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On the Retrieval and Analysis of Multilevel Clouds

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1 Introduction

An accurate satellite retrieval of cloud properties depends upon the detection and analysis of multilayered, overlapping cloud systems that surface observations show to be common. Multiple cloud layers are often found, for instance, in frontal situations, where cirrus overlays boundary layer convective cloud or low-to mid-level stratus cloud. Surface observers (Hahn et al., 1982) indicate that over ocean in the Northern Hemisphere between 30°N and 60°N, 51 percent of observations are of multilevel clouds. A satellite analysis by Coakley (1983) over the Pacific Ocean finds that more than 50 percent of 500 (250 km)^2 frames exhibit evidence of multilayered cloud systems. The questions addressed in this study are the following: What error is introduced when inferring the cloud pressure from a field-of-view (FOV) that contains some arbitrary amount of transparent cloud overlaying a lower-level black cloud, such as stratus, by making the assumption that there is only a single cloud layer in the FOV, and what may be done to improve the cloud retrieval?

The CO_2 slicing methods (e.g. McCleese and Wilson, 1976; Smith and Platt, 1978; Chahine, 1974) have been shown to provide accurate means of inferring cirrus cloud altitude from passive infrared radiance measurements. The CO_2 techniques have been applied to radiometric data from several instruments, notably the High Resolution Infrared Radiometric Sounder (HIRS/2, hereafter referred to as HIRS), the VISSR Atmospheric Sounder (VAS) (e.g., Menzel et al., 1983; Wylie and Menzel, 1989), and most recently to the High Resolution Interferometer Sounder (HIS) (Smith and Frey, 1990). The methods take advantage of the fact that infrared CO_2 sounding channels spaced closely in wavenumber each have varying opacity to CO_2, thereby causing each channel to be sensitive to a different level in the atmosphere. The techniques have been shown to be effective for single-layered, nonblack, mid- to high-level clouds such as cirrus, but are generally applied operationally to any given cloud occurrence. The CO_2 slicing algorithms are most accurate for clouds that occur in a single, well-defined layer, or for multi-layered cloud cases in which the uppermost cloud layer is nearly black. Significant cloud height retrieval errors may ensue if the HIRS field-of-view (FOV) is contaminated with low cloud. McCleese and Wilson (1976) have shown that the retrieved cloud height for the case of multiple cloud layers is a weighted average of the cloud heights actually present. The weight is approximately proportional to the product of the cloud height and the effective cloud amount. The effect of their result is that the uppermost cloud layer dominates the cloud pressure retrieval. Beyond stating that the higher cloud dominates the cloud pressure retrieval, there is no quantitative information to provide a way of estimating the errors in cloud pressure retrieval one should expect for certain common multilevel cloud situations or any suggestions on how to reduce the errors. In this paper we estimate the magnitude of the errors and use a simple algorithm to reduce the errors in optically thin cloud height retrieval.

2 Data

Bermuda was one of the sites chosen as part of the First Global Surface Radiation Satellite Data Validation Experiment held during April 1989. The purpose of this global experiment was to obtain high-quality

Surface Radiation Budget (SRB) observations to serve as validation targets, and later as development tools, for SRB retrievals that are based on satellite data. The data set for this project includes both satellite observations of the region and surface observations including lidar, Navy sondes, and SRB-sponsored sondes to provide temperature and humidity data and measurements of surface radiative fluxes. For this study, we will present results from a scene of cirrus overlaying a boundary layer stratus cloud for a 5° by 5° region centered at Bermuda taken on April 16, 1989, at approximately 6 UTC.

2.1 Satellite Data

The Advanced Very High Resolution Radiometer (AVHRR) instrument is flown on the NOAA series of operational satellites. The Sun-synchronous NOAA satellite has nominal Equator crossing times of 0730 and 1930 local solar time (LST). High-resolution (1.1-km) AVHRR data are used in this study. The AVHRR instrument is comprised nominally of five channels: visible (0.63 μm), near infrared (0.83 μm), and three infrared window channels of 3.7 μm, 10.8 μm, and 12 μm.

