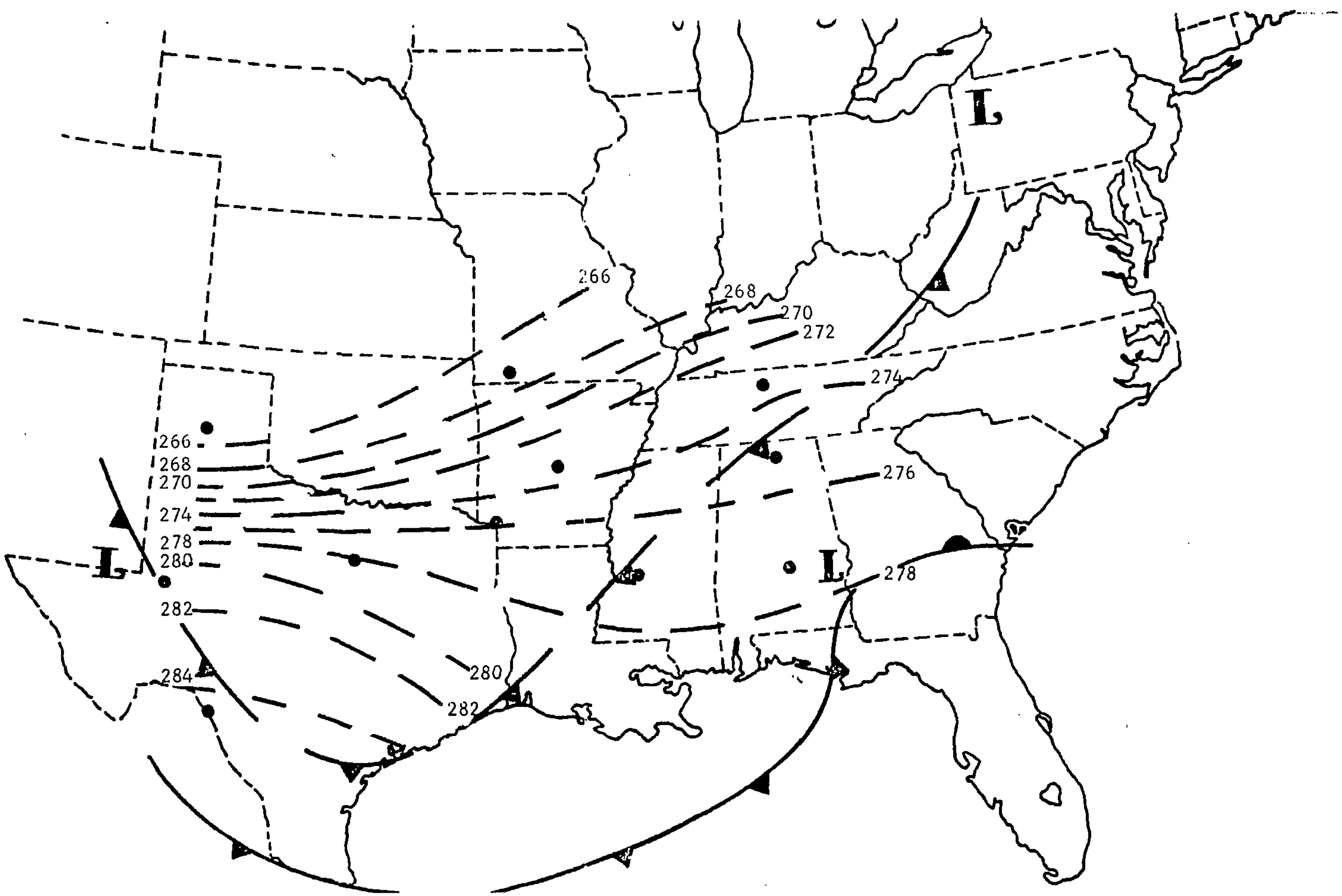


Fig. 28. AVE III 839 mb isotherms and surface frontal positions.

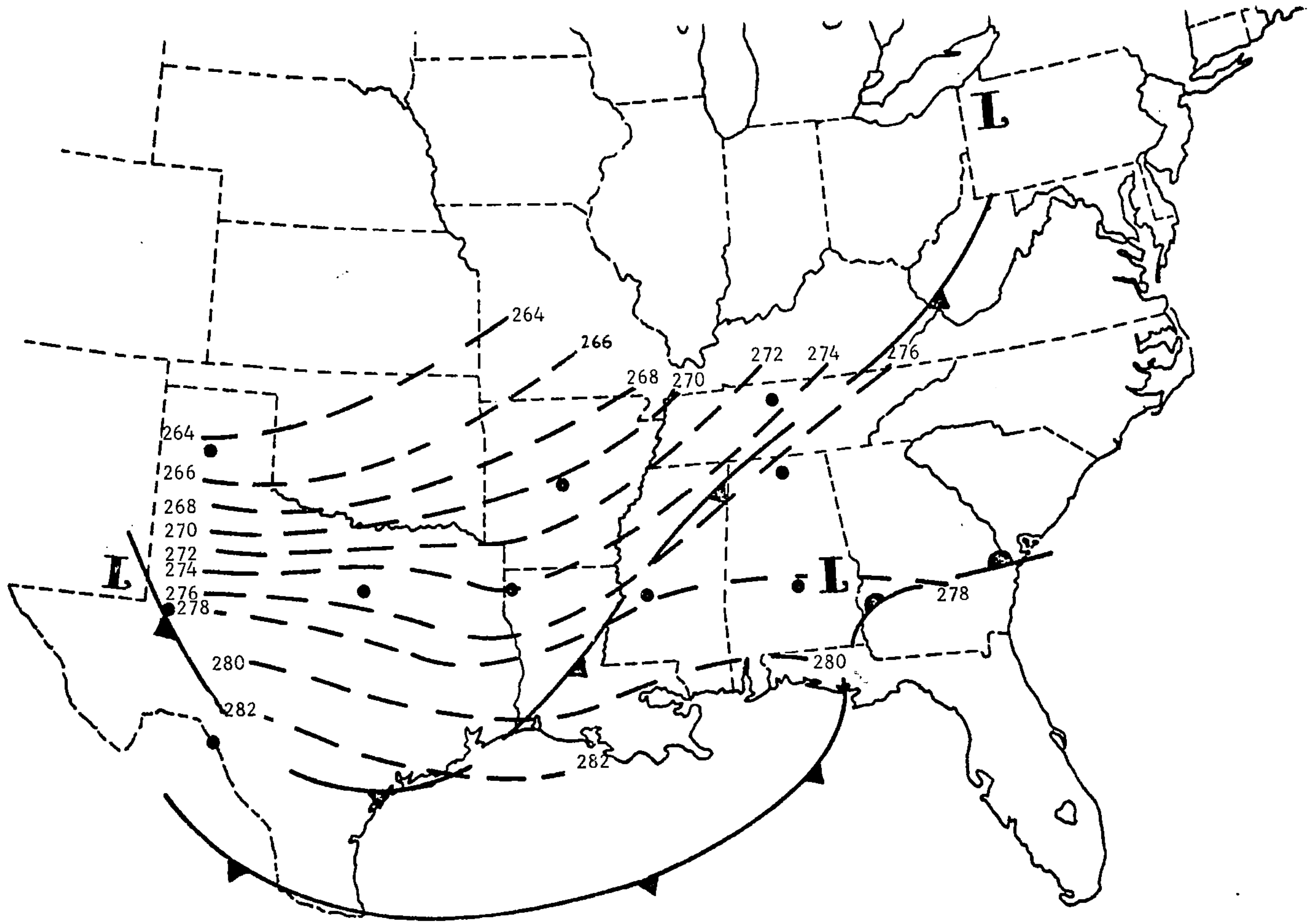


Fig. 29. Retrieved 839 mb isotherms and surface frontal positions.

