CLOUD TOP PRESSURES AND AMOUNTS USING HIRS CO_2 CHANNEL RADIANCES

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1. INTRODUCTION

The determination of cloud heights and amounts is important for cloud climatologics and atmospheric circulation studies using cloud tracers. Several methods for determining cloud heights using satellite data are currently available. (a) The IR window method compares the IR window channel brightness temperature with an in situ vertical temperature profile to infer the height of the cloud. Assuming the cloud is opaque and fills the satellite field of view, this method provides good heights for dense stratoforms of cloud (see Figure 1). However, it is inaccurate for semi-transparent cirrus clouds and small element cumulus clouds. (b) The bi-spectral method improves the IR window channel estimate of a cloud top height by allowing for fractional cloud cover and by determining the cloud emissivity from visible reflectance data. Using a multiple scattering model, the visible brightness of the cloud is used to calculate the optical thickness, from which the infrared emissivity of the cloud can be computed (Mosher, 1976; Reynolds and Vonder Haar, 1977). Nonetheless, the bi-spectral method is till inaccurate for semi-transparent cirrus clouds. (c) The CO_2 method combines IR window channel data with CO_2 absorption channel data to specify a cloud height. As derived from the radiative transfer equation, cloud pressure is determined from the ratio of the deviations in cloud produced radiances and the corresponding clear air values for two or more spectral channels (Smith and Platt, 1978). This multispectral CO_2 absorption method does not suffer from any of the previous assumptions and thus, in principle, works on all cloud types. In addition, cloud amounts (emissivities) are a by-product of the calculation.

The CO_2 technique for deriving cloud top altitudes using radiances observed by the VISSR Atmospheric Sounder (VAS) was developed by Menzel (1983). It has also been adapted to the polar orbiting High-resolution Infrared Radiometer Sounder (HIRS). The technique takes advantage of infrared channels with partial CO_2 absorption where the different channels are sensitive to different levels in the atmosphere. Thus, clouds appear on each channel in proportion to their level in the atmosphere. Low clouds will not appear at all on the high level channels, while high clouds appear on all channels. By modelling the upwelling infrared radiation from the earth atmosphere system in several VAS or HIRS channels simultaneously, it is possible to infer the cloud top height independent of radiative transmissivity of the cloud. This gives the CO_2 technique the ability to distinguish thin cirrus clouds that would normally be missed by other techniques due to the transmission of terrestrial radiation through the cirrus. The frequency of cirrus clouds usually has been underestimated in cloud population studies. The IR window and bi-spectral methods of analyzing cloud cover often mistake cirrus clouds for lower level clouds or completely miss them, because their infrared brightness temperatures are warmer than the temperature associated with their true altitudes. Thin cirrus are especially hard to identify on visible satellite images because they reflect little solar radiation and appear as dark or broken cloud fields. With the multi-spectral infrared sensor on the GOES-VAS or the NOAA-HIRS the identification of most cirrus is now possible.

The CO_2 technique has been installed on the Man-computer Interactive Data Access System (McIDAS) at the University of Wisconsin-Madison. It has been run operationally using the GOES-VAS imagery starting in October 1985. Statistics on cloud cover and especially cirrus cloud cover are being gathered for the continental United States and its bordering oceans. Since August 1986, cloud parameters are being calculated using the NOAA-HIRS radiances also, with a software module that has been appended to the International TOVS Processing Package (version 3). This paper describes the technique and presents the cloud statistics for 4-5 March 1982 of ALPEX using the HIRS data. The ALPEX has been used as the test bed for TOVS retrieval algorithms by the International TOVS Working Group.

2. CO_2 METHOD USING HIRS

The HIRS radiometer detects infrared radiation in eighteen spectral bands that lie between 3.9 and 15 microns at 25 to 40 km resolution (depending on viewing angle) in addition to visible reflections at the same resolution. The 15 micron CO_2 band channels provide a good sensitivity to the temperature of relatively cold regions of the atmosphere. A demonstration of the vertical resolution of the four relevant CO_2 channels is given by the temperature profile weighting function shown in Figure 2a. Each curve in the figure shows the sensitivity of the radiance observe in the spectral interval of the indicated channel to local variations in atmospheric temperature. Figure 2b shows the atmospheric transmission of radiance to space as a function of the emitting level. As may be seen, only clouds above the 400 mb level will have strong contributions to the radiance to space observed by the 14.2 micron band (HIRS channel 4), while the 14.0 micron band (HIRS channel 5) senses down to 600 mb the 13.7 micron band (HIRS channel 6) senses to 800 mb, and the 13.4 micron band (HIRS channel 7) senses down near the surface of the earth.