The High Resolution Infrared Radiation Sounder (HIRS/2) is one of the instruments that make up TOVS (TIROS Operational Vertical Sounder; TIROS is the Television and Infrared Observation Satellite). The TOVS instrument package is also flown on the NOAA series of satellites. The HIRS/2 instrument receives visible and infrared radiation through a single telescope, and splits the radiation into 19 infrared channels and 1 visible channel by means of a rotating filter wheel. Seven channels are located in the near-infrared region (3.7 to 4.6 μm), 12 channels are located in the infrared region (6.7 to 15 μm), and 1 channel is in the visible light region (0.69 μm). The HIRS FOV is approximately 18 km at nadir but enlarges to approximately 30 km $\times$ 58 km towards the edge of the scan line. HIRS was designed to provide temperature and water vapor sounding profiles, with the result that it has gaps between fields of view and cannot be used for imaging purposes.

2.2 Temperature and Humidity Profiles

During the Bermuda SRB mission, special rawinsonde launchings were used to enhance the standard National Weather Service soundings. For extended time or spatial observations, we use ECMWF (European Center for Medium-Range Weather Forecasting) gridded analyses as the primary source of temperature and humidity data.

2.3 Merging HIRS and AVHRR Data

In Baum et al. (1992), a technique was described in which AVHRR data were collocated with individual HIRS pixels. The HIRS pixel, having a nadir field-of-view (FOV) of approximately 18 km, is much larger than the 1.1-km AVHRR pixel. Further, the individual HIRS FOVs are spaced apart from each other both within a scan line and between scan lines. There is no reason, however, to use only the higher-resolution AVHRR data that are collocated with an individual HIRS FOV. A more logical approach is to use all of the AVHRR data and superimpose the HIRS FOVs over the AVHRR imaging data.

3 Methodology

3.1 HIRS Analysis

First, a set of theoretical optically thick cloudy-sky radiances I^i_{cld} are derived (e. g. Wielicki and Coakley, 1981) that are functions of cloud-top pressure P_{cld}, scan angle, and HIRS channel i. The cloud signal is the change in measured radiance at a particular wavenumber due to the presence of a single layer of cloud that may be optically thin or have partial cloud cover. The cloud signal is given by

$$\Delta I^i_{cld} = I^i_{calc} - I^i_{clear} = \epsilon^i A_{cld}[I^i_{cld}(P_{cld}) - I^i_{clear}], \quad (1)$$

where the superscript denotes channel wavenumber dependence. Here I_{clear}, I_{cld}, and I_{calc} are the clear-sky radiance, the black-cloud radiance, and the radiance of a partially filled FOV, respectively. The cloud emittance is given by ϵ^i.

The determination of the clear-sky radiance is of great importance. Clear-sky radiances may be calculated from a priori knowledge of the temperature and humidity profiles. These profiles may come from rawinsonde profiles or from gridded temperature and humidity products such as those provided by the National Meteorological Center (NMC) or by the European Center for Medium-Range Forcasting (ECMWF). Another method is to search the scene for nearby "clear" pixels and assume that the surface conditions do not change between the "clear" pixels and the cloud-filled pixels. However the clear-sky radiance is determined, the calculation of the theoretical upwelling radiance will be influenced by the presence of low-cloud contamination.