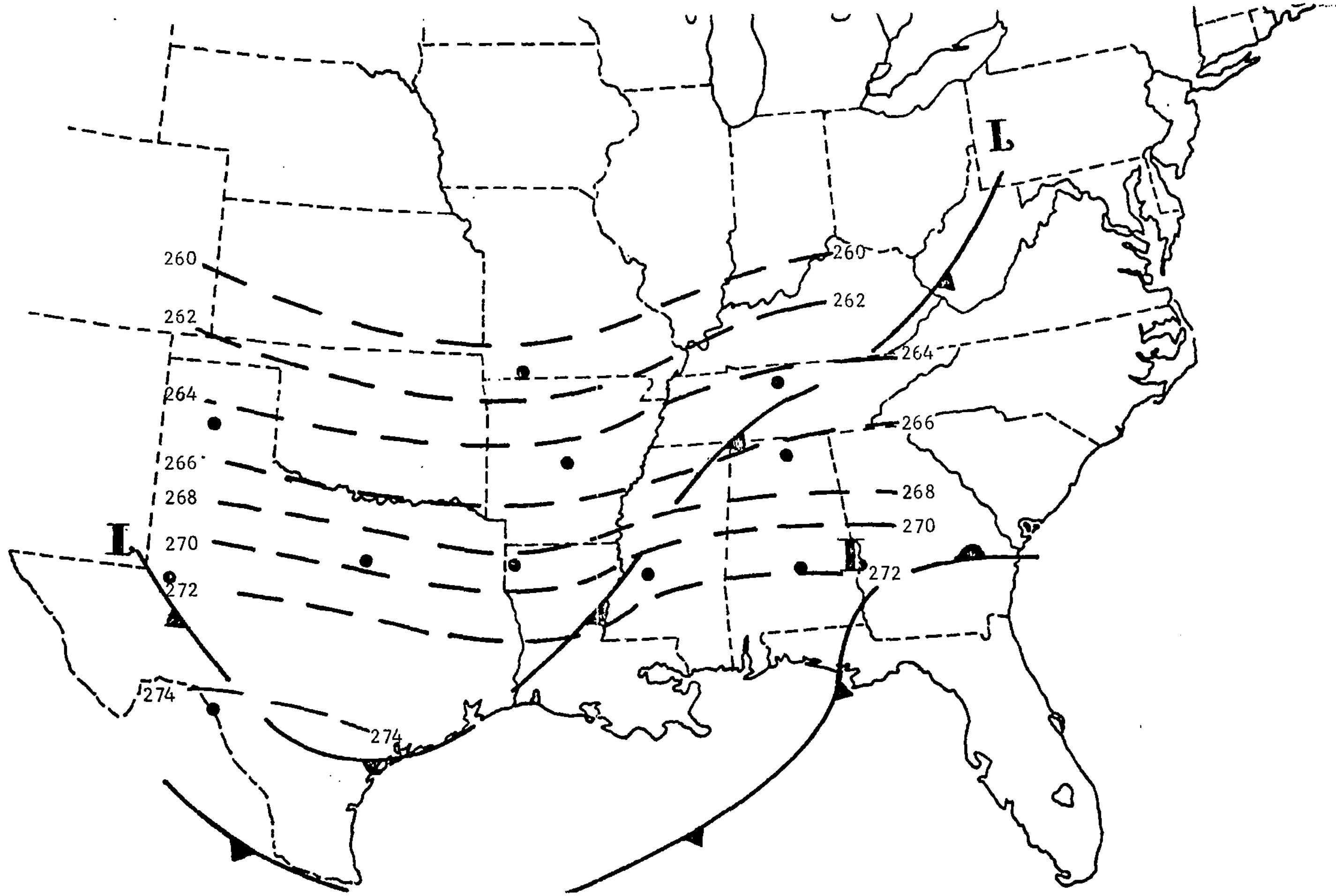


Fig. 30. AVE III 699 mb isotherms and surface frontal positions.