To assign a cloud top pressure to a given cloud element, the ratio of the deviations in cloud produced radiances, $I(\nu)$, and the corresponding clear air radiances, $I_{cl}(\nu)$, for two spectral channels of frequency ν_1 and ν_2 viewing the same field-of-view is written as

$$\frac{I(\nu_1) - I_{cl}(\nu_1)}{I(\nu_2) - I_{cl}(\nu_2)} = \frac{\varepsilon_1 \int_{P_s}^{P_c} \tau(\nu_1, p) \frac{dB[\nu_1, T(p)]}{dp} dp}{\varepsilon_2 \int_{P_s}^{P_c} \tau(\nu_2, p) \frac{dB[\nu_2, T(p)]}{dp} dp} . \tag{1}$$

In this equation ε is the cloud emittance, P_s the surface pressure, P_c the cloud pressure, $\tau(\nu, p)$ the fractional transmittance of radiation of frequency ν emitted from the atmospheric pressure level (p) arriving at the top of the atmosphere (p = 0), and $B[\nu, T(p)]$ is the Planck radiance of frequency ν for temperature T(p). If the frequencies are close enough together, then $\varepsilon_1 \cong \varepsilon_2$, and one has an expression by which the pressure of the cloud top within the field-of-view (FOV) can be specified. The observed cloud attenuation on the left side of equation (1) is determined from the HIRS observed radiances and clear air radiances provided from spatial analyses of HIRS clear-sky radiance observations or calculated from an in situ temperature and moisture profile. The calculated cloud attenuation on the right side of equation (1) is calculated from a temperature profile and the profiles of atmospheric transmittance for the spectral channels as a function of P_c, the cloud top pressure (discrete values at ∿50 mb intervals spanning 1000 to 100 mb are used). The optimum cloud top pressure is determined when the absolute difference $|\text{right}(\nu_1, \nu_2) - \text{left}(\nu_1, \nu_2, P_c)|$ is a minimum.

Once a cloud height has been determined, an effective cloud amount can be evaluated from the infrared window channel data using the relation

$$N\varepsilon = \frac{I(w) - I_{cl}(w)}{B[w, T(P_c)] - I_{cl}(w)} \tag{2}$$

Here N is the fractional cloud cover within the FOV, $N\varepsilon$ is the effective cloud amount, w represents the window channel frequency, and $B[w, T(p_c)]$ is the opaque cloud radiance.

Using the ratios of radiances of the four CO_2 spectral channels, four separate cloud top pressures can be determined (14.2/14.0, 14.0/13.7, 13.7/13.4 and 14.0/13.4). If $(I - I_{cl})$ is within the noise response of the instrument (∿ 1 $mW/m^2/sr^1/cm^{-1}$) the resulting P_c is rejected. Using the infrared window and the four cloud top pressures, four effective cloud amount determinations are made. As described by Menzel (1983), the most representative cloud height and amount are those that best satisfy the radiative transfer equation for the four CO_2 channels.

If no ratio of radiances can be reliably calculated because $(I - I_{cl})$ is within the instrument noise level, then a cloud top pressure is calculated directly from the HIRS observed 11.2 micron infrared-window channel brightness temperature and the temperature profile via the infrared window method. In this way all clouds are assigned a cloud top pressure either by CO_2 or infrared-window calculations.

The CO_2 technique is independent of the fractional cloud cover; heights and effective cloud amounts can be determined for partially cloudy FOVs. However, the CO_2 technique sees only the highest cloud and cannot resolve multi-layer clouds. Because the HIRS FOV resolution is very coarse, small element clouds are difficult to detect. Also, because the weighting functions for the HIRS channels are broad, there is an inherent lack of vertical resolution in the measurements. Nonetheless, reliable cloud parameters can be calculated with appropriate application of the technique.

3. VERIFICATION OF METHOD

Quantitative comparisons of CO_2 (or infrared window where necessary for low clouds) cloud top pressures have been made with determinations from radiosonde and radar echoes (Menzel, 1978). Radiosonde temperature and dew point temperature profiles can be used to infer cloud top pressures by noting that the dew point temperature profile becomes much drier as it emerges from the cloud. For about twenty different cloud forms, the HIRS CO_2 cloud top pressures were found to be within 50 millibars of the radar and radiosonde determinations. Comparable results have been achieved for the VAS CO_2 determinations (Menzel, 1983). These comparisons did not include cirrus clouds, as neither radiosonde or radar could provide reliable determinations.

A relative confirmation of the CO_2 cloud top pressure within cirrus clouds can be seen in Fig. 3. This figure shows the CO_2 and bi-spectral cloud top pressures plotted versus the position along the cirrus anvil emanating from a dense cumulus center. Moving from the dense cumulus clouds towards the thin cirrus, the CO_2 method maintains the height of the anvil while the bi-spectral method often underestimates the height. In the bi-spectral method, the IR window is sensing radiation from within and below the thin cirrus and therefore the brightness temperature is warmer than the cloud temperature causing the height miscalculation. The CO_2 method is independent of the fractional cloud cover and cloud emissivity, and thus provides a relatively consistent determination of the cirrus anvil height. Validation of the cirrus heights is currently being attempted with lidar intercomparisons.

