NOTES AND CORRESPONDENCE

Cirrus Cloud Retrieval Using Infrared Sounding Data: Multilevel Cloud Errors

BRYAN A. BAUM AND BRUCE A. WIELICKI

Atmospheric Sciences Division, NASA/Langley Research Center, Hampton, Virginia

29 July 1992 and 19 May 1993

ABSTRACT

In this study we perform an error analysis for cloud-top pressure retrieval using the High-Resolution Infrared Radiometric Sounder (HIRS/2) 15-μm CO_2 channels for the two-layer case of transmissive cirrus overlying an overcast, opaque stratiform cloud. This analysis includes standard deviation and bias error due to instrument noise and the presence of two cloud layers, the lower of which is opaque. Instantaneous cloud pressure retrieval errors are determined for a range of cloud amounts (0.1–1.0) and cloud-top pressures (850–250 mb). Large cloud-top pressure retrieval errors are found to occur when a lower opaque layer is present underneath an upper transmissive cloud layer in the satellite field of view (FOV). Errors tend to increase with decreasing upper-cloud effective cloud amount and with decreasing cloud height (increasing pressure). Errors in retrieved upper-cloud pressure result in corresponding errors in derived effective cloud amount. For the case in which a HIRS FOV has two distinct cloud layers, the difference between the retrieved and actual cloud-top pressure is positive in all cases, meaning that the retrieved upper-cloud height is lower than the actual upper-cloud height. In addition, errors in retrieved cloud pressure are found to depend upon the lapse rate between the low-level cloud top and the surface. We examined which sounder channel combinations would minimize the total errors in derived cirrus cloud height caused by instrument noise and by the presence of a lower-level cloud. We find that while the sounding channels that peak between 700 and 1000 mb minimize random errors, the sounding channels that peak at 300–500 mb minimize bias errors. For a cloud climatology, the bias errors are most critical.

1. Introduction

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

The CO_2 slicing methods (e.g., McCleese and Wilson 1976; Smith and Platt 1978; Chahine 1974) have been shown to provide an 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 Geostationary Operational Environmental Satellite (GOES) VISSR (Visible–Infrared Spin Scan Radiometer) Atmospheric Sounder (VAS) (e.g., Menzel et al. 1983; Wylie and Menzel 1989; Menzel et al. 1992), and, most recently, the High-Resolution Interferometer Sounder (HIS) (Smith and Frey 1990). The Moderate Resolution Imaging Spectrometer (MODIS) (King et al. 1992) under development for the Earth Observing System (EOS) has four channels in the 15-μm region that are similar to the HIRS channels. The *NOAA-11* HIRS and anticipated EOS MODIS 15-μm channels are listed in Table 1. Further information regarding the HIRS instrument characteristics may be found in Kidwell (1991), and information on MODIS may be found in Salomonson et al. (1989). Actual noise-equivalent radiances for MODIS may be smaller than those listed in the table (Menzel 1992, private communication).

The HIRS instrument is flown on the NOAA series of satellites and provides radiometric data used to estimate temperature and water vapor sounding profiles.

Corresponding author address: Dr. Bryan A. Baum, NASA/Langley Research Center, ASD/RSB MS 420, Hampton, VA 23681-0001.

TABLE 1. Typical HIRS and EOS MODIS 15-μm channels, central wavenumbers, half-power bandwidths, and noise-equivalent radiances.

Instrument	Platform	Channel	Wavelength (μm)	Bandwidth (μm)	Noise-equivalent radiance (mW m^{-2} sr^{-1} cm)
HIRS/2	*NOAA-11*	4	14.22	0.32	0.31
HIRS/2	*NOAA-11*	5	13.95	0.31	0.21
HIRS/2	*NOAA-11*	6	13.66	0.30	0.24
HIRS/2	*NOAA-11*	7	13.34	0.28	0.20
MODIS	EOS	33	13.335	0.30	0.18
MODIS	EOS	34	13.635	0.30	0.16
MODIS	EOS	35	13.935	0.30	0.14
MODIS	EOS	36	14.235	0.30	0.11

HIRS 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 (3.7–4.6 μm), 12 channels are located in the infrared region (6.7–15 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 × 58 km toward the ends of the scan. By comparison, the nominal MODIS instantaneous FOV size is 1 km at nadir for the equivalent infrared channels (Salomonson et al. 1989).