The cloud-top pressure may be determined using, for example, the radiance ratioing method as discussed in Wylie and Menzel (1989), Smith and Frey (1990), and Smith and Platt (1978). The technique involves taking a ratio of the cloud signals, defined to be the change in upwelling radiance seen by the satellite due to the presence of cloud. For two spectral channels at wavenumbers ν^i and ν^j that are looking at the same FOV, the equation for the ratio G of the cloud signals for two channels is

$$G(P_{cld}) = \frac{I^i_{meas}(\nu^i) - I_{clear}(\nu^i)}{I^j_{meas}(\nu^j) - I_{clear}(\nu^j)} = \frac{\epsilon^i \int_{P_{clear}}^{P_{cld}} \tau(\nu^i, P)\frac{dB[\nu^i, T(P)]}{dP}dP}{\epsilon^j \int_{P_{clear}}^{P_{cld}} \tau(\nu^j, P)\frac{dB[\nu^j, T(P)]}{dP}dP}. \quad (2)$$

In (2), I_{meas} and I_{clear} are the measured and clear-sky radiances, respectively; $dB[\nu, T(P)]$ is the Planck radiance calculated at temperature $T(P)$ and wavenumber ν; ϵ is the spectral emittance; and $\tau(\nu, P)$ is the fractional transmittance of radiation from the atmosphere at pressure P to the satellite radiometer. For two channels spaced closely in wavenumber, we make the assumption that $\epsilon^i = \epsilon^j$. The function G can be seen to be independent of both cloud opacity and the effective cloud amount. However, G is dependent on the weighting functions of the two channels, the cloud height, and the atmospheric temperature and humidity profile.

In order to calculate the G function, an estimate must be determined for the representative "clear" radiance appropriate for the HIRS FOV. The "clear" radiance may be taken either from a nearby "clear" FOV or from a theoretical upwelling radiance calculated from knowledge of the atmospheric temperature and humidity profiles. The operational approach outlined by Smith and Frey (1990) is to locate representative clear sky radiances from nearby regions and average the clear-sky radiances to form a composite "clear" radiance. In this study, however, we are able to provide additional information for the HIRS algorithm by using the collocated AVHRR data.

3.2 Spatial Coherence

When low clouds (below 700 mb) are present, a rough estimate of cloud pressure can be made using the HIRS 11-μm channel and assuming that the low cloud has an emittance of 1 and fully fills the HIRS FOV. A better way of deriving low cloud properties is to implement the spatial coherence techniques detailed in, for example, Coakley and Bretherton (1982) and Coakley (1983) using the higher spatial resolution AVHRR data. The spatial coherence method is designed to determine the properties of optically thick cloud that covers an areal extent much greater than the individual pixel size, and requires both completely cloud-covered and completely clear fields-of-view. The basic technique employed is to use the local spatial structure of the 10.8-μm field in order to identify the spatially uniform clear-sky and cloud radiances. The method is well suited for analysis of an extensive, optically thick cloud such as stratocumulus that resides in a well-defined layer. The method fails for the case of subresolution clouds in which all clouds are smaller than the FOV, such as trade cumulus, and clouds with variable emissivity such as high, thin cirrus.

For the Bermuda data, we implemented an automated feet detection technique (Coakley, personal communication, 1991) to determine the clear-sky and cloudy-sky radiances. When using 1.1-km AVHRR data, we find that one or at most two feet are determined for each HIRS FOV for this particular case study, with few exceptions.

4 Theoretical Error Analysis

What errors are expected theoretically when a field-of-view (FOV) contains more than one layer of cloud and the upper cloud layer is semi-transparent? For simplicity, we assume that cirrus is present over a black surface, whether it be the actual surface or a lower cloud deck. The upwelling infrared radiation from the Earth-atmosphere system can be modeled for several of the HIRS-2 15-μm CO_2 sounding channels given a knowledge of the background temperature and humidity profiles and also the profiles of trace gases such as CO_2 and ozone. For a single-layered cloud, it is then possible to infer the cloud-top pressure regardless of the cloud's transmittance by using a combination of HIRS channels. For two cloud layers, the upwelling radiances for the HIRS 15-μm channels are determined for the case in which a black cloud is located at a fixed pressure level, such as 850 mb. For these cases, the inferred HIRS cloud-top pressures are determined by assuming that there is no lower cloud.