VAS and HIRS CO_2 cloud parameters have been determined on several days from radiance observation within 30 minutes of one another. The intercomparison showed results within the estimated accuracy of the cloud top pressure, 50 mb, and the cloud amount, 20%. These good VAS and HIRS comparisons are very reassuring; two different radiometers in different earth orbits are yielding comparable determinations using the CO_2 method.

4. ALPEX RESULTS

THE CO_2 technique has been applied to the HIRS data from the NOAA-7 overpasses of the ALPEX region on 4-5 March 1982. The processing was accomplished as follows. For every box of 3 by 3 FOV, the clearest FOV was selected and a temperature profile was calculated from the HIRS radiance using the simultaneous physical retrieval (Smith et al., 1985). The ALPEX surface observations were used to adjust the profile; topography was also incorporated. Transmittances were determined from line-by-line calculations with the spectral response functions for the appropriate HIRS channels. HIRS clear FOV radiances were then calculated from the temperature profile for the four CO_2 channels and the infrared window. The cloud top pressure and amount were determined for the center and the four corner FOVs of each box resulting in roughly 70 km spacing.

Figure 4a shows the cloud top pressures (in centibars) over the ALPEX region from 0200 GMT March 4, 1982 superimposed on the infrared window image (only a sampling of the 356 determinations are shown).

Clear areas are designated at 100 centibars, regardless of topography. Sometimes the infrared window method mistates the surface pressure in clear areas. This occurs when there is a low level inversion and the surface temperature is identical to the temperature at 700 or 800 mb. The 700 mb reports in southern Italy and the 780 mb reports in Greece and Bulgaria are examples of this. A schema using the two infrared windows to screen low level inversions is being implemented (four micron must be somewhat colder than 11 micron for nocturnal inversions).

Figure 4b shows the corresponding cloud amounts. Cloud amounts greater than 100% are computationally possible when the opaque cloud radiance is calculated to be less than the observed radiance in the window channel; values within 5% of total cloud should be interpreted as total cloud.

Table 1 shows the statistics of the cloud observations during this overpass for ten intervals of cloud top pressure and for five intervals of effective cloud amount. The left column gives the frequency of cloud reports by pressure regardless of the cloud amount/emissivity. The next five columns show the distribution of cloud reports for five intervals of cloud amount or emissivity. The low cloud amount/emissivities (center columns) indicate thin or cirrus clouds which were partially transmitting infrared radiation, while the right column summarizes the reports of opaque clouds that did not transmit upwelling radiation. The sum of the five right columns should account for all of the cloud reports (100%). The most immediate finding is that 32% (summing columns 2 thru 5 less the clear sky percentage) of the area was covered with thin or cirrus clouds (emissivities less than .8); approximately 48% was covered with thick opaque clouds and truly clear sky conditions occurred about 20% of the time. The cloud top pressures were distributed with 8% above 400 mb, 24% between 400 and 600 mb, 30% between 600 and 800 mb, 18% between 800 and 1000 mb, and 20% at the surface (clear sky conditions). The thin clouds were mostly above 600 mb.

Table 2 shows the combined statistics for the four overpasses at 0200 and 0300 GMT on 4 and 5 March. Again, transmissive thin clouds are found to occur at roughly one-third of all observations.

5. CONCLUSION

The CO_2 method for calculating cloud top pressures and effective cloud amounts is producing good results with HIRS radiances. Cloud parameter determinations have been found to be reliable in all cloud types, including thin cirrus clouds where other techniques have been inconsistent. Cloud parameter determinations from the VAS and HIRS have been intercompared and have been found to agree within the accuracy of the CO_2 method. Observations from HIRS during 4-5 March 1982 of ALPEX reveal that roughly 30% of Europe was covered with thin clouds (radiative attenuation less than 80%), 50% was covered with thick opaque clouds, and 20% had clear sky conditions.

The most obvious finding in this work is the high occurrence of transparent or thin cirrus clouds. Since cirrus clouds have a large impact on the radiative balance of the earth, the ISCCP global cloud climatology studies must include reliable cirrus detection schemas.

6. REFERENCES

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TABLE 1. Cloud statistics for 356 observations over the European region (shown in Figure 4) on 4 March 1982 at 0200 GMT.