The CO_2 slicing methods take advantage of the fact that each of the infrared sounding channels within the 15-μm CO_2 band have varying opacity to CO_2, thereby causing each channel to be sensitive to a different layer 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 multilayered cloud cases in which the uppermost cloud layer is nearly black. The HIRS-derived cloud pressure is expected to be near cloud center for optically thin cloud where the extinction optical depth is much less than 1. The cloud pressure is expected to increase to cloud top for more nearly opaque cloud where the extinction optical depth is much greater than 1. Significant cloud-height retrieval errors may ensue if the HIRS FOV is contaminated with low cloud, as shown in the following discussion.

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. They performed numerical simulations of cloud configurations for the *Nimbus-5* sounding channels. However, no quantitative information was provided to aid in estimating the errors in cloud pressure retrieval that one should expect for common multilevel cloud situations, like cirrus over stratus. In a recent article, Menzel et al. (1992) presented an error analysis performed for the (GOES) VAS. As part of their analysis, the errors in high-cloud pressure retrieval associated with the presence of a lower cloud layer were found to result in a maximum error in retrieved upper-cloud pressure of approximately 100 mb. The GOES VAS has three CO_2 sounding channels that are similar to those of HIRS, but HIRS has more sounding channels. With the greater selection of channel pairs with the HIRS instrument, we will show how the presence of a low cloud can bias cloud pressure retrieval results for four different channel combinations. For the four channel combinations, we will also show the standard deviation and bias error due to HIRS instrument noise. We will also discuss the effect of the lapse rate assumed in the lowest levels of the atmosphere.

2. Satellite radiances

The clear-sky spectral radiance $I_{clr}(\nu^i, P_s)$ for a black surface ($\epsilon_s^i = 1$, i is channel number) is given by

$$I_{clr}(\nu^i, P_s) = B(\nu^i, T_s)t(\nu^i, P_s) + \int_{P_s}^{0} B[\nu^i, T(P)] \frac{dt(\nu^i, P)}{d\ln P} d\ln P, \quad (1)$$

where $B(\nu^i, T)$ is the Planck radiance at temperature T, ν^i is the wavenumber of channel i, $t(\nu^i, P)$ is the transmittance from atmospheric level P to the satellite at $P = 0$, and the subscripts "s" and "clr" denote surface and clear-sky conditions, respectively. For an overcast cloud (c) in an FOV, the radiance for an overcast black ($\epsilon = 1$) cloud (ob) at pressure level P_c is given by

$$I_{ob}(\nu^i, P_c) = B(\nu^i, T_c)t(\nu^i, P_c) + \int_{P_c}^{0} B[\nu^i, T(P)] \frac{dt(\nu^i, P)}{d\ln P} d\ln P. \quad (2)$$

The theoretical upwelling radiance I for a partially cloud-filled FOV is given by

$$I(\nu^i, P_c, \epsilon_c A_c) = I_{clr}(\nu^i, P_s) + \epsilon_c^i A_c[I_{ob}(\nu^i, P_c) - I_{clr}(\nu^i, P_s)]. \quad (3)$$