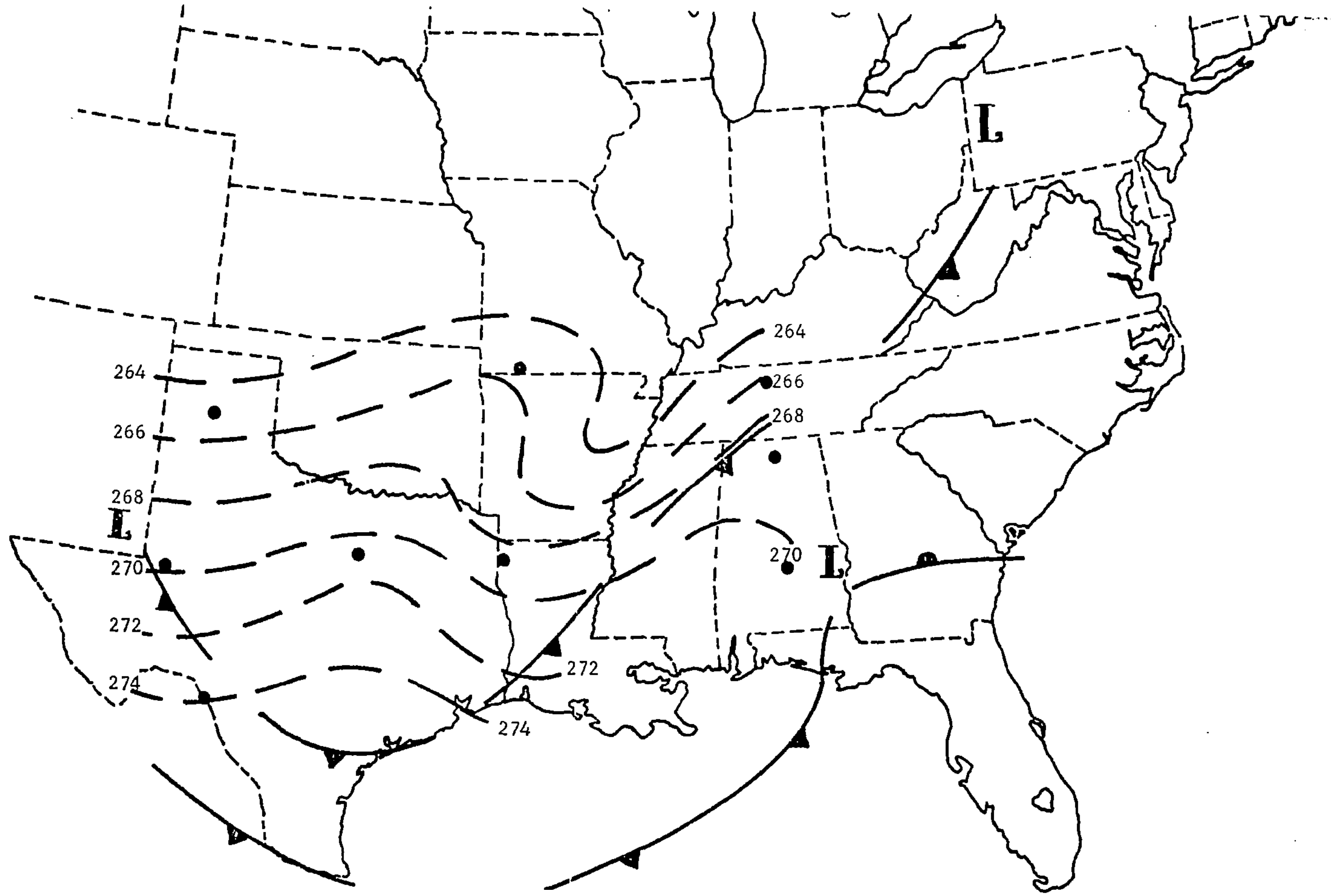


Fig. 31. Retrieved 699 mb isotherms and surface frontal positions.

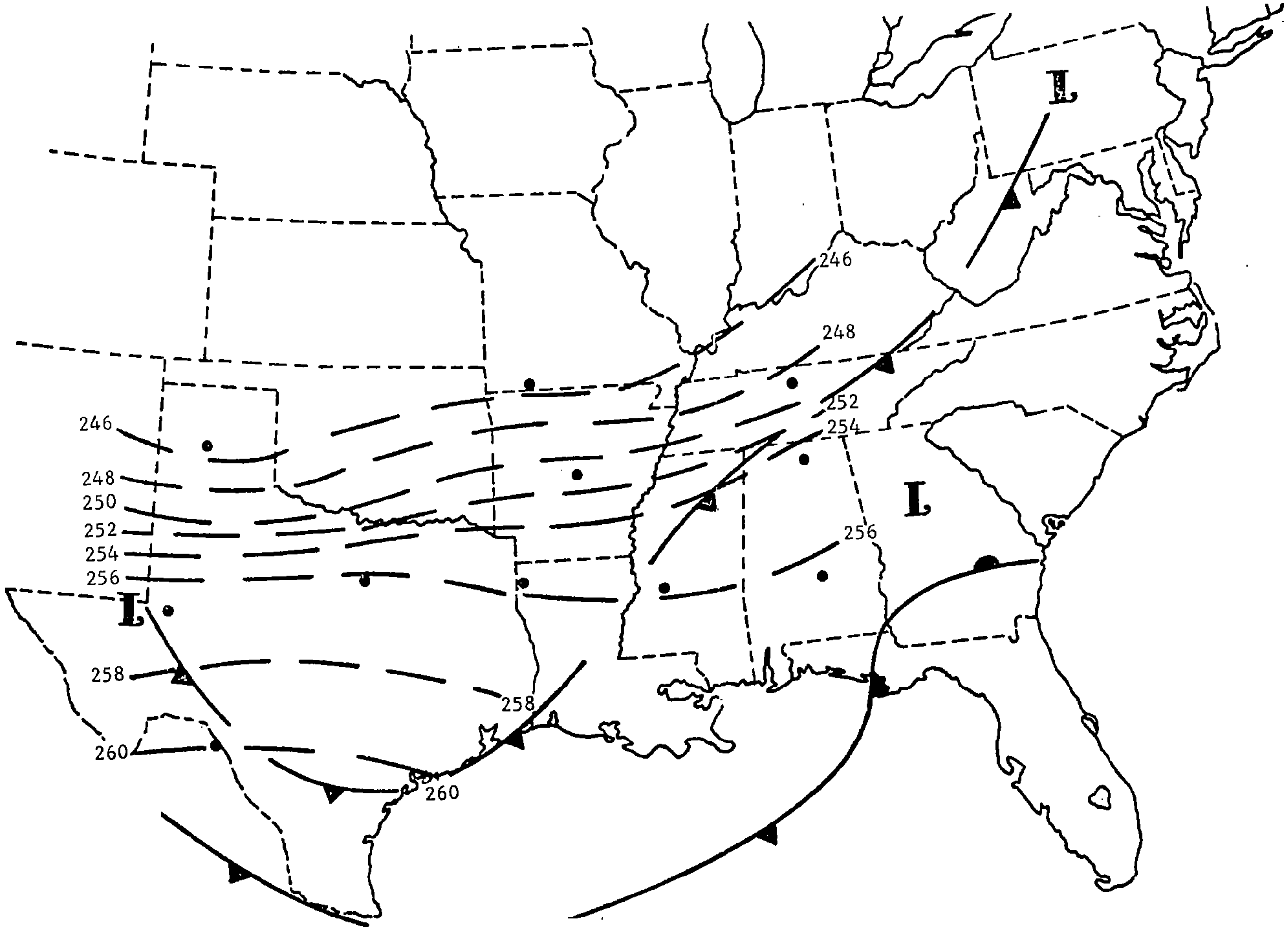


Fig. 32. AVE III 509 mb isotherms and surface frontal positions.