Level	All Cloud OBS	Cloud Amount 0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
100 to 199 mb	0 %	0 %	0 %	0 %	0 %	0 %
200 to 299 mb	3	2	1	0	0	0
300 to 399 mb	5	0	0	1	1	3
400 to 499 mb	12	3	3	1	1	4
500 to 599 mb	12	1	2	3	3	3
600 to 699 mb	13	0	1	2	2	8
700 to 799 mb	17	0	0	1	2	14
800 to 899 mb	13	0	0	1	1	11
900 to 999 mb	5	0	0	0	0	5
1000 to 1099 mb	20	20	0	0	0	0
Total	100 %	26 %	7 %	9 %	10%	48 %
		20% Clear		32% Cirrus		48% Cloudy

TABLE 2. Cloud statistics for 1472 observations over the extended European region on 4-5 March 1982 at 0200 and 0300 GMT (four overpasses in all).

Level	All Cloud OBS	Cloud Amount 0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
100 to 199 mb	0 %	0 %	0 %	0 %	0 %	0 %
200 to 299 mb	3	2	1	0	0	0
300 to 399 mb	6	1	1	1	1	2
400 to 499 mb	12	2	3	1	1	5
500 to 599 mb	11	0	2	3	2	4
600 to 699 mb	12	0	1	2	3	6
700 to 799 mb	17	0	1	2	2	12
800 to 899 mb	8	0	0	0	0	8
900 to 999 mb	8	0	0	0	0	8
1000 to 1099 mb	23	23	0	0	0	0
Total	100 %	28 %	9 %	9 %	9%	45 %
		23% Clear		32% Cirrus		45% Cloudy

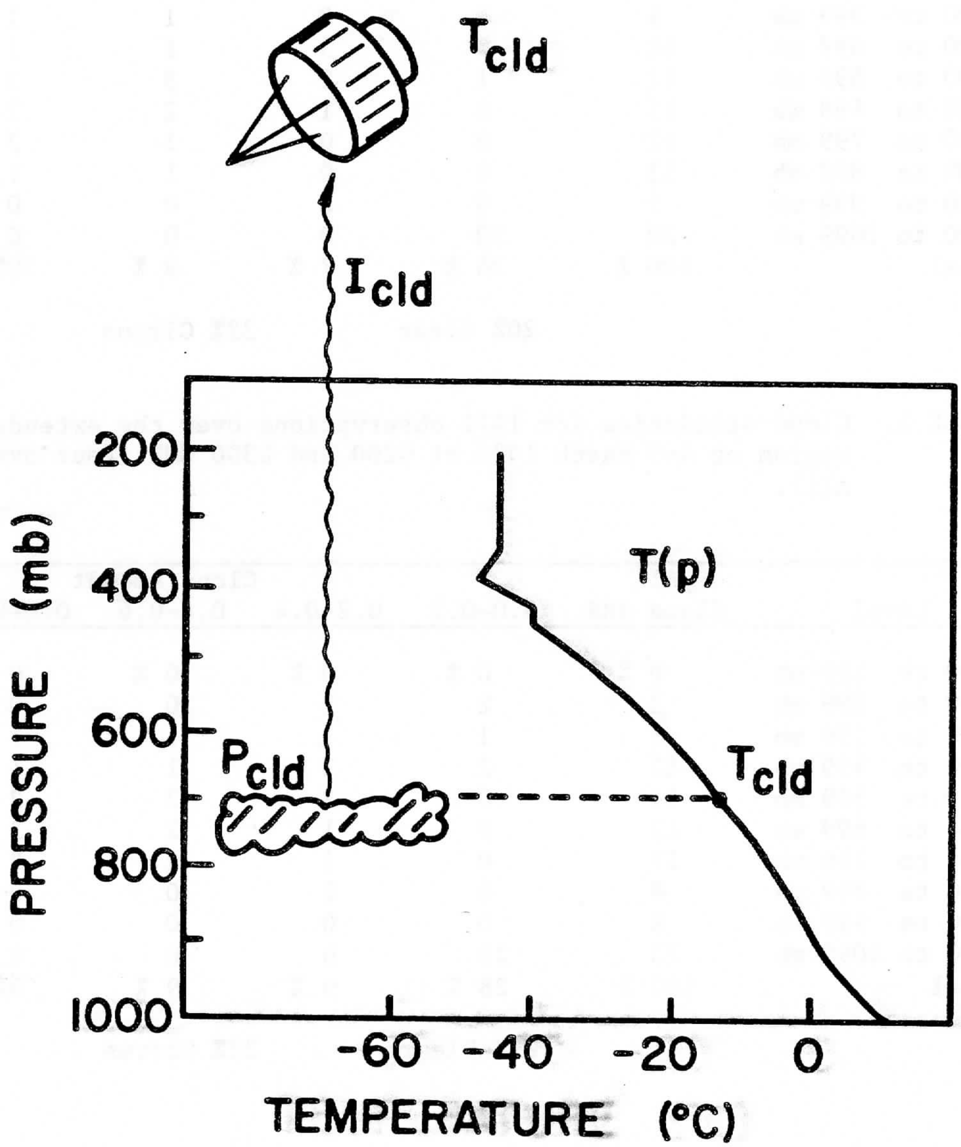

Figure 1. A schematic of the infrared window method where the satellite observed brightness temperature, T_{cld}, is used in conjunction with an in situ temperature profile to infer the cloud top pressure, P_c.