In this formulation, the cloud emittance ϵ_c^i of channel

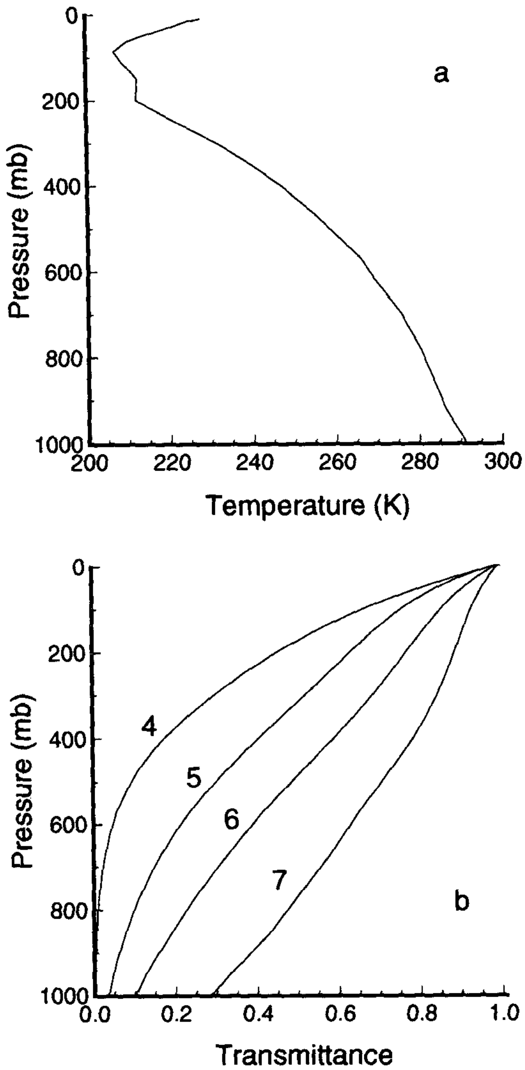

FIG. 1. (a) Average midlatitude temperature profile used in this study. (b) *NOAA-11* HIRS transmittances for channels 4, 5, 6, and 7.

i is multiplied by the cloud fractional coverage A_c, and the quantity $\epsilon^i_c A_c$ is referred to as the effective cloud amount.

For the case of a transmissive upper-cloud (uc) layer ($\epsilon^i_{uc}A_{uc} < 1$) overlying an overcast black lower-cloud (lc) layer ($\epsilon^i_{lc}A_{lc} = 1$), the upwelling radiance is calculated from

$$I_{uc}(\nu^i, P_{uc}, P_{lc}, \epsilon^i_{uc}A_{uc}) = I_{ob}(\nu^i, P_{lc}) + \epsilon^i_{uc}A_{uc}[I_{ob}(\nu^i, P_{uc}) - I_{ob}(\nu^i, P_{lc})], \quad (4)$$

where $I_{ob}(\nu^i, P_{lc})$ is calculated from (2) with $P_c = P_{lc}$, while $I_{ob}(\nu^i, P_{uc})$ is determined from (2) using $P_c = P_{uc}$. In other words, (4) is found by replacing I_{clr} with $I_{ob}(\nu^i, P_{lc})$ in (3).

The transmission functions used to generate the theoretical upwelling radiances are calculated (Woolf 1992, personal communication) for a given temperature and humidity profile from the methods detailed in Weinreb et al. (1981). The calculations take into account the satellite zenith angle, absorption by well-mixed gases (including nitrogen, oxygen, and carbon dioxide), water vapor (including the water vapor continuum), and ozone. For the midlatitude temperature profile shown in Fig. 1a, the transmittance profiles are shown in Fig. 1b for the HIRS channels specified in Table 1. Inspection of these transmittance profiles shows that channels 4 and 5 receive little energy from near the surface by virtue of their low surface transmittances. In other words, these channels are insensitive to surface conditions. Channel 6 has a limited dependence on surface conditions since the transmittance is roughly 10% at the surface. Since channel 7 has a surface transmittance of almost 30% at the surface, this channel is most sensitive to the surface temperature.

The weighting functions ($d\tau / d \ln P$) shown in Fig. 2 are only slightly dependent on the temperature and water vapor profiles. The weighting functions for channels 4, 5, 6, and 7 have maxima at approximately 400, 530, 890, and 1000 mb, respectively, for the midlatitude spring–fall temperature profile (CESA 1966) chosen for this study. If a cloud is located well below the maximum of a weighting function for any particular channel, the cloud signal becomes too low, relative to the noise, to be useful in determining cloud radiance.