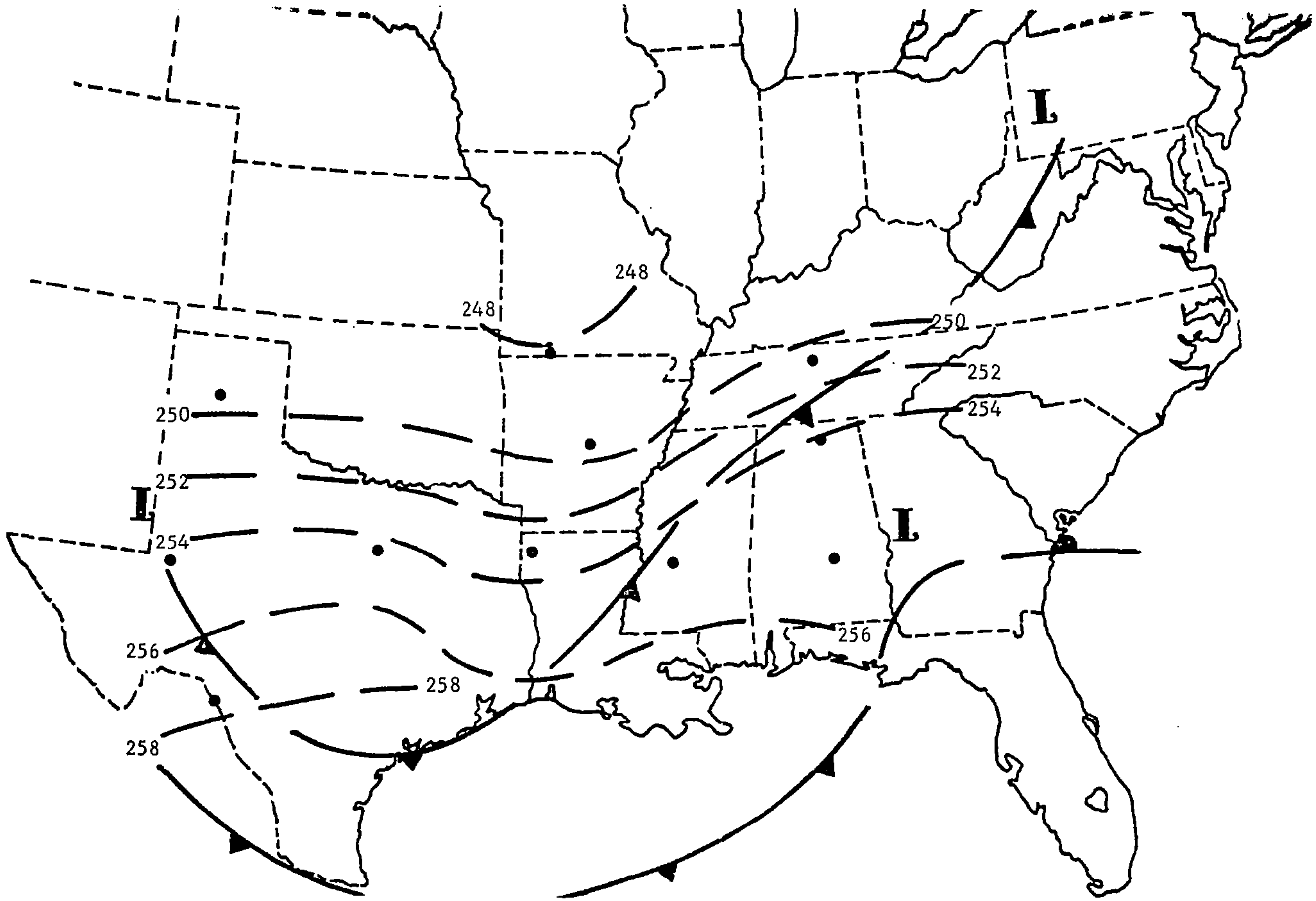
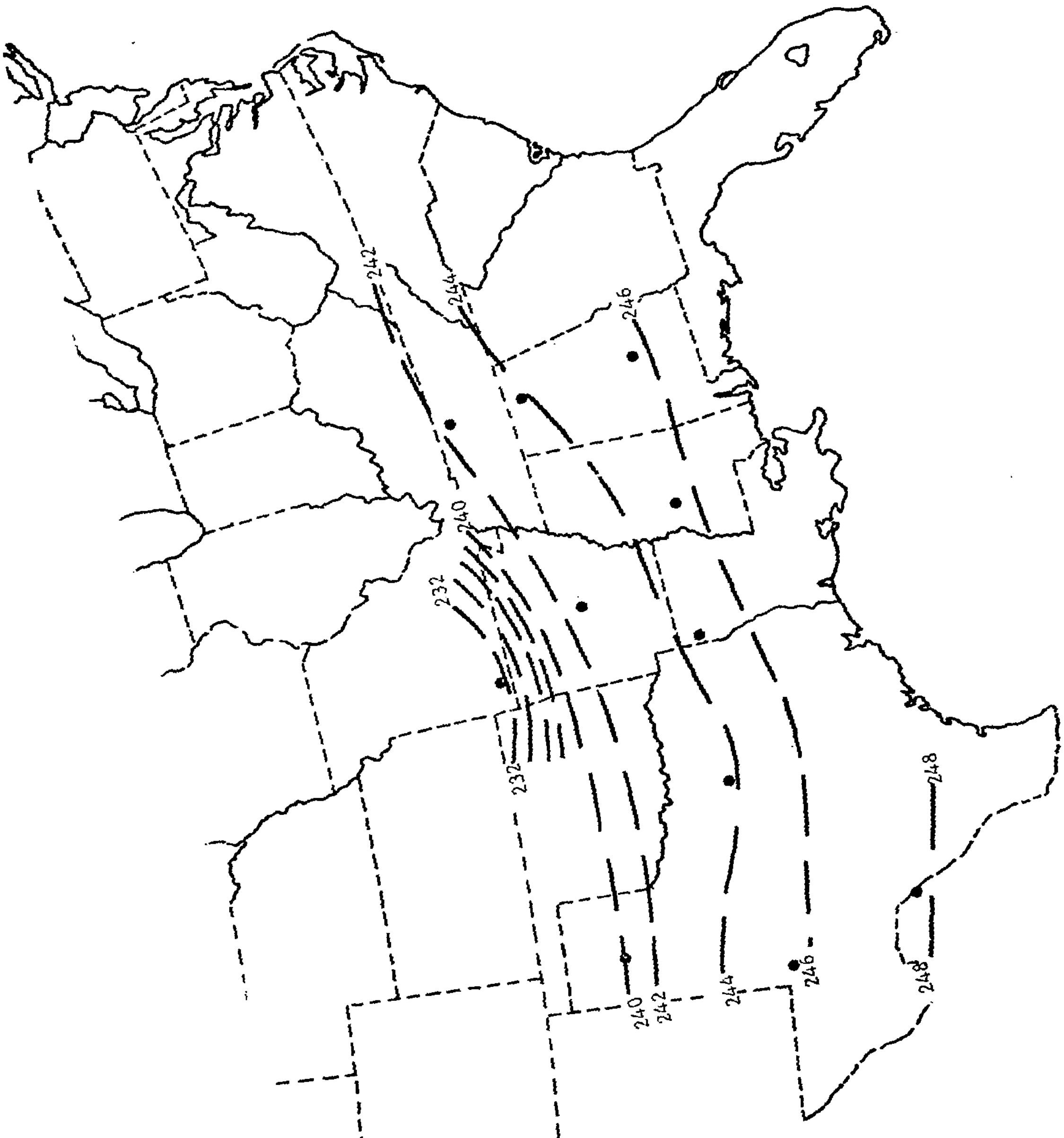