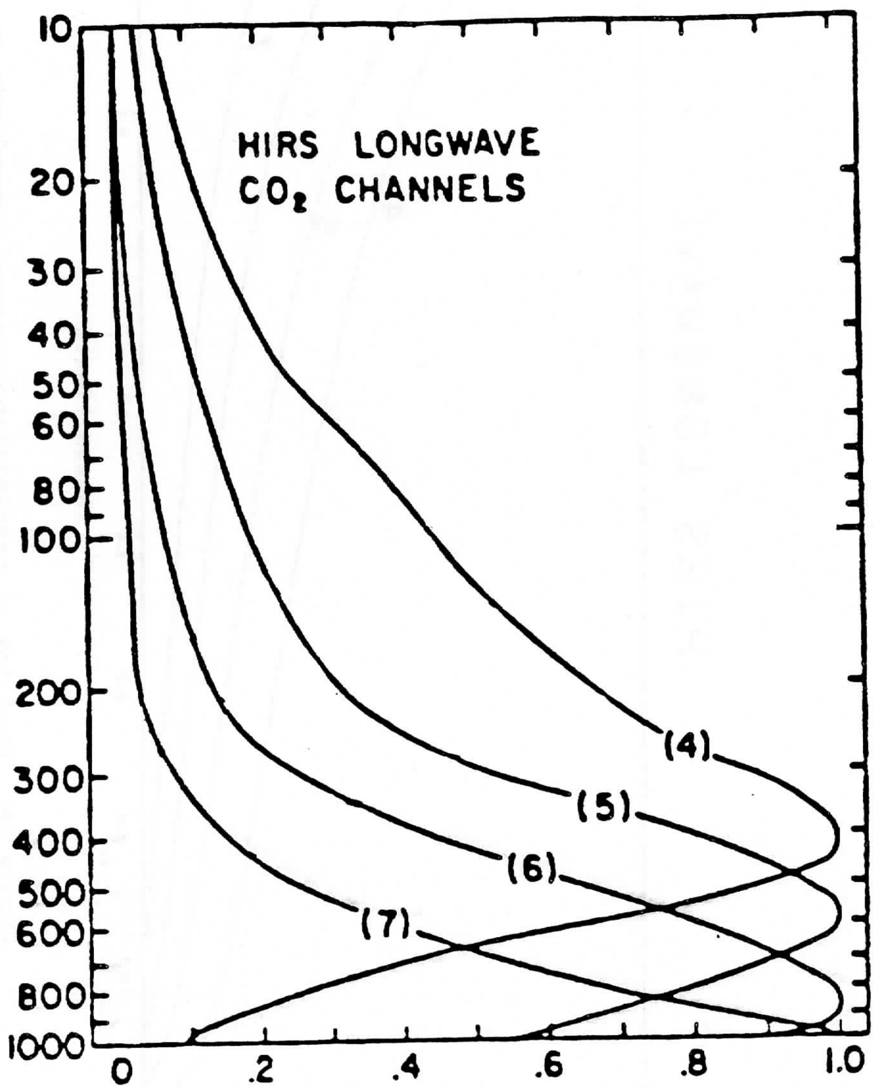

Figure 2a. Weighting functions for HIRS channels 4-7 centered at 14.2, 14.0, 13.7, and 13.4 microns.