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

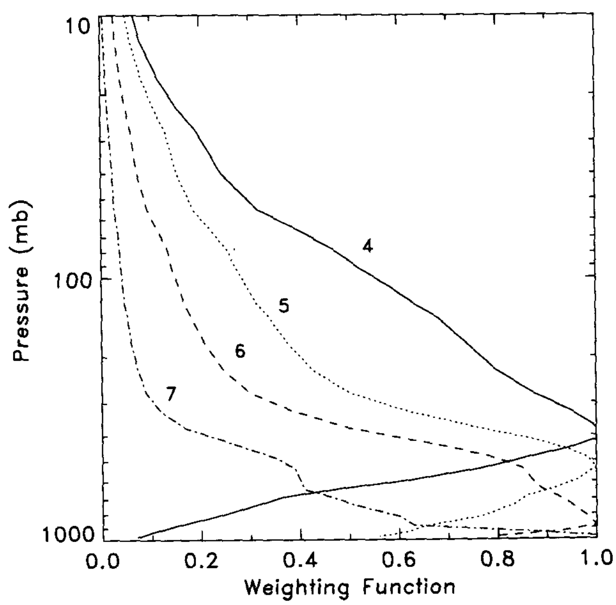

FIG. 2. *NOAA-11* HIRS weighting functions $d\tau / d \ln P$ for channels 4, 5, 6, and 7 for nadir viewing conditions.

humidity products such as those provided by the National Meteorological Center (NMC) or by the European Centre for Medium-Range Weather Forecasts (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-level cloud contamination.

In the next section, we briefly present two of the techniques that have been proposed and widely used for the calculation of cloud pressure. The first technique, proposed by Chahine (1974), is based upon the minimization of the root-mean-square (rms) difference between calculated and observed radiances. The second technique, proposed by McCleese and Wilson (1976) and Smith and Platt (1978), for example, is a radiance ratioing method. A brief description of the application of each method is given below.

3. Methodology

a. Root-mean-square method

The implementation of the rms method requires a knowledge of temperature and humidity profiles. The rms radiance difference for N channels (Chahine 1974; Wielicki and Coakley 1981) is determined from

$$I_{\rm rms}(P_c, \epsilon_c^i A_c) = \left\{ \sum_{i=1}^{N} [I_{\rm meas}^i - I^i(\nu^i, P_c, \epsilon_c A_c)]^2 \right\}^{1/2}, \tag{5}$$

where $I_{\rm meas}^i$ denotes the measured radiance of channel i, and $I^i(\nu^i, P_c, \epsilon_c^i A_c)$ is determined from (3). The retrieved cloud pressure errors will be the result of using (3) rather than (4) to compute the theoretical upwelling radiances when more than one cloud layer is present in an FOV. The atmosphere between 200 and 950 mb is divided into 25-mb intervals for the rms calculations. Thus, the derived cloud pressure will correspond to the rms minimum at a predefined interval.

The rms method, as stated in (5), has no provision for weighting the cloud signal from the various channels. The cloud signal for any particular channel increases with surface transmission so that the largest cloud signal will be recorded for channel 7, and the smallest cloud signal for channel 4. Thus, the application of the rms method tends to weight the results toward the channels with greater transmittance.

b. Radiance ratioing method

The cloud-top pressure may also be determined using 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 a single cloud layer is

$$G(P_c) = \frac{I_{\rm meas}^i(\nu^i) - I_{\rm clr}(\nu^i)}{I_{\rm meas}^j(\nu^j) - I_{\rm clr}(\nu^j)} = \frac{I_{\rm ob}(\nu^i, P_c) - I_{\rm clr}(\nu^i, P_s)}{I_{\rm ob}(\nu^j, P_c) - I_{\rm clr}(\nu^j, P_s)}, \tag{6}$$

where G is the ratio of cloud signal for two different channels. We make the assumption that $\epsilon^i = \epsilon^j$ for two channels spaced closely in wavenumber. The function G can be seen to be independent of both cloud opacity and effective cloud amount. However, G is dependent on the weighting functions of the two channels, the cloud height, and the atmospheric temperature profile.