Fig. 33. Retrieved 509 mb isotherms and surface frontal positions.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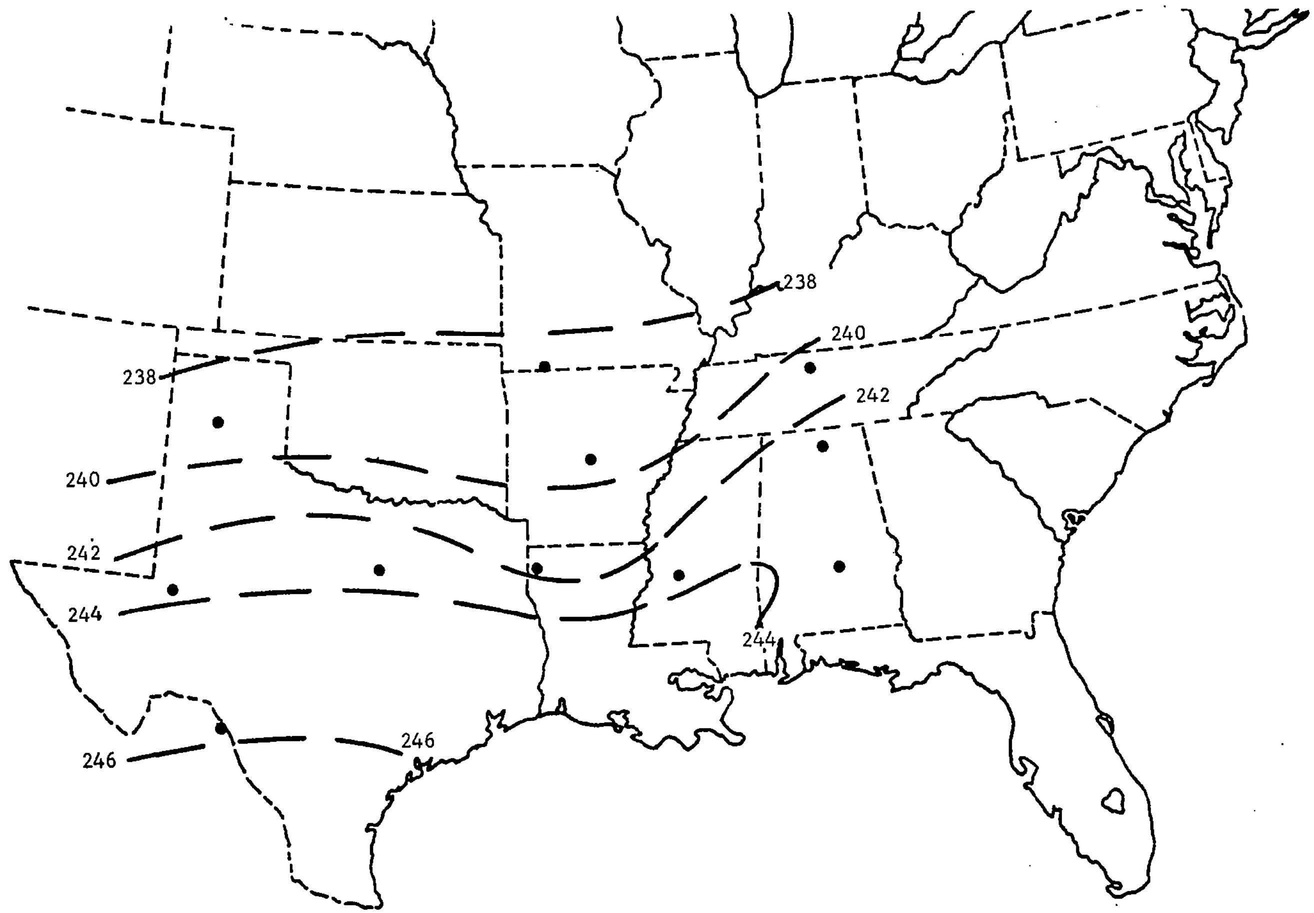

Fig. 35. Retrieved 412 mb isotherms.

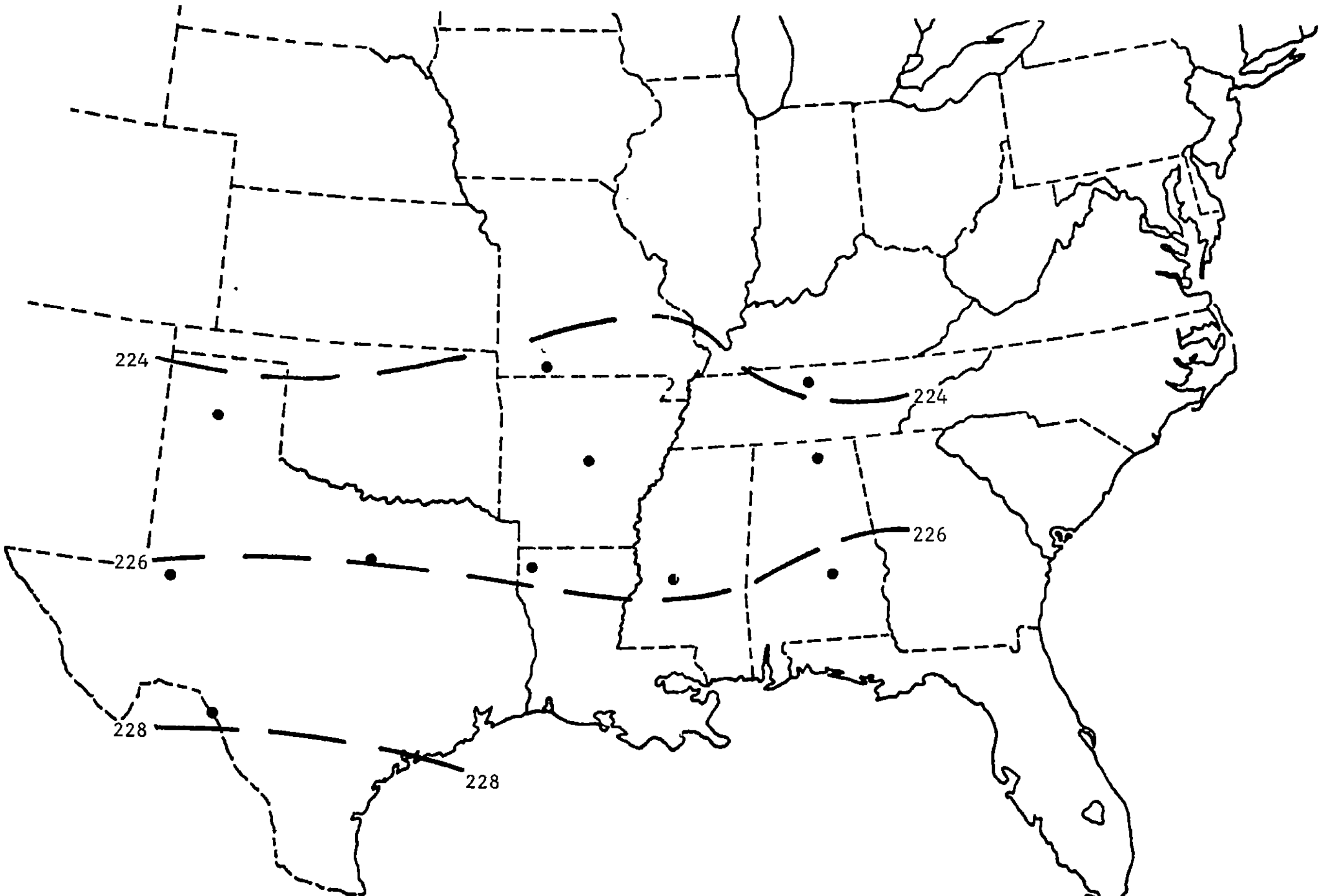

Fig. 36. AVE III 299 mb isotherms.