The effect of lower cloud contamination in a HIRS FOV is given in Fig. 1a for the HIRS 5/6 channel combination and in Fig. 1b for the 6/7 HIRS channel combination. The central wavenumbers for NOAA-11 HIRS channels 5, 6, and 7 are 13.95 μm, 13.66 μm, and 13.34 μm, respectively. Note that no other retrieval errors, such as instrument noise or uncertain clear-sky radiances, are present. In Figs. 1a and 1b, the low cloud is "black" and is located at 850 mb. Channel 7 has a higher transmissivity at the surface than channel 6, which in turn has a higher transmissivity than channel 5. Thus, channel 7 is more sensitive to variations in surface temperature than either channel 5 or channel 6. The "measured" HIRS radiances for the chosen channels are derived from the theoretical upwelling radiance profiles calculated from midlatitude temperature and humidity profiles measured at Bermuda on April 16, 1989, at approximately 6 UTC. Calculations are performed for a range of upper-layer cloud heights ranging from 250 mb to 670 mb and a range of effective cloud amounts. Contours are drawn at 25-mb intervals for the difference between the retrieved cloud pressure and the actual cloud pressure of the upper cloud layer. The difference in retrieved versus actual cloud pressure, a bias, is positive, showing that the retrieved cloud pressure is higher than the actual cloud pressure for all cases. A higher retrieved cloud pressure means that the retrieved cloud heights will be lower than the actual cloud heights. It can be seen from inspection of Figs. 1a and 1b that the cloud retrieval error is greater for the 6/7 channel combination than for the 5/6 channel combination. The error increases for the channel combination that has the greatest transmittance at or near the surface. As an example, we take the case of using the 6/7 HIRS channel combination to examine a HIRS FOV in which a high cloud with an effective cloud amount of 0.5 overlays a black stratus cloud located at 850 mb. From Fig. 1b, we find that the retrieved cloud pressure will actually be approximately 50 mb higher. A 50-mb pressure difference in this case relates to a cloud height error of approximately 1 km. The cloud pressure error can be seen to increase rapidly with decreasing effective cloud amount. Lidar studies (Platt et al., 1987) indicate typical cirrus emittances of 0.1 to 0.35, which would give errors of 75 to 200 mb for the HIRS 6/7 channel combination and 50 mb to 150 mb for the HIRS 5/6 channel combination.

5 Bermuda Data

The Bermuda data are used to provide an example of retrieving cirrus cloud heights in a multilevel cloud scenario. The scene chosen for study is of a large stratus cloud deck with cirrus of varying thickness overlaying the lower cloud. The results from HIRS 6/7 cloud height analysis with no correction due to the presence of a lower cloud deck is shown in Fig. 2.

One way of reducing the error in the HIRS cloud pressure retrieval is to incorporate spatial coherence results into the cloud retrieval algorithm to locate the lower cloud deck. The application in the spatial coherence algorithm results in the determination of a clear-sky foot at approximately 95 ± 1 $mWm^{-2}str^{-1}cm$. A contour plot of the retrieved radiances using spatial coherence analysis is shown in Fig. 3. For groups of 1.1-km AVHRR pixels located over the lower cloud deck, the arch feet indicate that the radiance of the lower cloud deck varies between 84 ± 2 $mWm^{-2}str^{-1}cm$.

Our algorithm may be described as a three-step process. First, calculate the HIRS cloud height assuming one cloud layer in the FOV. Second, apply the spatial coherence algorithm to the collocated AVHRR 11-μm data and determine the average radiance of the lower cloud layer. The third step is to recalculate the HIRS cloud height based on the lower cloud deck radiances. The surface in the HIRS algorithm is redefined to be the height of the lower cloud as determined by spatial coherence analysis of the AVHRR data. This approach will most affect the HIRS cloud height retrievals for those pixels that contain optically thin cloud.