In the more general case in which an upper cloud overlies an overcast lower cloud, the G ratio is defined as

$$G(P_{\rm uc}) = \frac{I_{\rm meas}^i(\nu^i) - I_{\rm ob}(\nu^i, P_{\rm lc})}{I_{\rm meas}^j(\nu^j) - I_{\rm ob}(\nu^j, P_{\rm lc})} = \frac{I_{\rm ob}(\nu^i, P_{\rm uc}) - I_{\rm ob}(\nu^i, P_{\rm lc})}{I_{\rm ob}(\nu^j, P_{\rm uc}) - I_{\rm ob}(\nu^j, P_{\rm lc})}, \tag{7}$$

where $I_{\rm ob}(\nu^i, P_{\rm lc})$ is determined from (2) with $P_c = P_{\rm lc}$. The application of the above equation assumes that the low-level cloud-top pressure is known. The cloud pressure retrieval errors will occur if Eq. (6) is used instead of Eq. (7). Just as $I_{\rm clr}$ can often be measured from nearby clear sky, the low-level cloud radiance $I_{\rm ob}(\nu^i, P_{\rm lc})$ can often be measured from nearby low clouds.

In order to calculate the G function for the single cloud-layer case, an estimate must be determined for the representative clear-sky radiance appropriate for the HIRS FOV. 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. The current study assumes perfect knowledge of the clear-sky radiance and focuses only on errors caused by multilevel cloud.

The error analyses that follow are performed for a variety of the channel combinations using channels 4, 5, 6, and 7 from the HIRS/2 instrument flown on NOAA operational satellites.

4. Results

The effect of opaque lower-cloud contamination at 850 mb on cloud pressure retrieval for an HIRS FOV is shown in Fig. 3 for four two-channel combinations implementing the ratio method. Calculations are performed for a range of $P_{\rm uc}$ ranging from 250 to 850 mb and a range of $\epsilon_{\rm uc}^i A_{\rm uc}$ between 0.1 and