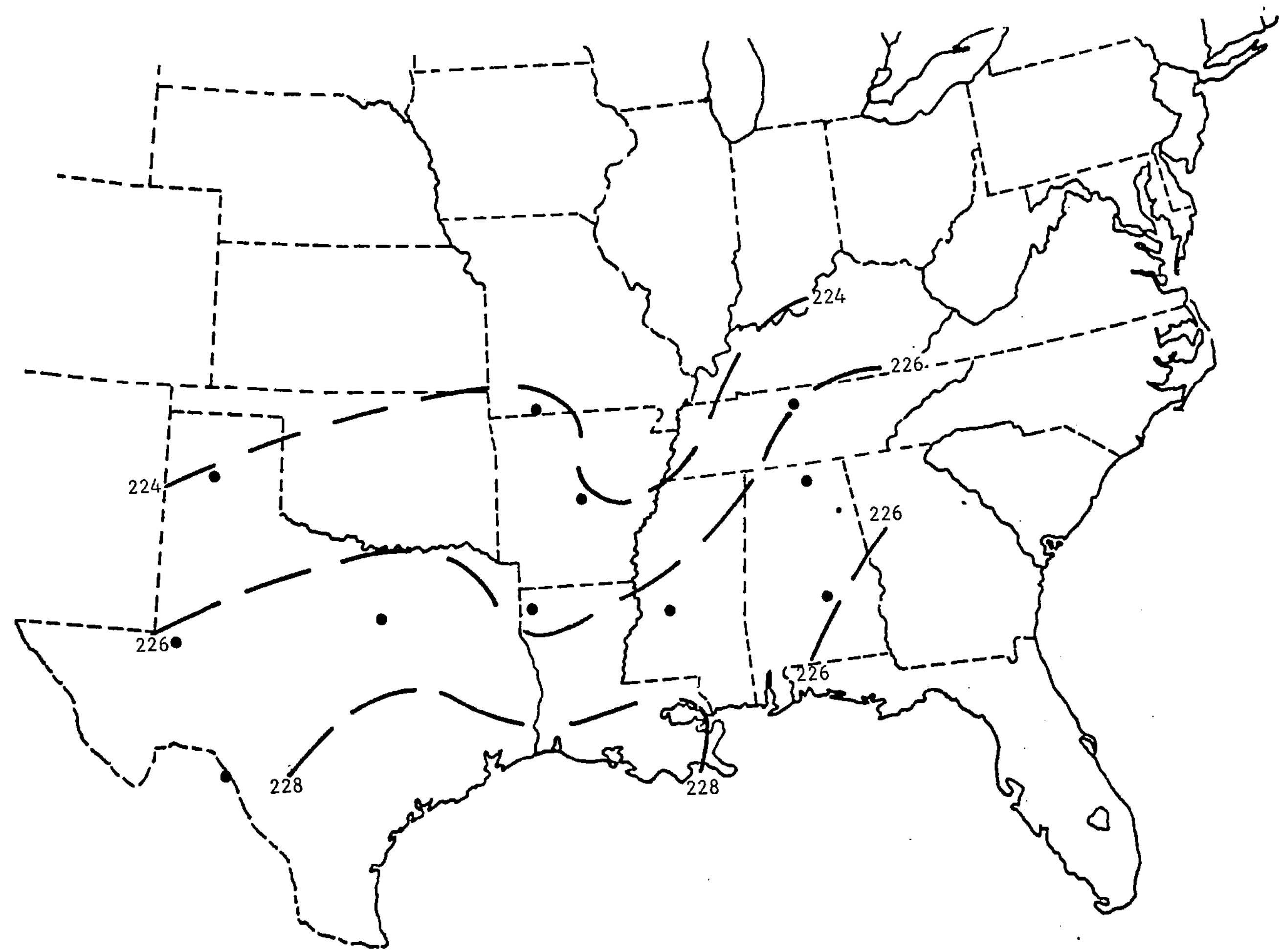

Fig. 37. Retrieved 299 mb isotherms.

of clear and cloudy results and the frequent reporting of results obtained exclusively from simulated data, and the comparison of results achieved with analyzed charts as well as radiosonde data from nearby stations. There are no reports of single FOV profiles achieved for exclusively cloud-contaminated cases in recent literature. The results achieved in this study are considered significant in that improvement over a guessed profile was achieved for a single FOV. The improvement shown from surface to cloud top is especially significant because it is in this region that profiles retrieved through use of previously-mentioned single FOV cloud models tend to deteriorate as cloud cover increases.

The results achieved for overcast cases require explanation as these cases cannot normally be handled through use of previously published cloud models.

For the model presented in the present study a low estimate of the top of a single layer overcast requires a search at successively higher levels until computed radiance from the estimated overcast top to the top of the atmosphere is less than measured radiance. The lowest level in the atmosphere where this result is possible must correspond to the level of greatest cloud cover possible of all the possible cloud amount and height combinations which will yield the correct radiances. With an accurate estimate of the top of the overcast, retrieval of a reasonably accurate profile from this point to the top of the atmosphere should be possible regardless of the retrieval method. Where thick clouds are present above the overcast, as was apparently the case at Stephenville, a poor estimate of the known overcast height will give a poor retrieval.

It appears that when cloud conditions were correctly specified, retrieved temperature profiles below the overcast layer also showed some improvement compared to the guessed profile even though the contribution of the atmosphere below cloud level to the measured radiance values was assumed to be nil. It is believed that the improvement occurred because the Planck functions upon which temperatures at all levels are based were determined through use of the ratio of measured to computed radiance [Ref. (40)], regardless of the contributions of specific levels to the total radiance values. For any one iteration, computed temperatures at all levels in the troposphere should increase (decrease) if all measured radiance values are greater (less) than computed radiance values for channels whose weighting functions peak in the troposphere. This result would be anticipated if guessed profile temperatures were less (more) at all levels than the true atmospheric temperature values. The initial guessed profiles used in the present study usually approximated this situation in that they were uniformly greater or uniformly less for a given location than true values at corresponding levels. As retrieved profiles tend to retain the shape of the guessed profile (i.e. adjustments to the guessed profile occur nearly uniformly with height), the relationship of true to calculated temperatures below an overcast tended to show improvement.

d. Applicability to mesometeorological research

It is believed that the procedures employed in the present research may have applicability to mesometeorological research. For any time at which a resonable guessed profile can be forecast and radiance data is available, temperature profiles can be retrieved and used to fill the data gaps between the synoptic hours. Also, excellent spatial resolution is achieved through use of a single FOV method, and it appears feasible to study patterns of temperature change over relatively small areas through use of retrieved temperature profiles. It appears that the best procedure to follow in retrieving profiles for mesometeorological research would be to use a guessed profile obtained through use of a known shelter temperature, a few other widely separated tropospheric temperature values obtained by averaging over an air mass or a section of an air mass, and a constant lapse rate between the chosen temperature values. Where fine detail of the true atmospheric profile is thought to be present, it would appear best in most cases to use a relatively smooth profile as a guess and then add the suspected detail to the retrieved profile.

e. Possible sources of error

No attempt was made to provide an accurate estimate of the temperature profile above the troposphere. To accomplish this would require that an estimate of the tropopause height be included in the guessed profile for each station. The problem is essentially the same as encountered when attempting to account for other inversions in the true profile. If structure such as the tropopause is introduced in the first guess, it must be present or serious errors are caused (Wolski, 1975). However, it is also to be expected that failure to introduce the tropopause, and consequently its correct contribution to the calculated radiance values, would lead to some error in the retrieved profiles at all levels.