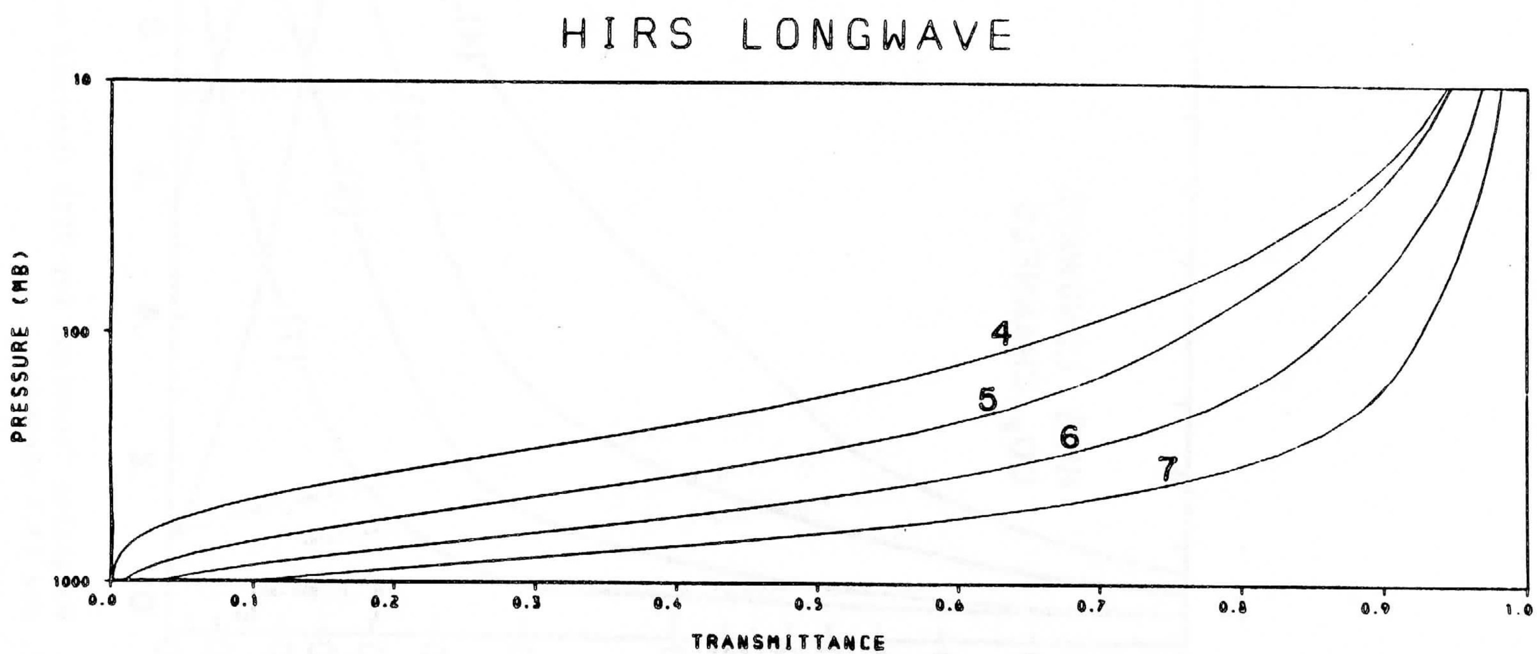

Figure 2b. Profiles of transmittance versus atmospheric pressure for HIRS channels 4-7.