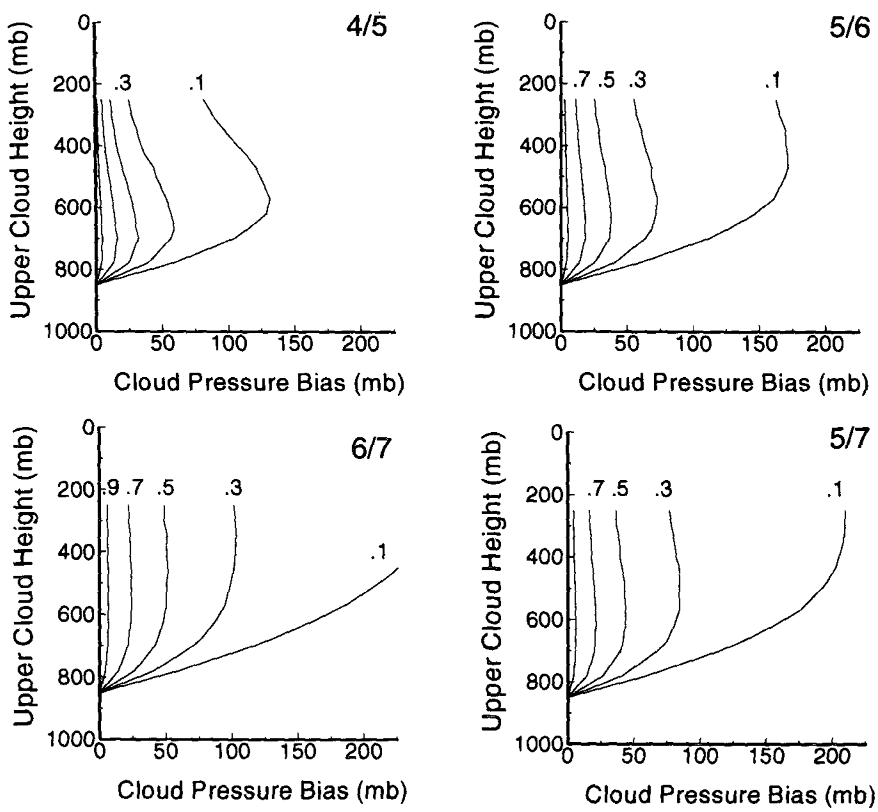

FIG. 3. Multilevel cloud pressure retrieval bias errors (mb) for several $\epsilon_{uc}A_{uc}$ as a function of the pressure of the upper transmissive cloud layer. Results are presented for the HIRS 4/5, 5/6, 6/7, and 5/7 channel ratio combinations. The opaque lower cloud-top pressure is held constant at 850 mb.

1.0. The implementation of either the rms or the ratio methods will result in a single derived cloud pressure for a chosen HIRS FOV and channel combination. For the case in which a HIRS FOV has two distinct cloud layers, the difference in retrieved P_c minus actual P_{uc} is positive in all cases. A positive difference means that the retrieved upper-cloud height is lower than the actual upper-cloud height. The retrieved cloud pressure will be between the upper- and lower-cloud layers when two layers of cloud are present in a HIRS FOV.

The retrieved cloud pressure errors are greatest for the HIRS channel combinations 5/7 and 6/7. The errors are expected to be greatest for channel combinations that use channel 7 since this channel has the highest surface transmissivity of all the HIRS 15-μm channels. The low surface transmission for HIRS channels 4, 5, and 6 results in decreased cloud pressure retrieval errors for the 5/6 and 4/5 ratios. The retrieved cloud pressure error increases with decreasing $\epsilon_{uc}A_{uc}$. Once $\epsilon_{uc}A_{uc}$ drops below approximately 0.5 for the 6/7 HIRS channel combination, the error in retrieved cloud pressure increases quickly past 50 mb. The resulting error in cloud height is greater than 1 km for mid- to high-level clouds. The results for the 5/6 channel combination show that the decreased sensitivity of channel 5 to the surface led to a decrease in upper-cloud pressure retrieval errors when compared with the 6/7 channel combination. For the 4/5 HIRS channel combination, the retrieved upper-cloud pressure errors are much smaller even at lower $\epsilon_{uc}A_{uc}$ values. In all cases, the retrieved upper-cloud pressure error is less than 50 mb when the effective cloud amount is greater than approximately 0.5.

The rms results are not shown since the results are similar to the ratio method using the 6/7 channel combination. The rms results are consistent with the fact that the method, as implemented in (5), is weighted toward the channels that have the highest cloud signal.

An error in cloud pressure P_{uc} retrieval leads to an error in the calculation of $\epsilon^i_{uc}A_{uc}$. For the pressure errors presented in Fig. 3, corresponding $\epsilon^i_{uc}A_{uc}$ errors are shown in Fig. 4 for the same conditions. The retrieved $\epsilon^i_{uc}A_{uc}$ are calculated by using the lowest sounding channel of the pair of channels chosen for the ratio method. The error in $\epsilon^i_{uc}A_{uc}$ is defined to be the retrieved value minus the true value. Since this quantity is positive, this means that the retrieved value will be too high for cases in which there is lower-cloud contamination in a HIRS footprint.