Another possible source of error is the procedure for calculating the weighted average used in temperature computations.

An attempt was made to modify the retrieval computer program so that temperature at a given atmospheric level in the troposphere was computed through use of (40) but only at the frequency that provided maximum input to the measured radiance at that level (e.g. channel 4 was used between 500 and 300 mb [Ref. Fig. 1b]). Retrieved profiles were uniformly less accurate than for comparable retrievals using previously-discussed procedures and displayed significant computational instability.

The question of whether a special weighting function [Ref. (45)] is required in computing the weighted average used for temperature calculations was also investigated. Equation (43) was therefore used instead of (45) in temperature calculations (but not to calculate radiance values) and the resulting retrievals were compared with those obtained through use of (45). Significant differences were only noted for the overcast cases. At Monette, comparison with the AVE III profile revealed that errors in the retrieved temperatures using (43) were over 2K more than most comparable retrieved values using (45).

6. CONCLUSIONS

A method has been presented to retrieve single FOV tropospheric temperature profiles directly from cloud-contaminated radiance data through use of auxiliary data such as observed shelter temperatures and estimated cloud-top height. The iterative technique utilized was an extension of the work of Chahine (1970) as modified by Smith (1970) and Duncan (1974a). A model was formulated to calculate cloud parameters for use with the RTE through use of a one-dimensional search [or (51)] at an estimated cloud-top level where it has been shown to be possible to calculate an effective cloud amount that will satisfy the RTE and provide an approximation of measured radiance for the guessed profile.

The method was evaluated through use of simulated data and for a coincident data sample from the AVE III experiment and NOAA-4 satellite for an area dominated by an active cold front and covered by considerable cloudiness at various levels.

The major conclusions derived from the present research are:

(1) A single FOV method of retrieving temperature profiles from cloud-contaminated radiance data that improves the accuracy of guessed profiles has been developed. Through use of a single FOV method many temperature profiles can be retrieved for the same area in which a single average temperature profile can be retrieved through use of a multiple FOV technique. It is significant that in the method presented improvement in the guessed profile was noted under the cloud layer where retrievals using other single FOV techniques tend to deteriorate. The method requires estimates of surface temperature and average cloud-top height that are not grossly in error.

(2) It is possible to make an accurate estimate of the average tops of a thick overcast layer through use of the cloud model developed as an integral part of the single FOV retrieval method discussed above when there are no thick clouds present above the overcast layer and the guessed temperature profile is relatively accurate.

(3) For most overcast situations it should be possible to achieve accurate retrievals at least down to cloud-top level.

(4) Observed cloud parameters are not obtained with sufficient precision to use directly in the RTE. Significant errors in retrieved profiles resulted when this procedure was tested.

Though not conclusions, the following items should be noted:

(1) Through judicious choice of a guessed profile, it appears possible to improve guessed profiles independent of the cloud amount present. Profiles retrieved during the parametric study from guessed profiles that were uniformly colder or warmer at all levels than the true values exhibited this characteristic.

(2) Improvement in the guessed profile through utilization of the procedures discussed in this study should occur whenever a reasonable estimate of the true lapse rate is forecast. However, the absolute accuracy of the retrieved profile is also a function of the a priori knowledge of the state of the atmosphere possessed by the researcher.

(3) It appears that suspected detail should not be included in the guessed profile, but might profitably be added to the retrieved profile.

(4) Use of the techniques described above to provide useful data for mesometeorological research appears feasible for any time radiance data is available and a reasonable guessed profile can be forecast. A guessed profile utilizing a constant lapse rate between average air mass temperature values known with some accuracy (e.g. obtained from NMC analyses) should normally lead to an accurate retrieval. Also, through use of the many temperature profiles that can be retrieved over a relatively small horizontal area with a single FOV method, it should be possible to determine an accurate pattern of temperature change.

(5) The largest errors in retrieved profiles should be anticipated in the vicinity of moving frontal disturbances. Knowledge of the observed shelter temperature reduces this source of error.

(6) Due to the fact that the observed shelter temperature was used in the guessed profiles, fictitious features were introduced when the upper-level guess was based on data averaged across a frontal zone.

(7) No significant improvement in retrieved profiles from simulated data was obtained by refining estimates of cloud cover through use of successively retrieved profiles. For AVE III data deterioration in retrieved profiles was noted.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

The following specific suggestions are presented:

(1) Further testing of the method outlined in the present research for various cloud conditions and guessed profiles would provide useful information.

(2) The extent of degradation of the retrieved temperature profiles caused by errors in tropopause height should be determined.

(3) The method should be tested with data from the Nimbus series of satellites.

(4) The extent of improvement of retrieved profiles that could be obtained through use of microwave data should be determined.

(5) Retrieved profiles could be compared with profiles obtained using various cloud models and/or retrieval techniques.

(6) Smith et al. (1974) presented a method for determining effective cloud height which may be used with auxiliary data for a single FOV. It would be interesting to compare results obtained through use of these procedures with those obtained using the procedures discussed above for the same data set. This suggestion was made by Smith (1976)[5].

(7) Using available radiosonde data at surrounding points, temperature profiles should be estimated. The extent that these profiles can be improved through use of the method outlined in the present research should be examined.

(8) A temperature profile estimated from surrounding radiosonde data should be used to prepare a guessed profile for a specific point. If surface temperatures and cloud observations are available, then temperature profiles may be retrieved for a relatively small area; and the pattern of temperature change, the thermal wind and temperature gradients may be examined.

(9) In the cloud model outlined in the present research an estimated height level was rejected if calculated window channel radiances did not lie between radiances calculated for zero and overcast

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[5] Smith, W. L., 1976: Personal communication.

(1.0) cloud cover for the same level. These limits could be refined for many cases to provide better estimates of cloud height. For example, if 0.3 of cloud is observed, limits of 0.1 and 0.5 might be tested.

(10) As mentioned previously, no significant improvement in retrieved profiles was obtained by refining estimates of cloud cover through use of successively retrieved profiles. However, both for the simulated and AVE III data, this procedure was tested while allowing 50 iterations on a guessed profile once a cloud amount had been estimated. It may be that through use of 10 or less iterations computational instability could be avoided and better results achieved.