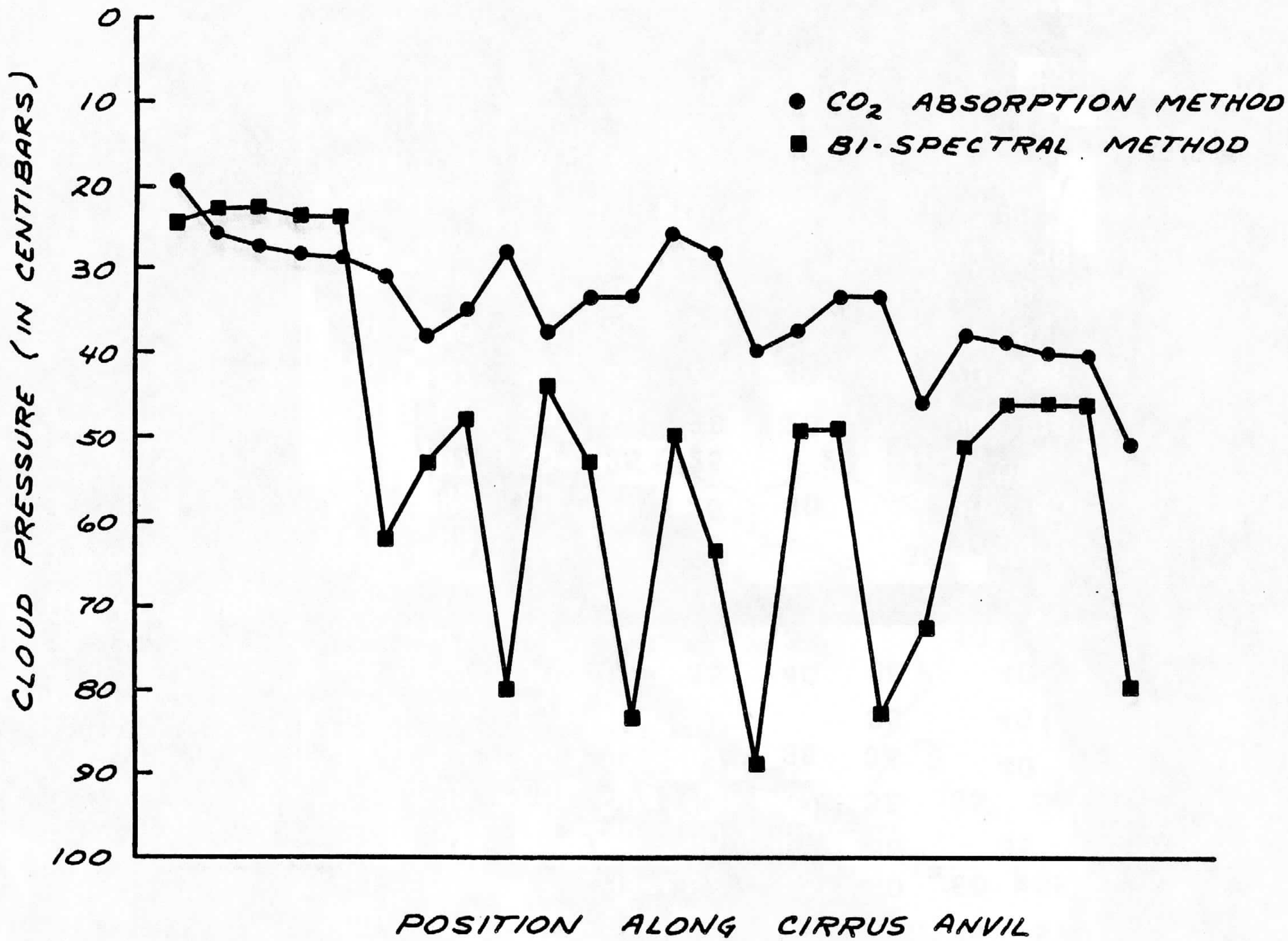

Figure 3. Cloud top pressures (in centibars) plotted versus the position along the cirrus anvil emanating from the dense cumulus center.