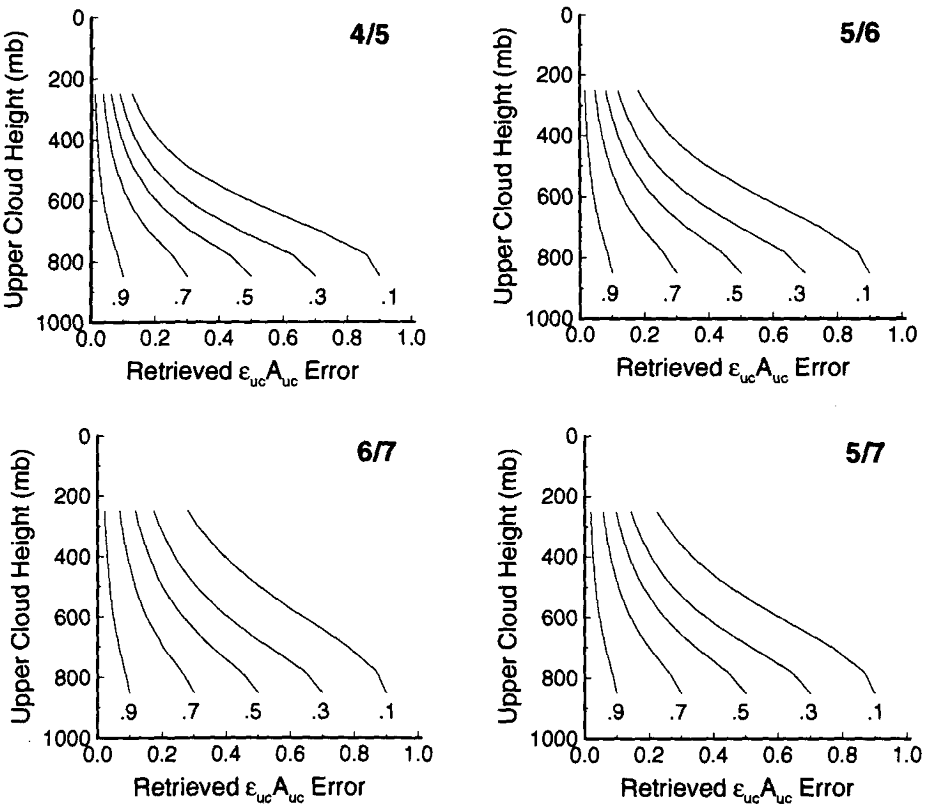

FIG. 4. Upper-cloud effective cloud amount retrieval bias errors for several $\epsilon_{uc}A_{uc}$ as a function of the pressure of the upper transmissive cloud layer. These results, derived from the pressure biases presented in Fig. 3, are presented for the HIRS 4/5, 5/6, 6/7, and 5/7 channel ratio combinations. The opaque lower cloud-top pressure is held constant at 850 mb.

The 5/7 combination is similar to the VAS combination used by Menzel et al. (1992). However, the cloud retrieval bias errors presented in this study are up to 40 mb higher for thin ($\epsilon_{uc}A_{uc} = 0.3$) upper-layer cloud than those reported by Menzel et al. (1992). We suggest that this difference is caused by the temperature profiles used in each study. Menzel et al. (1992) use a very stable temperature profile from 25 October 1990, in which the lapse rate is approximately 2.3 K km^{-1} below approximately 780 mb. We obtain similar results to those of Menzel et al. (1992) if we use the same temperature profile. The temperature profile used in this study is of a midlatitude profile that has a more typical lapse rate near the ground of approximately 6 K km^{-1}. We can examine the effect of varying the lapse rate between the lower cloud-top pressure, say 850 mb, and the surface pressure of 1000 mb by assuming three lapse rates of 2, 4, and 6 K km^{-1}. The results of this exercise are shown in Fig. 5 for the 5/7 channel combination similar to that of the VAS. What we find is that increasing the lapse rate leads to increasing upper-cloud pressure bias errors. For example, by increasing the lapse rate from 2 to 6 K km^{-1} and assuming that an upper cloud located at 300 mb has an effective cloud amount of 0.3, the upper-cloud pressure bias error increases from about 40 to about 80 mb. Since (6) and (7) show that the cloud retrieval error should scale as $I_{clr}(\nu^i) - I_{ob}(\nu^i, P_{lc})$, a larger lapse rate will increase the difference in temperature between the lower cloud and the surface and thereby increase the error incurred by using I_{clr} instead of $I_{ob}(\nu^i, P_{lc})$. In the extreme case of an isothermal atmosphere between P_s and P_{lc}, there will be no error in the derived P_{uc}.