The results of recalculating the HIRS cloud heights are given in Fig. 4 for the 6/7 HIRS channel combination. In this figure, the difference is defined as the corrected minus the uncorrected HIRS cloud height in km. The range of height correction falls between 0.25 and 1.5 km for this scene.

This technique by itself cannot determine with certainty that multilevel clouds may be present in a single HIRS FOV. However, there are other textural techniques using the AVHRR data that may provide additional information on the composition of a group of pixels in order to aid classification.

6 Conclusions

Significant errors in cloud pressure retrieval, using the conventional sounding channel methods outlined in this study, may be the result if more than one cloud layer is present. Progress in identifying and analyzing multilevel cloud scenes may be made by using the methodology detailed by Baum et al. (1992) for merging data from both the AVHRR and HIRS satellite instruments aboard the NOAA operational platforms. In this study, we show how the spatial coherence algorithm may be used to determine whether low clouds exist in the scene of study, determine the low cloud height, and use that low cloud height in subsequent analysis of the HIRS data. Spatial coherence is one of the simplest textural techniques by which to determine whether multilevel clouds are present. A more complex scheme could be implemented that utilizes more textural features such as that proposed by Welch et. al. (1988).

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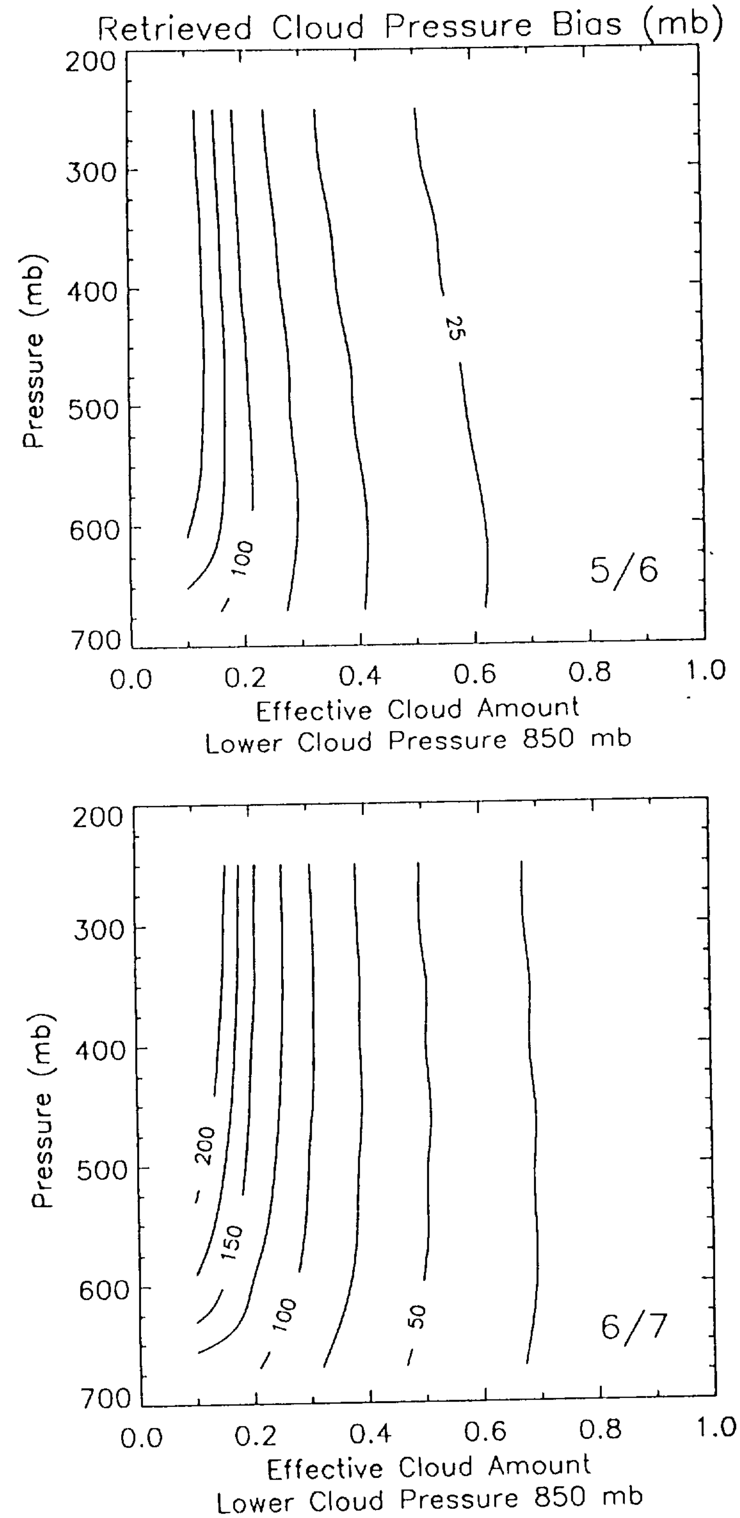