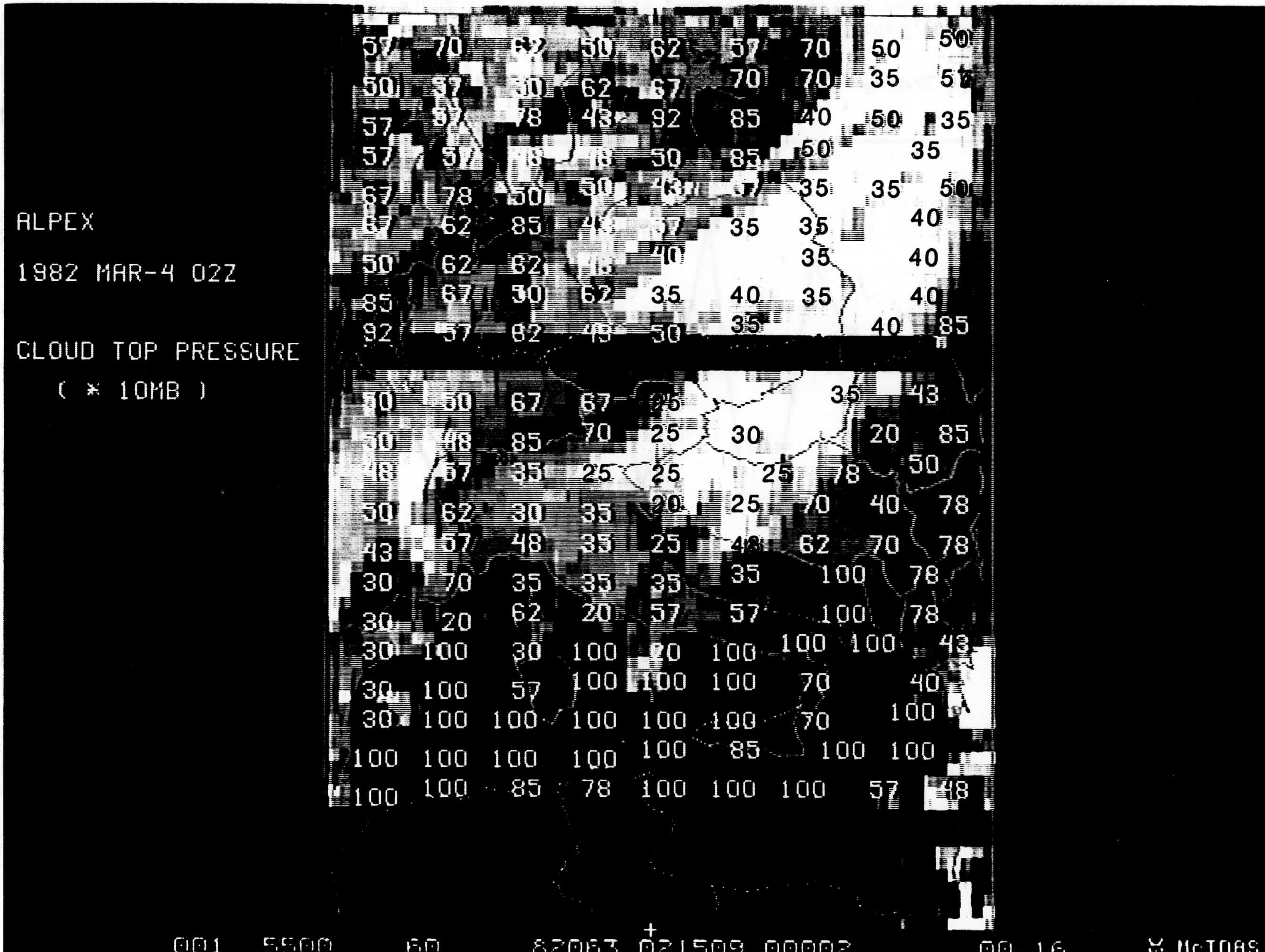

Figure 4a. Cloud top pressures, in centibars, superimposed on the HIRS infrared window image for 200 GMT March 4, 1982 over central Europe.

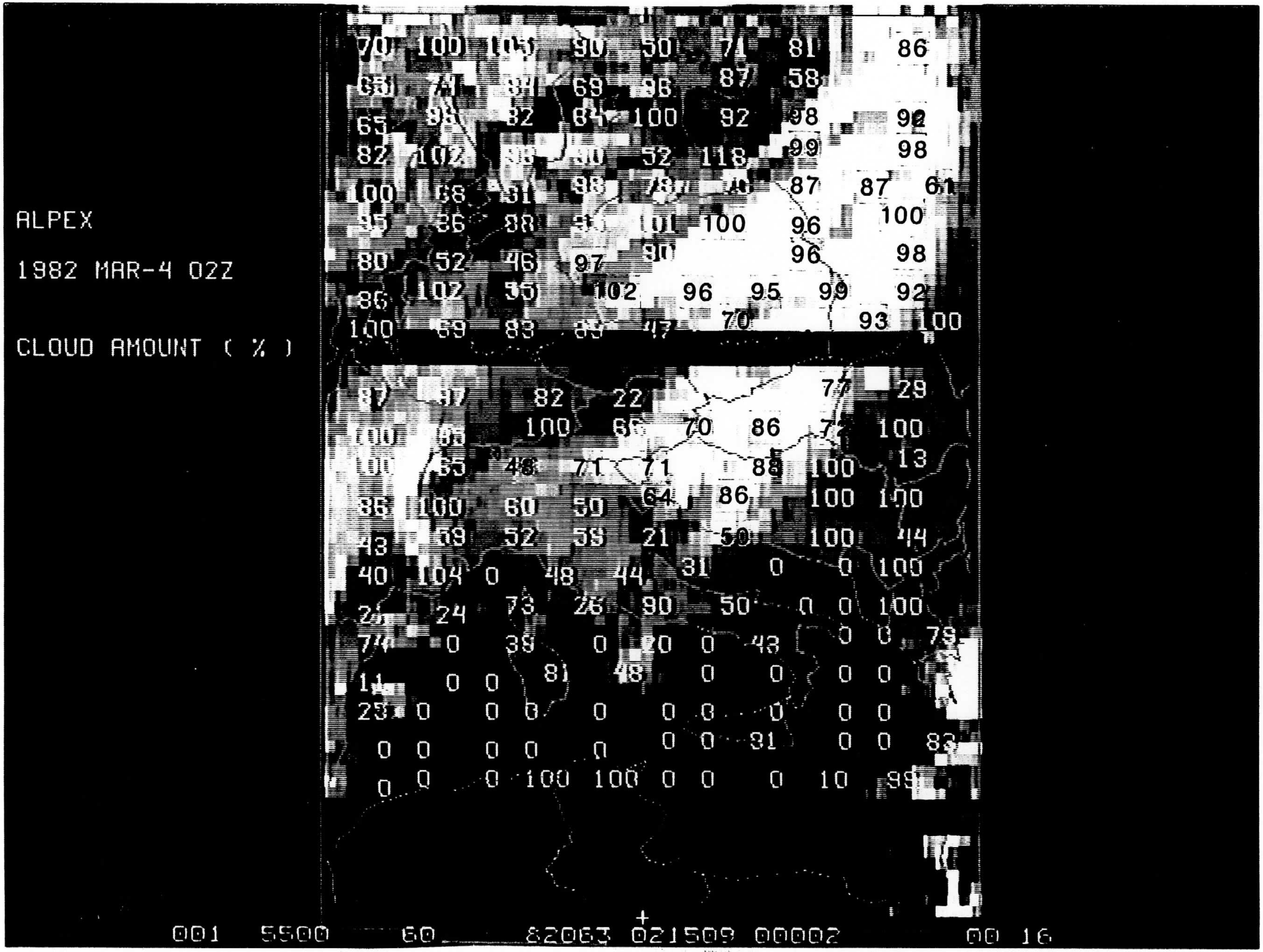

Figure 4b. Effective cloud amounts, fractional cloud cover times emissivity, for 200 GMT March 4, 1982 over central Europe.

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