REFERENCES

Alexander, G. D., 1974: Comparison of three iterative methods for inverting the radiative transfer equation. Preprints Sixth Conference on Aerospace and Aeronautical Meteorology, El Paso, 231-238.

Allison, L. J., A. Arking, W. R. Bandeen, W. E. Shenk and R. Wexler, 1975: Meteorological satellite accomplishments. U.S. National Report 1971-1974, Reviews of Geophysics and Space Physics, 13, No. 3, 737-746.

Barcilon, V., 1975: On Chahine's relaxation method for the radiative transfer equation. J. Atmos. Sci., 32, 1626-1630.

Chahine, M. T., 1968: Determination of the temperature profile in an atmosphere from its outgoing radiance. J. Opt. Soc. Am., 58, 1634-1637.

_____, 1970: Inverse problems in radiative transfer: determination of atmospheric parameters. J. Atmos. Sci., 27, 960-967.

_____, 1974: Remote sounding of cloudy atmospheres. I. The single cloud layer. J. Atmos. Sci., 31, 233-243.

_____, 1975: An analytical transformation for remote sensing of clear-column atmospheric temperature profiles. J. Atmos. Sci., 32, 1946-1952.

Chow, M. C., 1975: A study of the effects of vertical resolution and measurement errors on an iteratively inverted temperature profile. J. Atmos. Sci., 32, 419-426.

Conrath, B. J. and Revah, I., 1972: A review of non-statistical techniques for the estimation of vertical atmospheric structure from remote infrared measurements. Proceedings of the NASA Workshop on the Mathematics of Profile Inversion. NASA TMX-62150, 36-49.

Duncan, L. D., 1974a: An iterative inversion of the radiative transfer equation for temperature profiles. ECOM Research and Development Technical Report ECOM-5534, U.S. Army Electronics Command, White Sands, New Mexico, 18 pp.

_____, 1974b: Approximations in evaluating the Radiative Transfer Equation. ECOM Research and Development Technical Report ECOM-5545, U.S. Army Electronics Command, White Sands, New Mexico, 10 pp.

Fritz, S., D. Q. Wark, H. E. Fleming, W. L. Smith, H. Jacobowitz, D. T. Hilleary and J. C. Alsihouse, 1972: Temperature sounding from satellites. NOAA Technical Report NESS 59, National Environmental Satellite Service, Washington, D. C., 49 pp.

Fuelberg, H. E. and R. E. Turner, 1975: Data for NASA's AVE III experiment: 25-mb sounding data and synoptic charts. NASA Technical Memorandum, NASA TM X-64938, George C. Marshall Space Flight Center, Alabama, 462 pp.

Jastrow, R. and M. Halem, 1973: Accuracy and coverage of temperature data derived from the IR radiometer on the NOAA-2 satellite. J. Atmos. Sci., 30, 958-964.

Joint Planning Staff (JPS) Global Atmospheric Research Programme (GARP), 1973: Indirect measurements of temperature and humidity from satellites (November 1972). Appendix III Garp Publication Series No. 11. The First Garp Global Experiment Objectives and Plans, World Meteorological Organization, 63-68.

Kaplan, L. D., 1959: Inference of atmospheric structure from remote radiation measurements. J. Opt. Soc. Amer., 10, 1004-1007.

McMillin, L. M., D. Q. Wark, J. M. Siomkajlo, P. G. Abel, A. Werbowetzki, L. A. Lauritson, J. A. Pritchard, D. S. Crosby, H. M. Woolf, R. C. Luebbe, M. P. Weinreb, H. E. Fleming, F. E. Bittner and C. M. Hayden, 1973: Satellite infrared soundings from NOAA spacecraft. NOAA Technical Report, NESS 65, National Environmental Satellite Service, Washington, D. C., 112 pp.

Rodgers, C. D., 1970: Remote sounding of the atmospheric temperature profile in the presence of cloud. Quart. J. Roy. Meteor. Soc., 96, 654-666.

Smith, W. L., 1968: An improved method for calculating tropospheric temperature and moisture profiles from satellite radiometer measurements. Mon. Wea. Rev., 96, 387-396.

______, 1970: Iterative solution of the radiative transfer equation for the temperature and absorbing gas profile of the atmosphere. Appl. Opt., 98, 1993-1999.

______, H. M. Woolf and W. C. Jacob, 1970: A regression method for obtaining real-time temperature and geopotential height profiles from satellite spectrometer measurements and its application to Nimbus III SIRS observations. Mon. Wea. Rev., 98, 582-603.

______, H. M. Woolf and H. R. Fleming, 1972: Retrieval of atmospheric temperature profiles from satellite measurements for dynamical forecasting. J. Appl. Meteor., 11, 113-122.

_____, H. M. Woolf, P. G. Abel, C. M. Hayden, M. Chalfant and N. Grody, 1974: Nimbus-5 sounder data processing system. Part I: Measurement characteristics and data reduction procedures. NOAA Technical Memorandum NESS 57, National Environmental Satellite Service, Washington, D. C., 99 pp.

_____, P. G. Abel, H. M. Woolf, A. W. McCulloch and B. J. Johnson, 1975: The High Resolution Infrared Radiation Sounder (HIRS) experiment. _The Nimbus 6 User's Guide_, NASA, Goddard Space Flight Center, Greenbelt, Maryland, 37-58.

Staelin, D. H., 1974: Review of Nimbus-5 microwave spectrometer results. _Preprints Sixth Conference on Aerospace and Aeronautical Meteorology_, El Paso, 216-221.

_____, A. H. Barett, P. W. Rosenkranz, F. T. Barath, E. J. Johnson, J. W. Waters, A. Wouters and W. B. Lenoir, 1975: The Scanning Microwave Spectrometer (SCAMS) experiment. _The Nimbus 6 User's Guide_, NASA, Goddard Space Flight Center, Greenbelt, Maryland, 59-86.

Wark, D. Q., and H. E. Fleming, 1966: Indirect measurements of atmospheric temperature profiles from satellites. I. Introduction. _Mon. Wea. Rev._, _94_, 351-362.

Waters, J. W., K. F. Kunzi, R. L. Pettyjohn, R.K.L. Poon and D. H. Staelin, 1975: Remote sensing of atmospheric temperature profiles with the Nimbus 5 microwave spectrometer. _J. Atmos. Sci._, _32_, 1953-1969.

Werbowetzki, A., 1975: Indirect sounding of the atmosphere from NOAA spacecraft--regression after categorization method and results. _Preprints Fourth Conference on Probability and Statistics in Atmospheric Sciences_, Tallahassee, 165-170.

Wolski, R. J., 1975: Estimation of the tropopause height and its importance to the inference of vertical temperature profiles from satellite radiance measurements. Technical Note BN 814, Institute for Fluid Dynamics and Applied Mathematics, University of Maryland, College Park, Md., 64 pp.

Yamamoto, G., 1961: Numerical method for estimating the stratospheric temperature distribution from satellite measurements in the CO_2 band. _J. Meteor._, _18_, 581-588.

NASA-Langley, 1976