Figure 1: HIRS Pressure Retrieval Bias Error. The cloud pressure bias is defined as the retrieved cloud pressure minus the true cloud pressure.

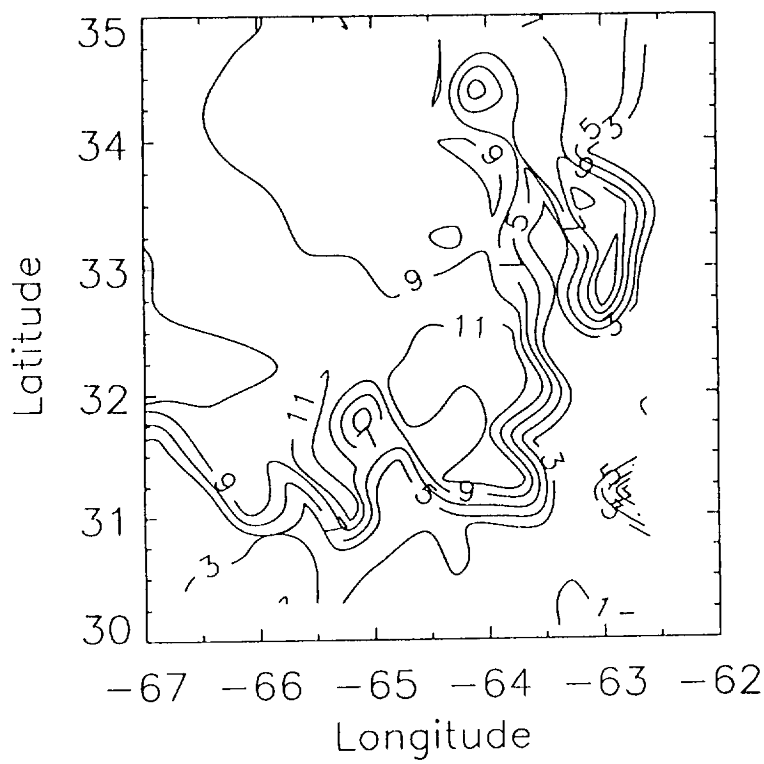

Figure 2: HIRS Channel 6/7 cloud height results for the multilevel cloud scene of April 16, 1989, at approximately 6 UTC, in the vicinity of Bermuda. The cloud heights are uncorrected for the presence of a lower cloud deck located at approximately 1.5 km. Height contours are in km.

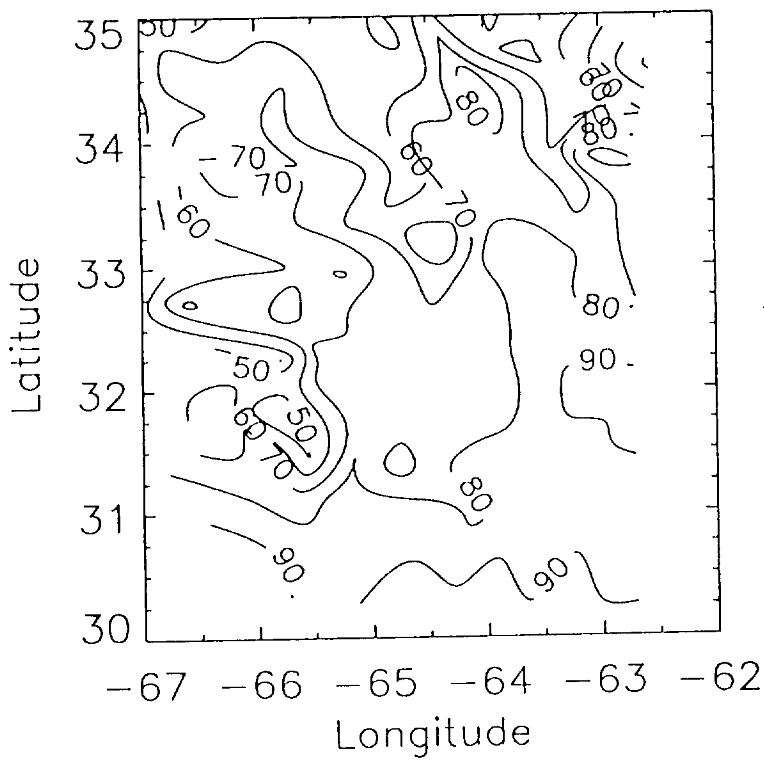

Figure 3: Spatial coherence results for the multilevel cloud scene of April 16, 1989, at approximately 6 UTC, in the vicinity of Bermuda. Radiances are in units of $mWm^{-2}str^{-1}cm$.

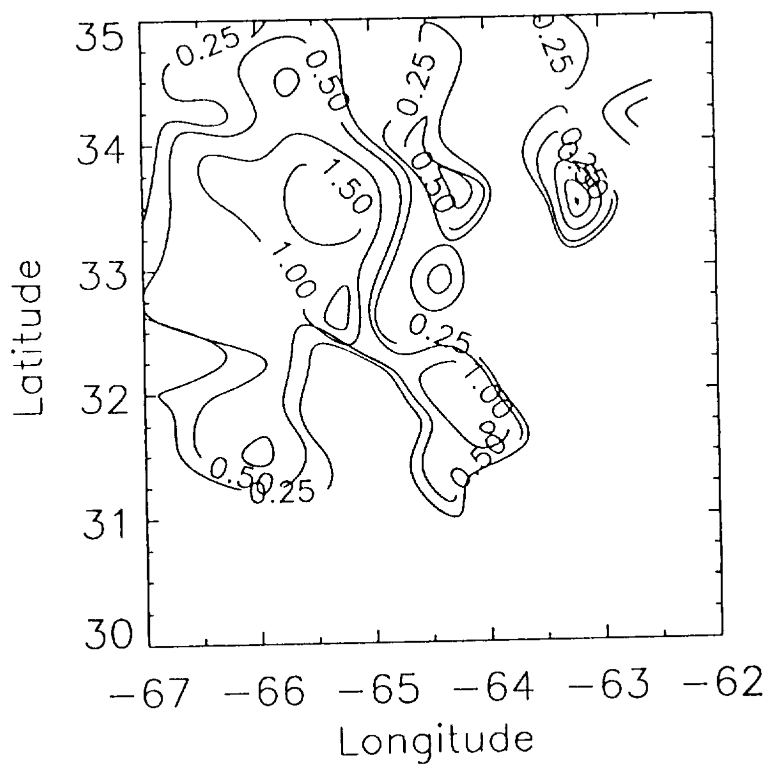

Figure 4: HIRS Channel 6/7 cloud height difference results for the multilevel cloud scene of April 16, 1989, at approximately 6 UTC, in the vicinity of Bermuda. The cloud height differences are defined as the corrected cloud height minus the uncorrected cloud height in km.