In Fig. 6, we repeat the calculations presented in Fig. 3 but with a low-level cloud-top pressure at 700 mb. The upper-cloud pressure retrieval biases are increased from the case in which the lower-cloud pressure is 850 mb. This result is expected since there is a larger difference between the radiance of lower cloud at 700 mb and the surface pressure. These results reinforce the idea that the presence of a low-level cloud will result in upper-cloud pressure retrieval biases.

a. Consideration of other error sources

Wielicki and Coakley (1981) considered errors due to instrument noise, uncertainties in temperature profiles and water vapor profiles, and biases due to boundary condition constraints. The standard deviation errors shown in their study were the variations of re-

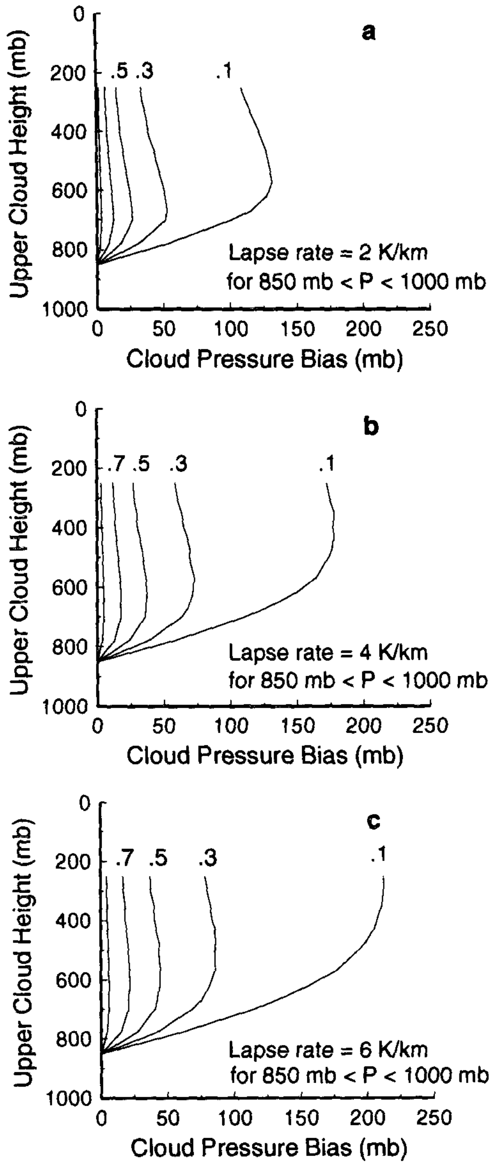

FIG. 5. Effect of lapse rate on upper-cloud pressure retrieval bias errors for several $\epsilon_{uc}A_{uc}$ as a function of the pressure of the upper transmissive cloud layer. The temperature profile is the same as that shown in Fig. 1a between 0.1 and 850 mb but with a lapse rate between 850 and 1000 mb of (a) 2 K km^{-1}, (b) 4 K km^{-1}, and (c) 6 K km^{-1}. These results are presented for HIRS channels 5/7. The opaque lower cloud-top pressure is held constant at 850 mb.

trieved cloud pressure about the retrieved mean cloud pressure, and the cloud pressure bias amounts were due to differences between actual mean and retrieved mean cloud pressure amounts. Errors due to uncertainties in temperature profiles and water profiles dominated errors due to instrument noise for temperature rms errors of greater than or equal to 1.5°C for the 6/7 channel combination, for example. While the lowest sounding channels gave the smallest errors, the errors were of the same order for all channel combinations. Wielicki and Coakley (1981) also showed that the uncertainties in the temperature profile dominated those due to those in the water vapor profile, and the errors were strongly related to the cloud signal. This is in contrast to the errors due to instrument noise where the errors varied for different spectral regions.

The cloud pressure retrieval error results for multilevel cloud scenarios presented in the previous section are instantaneous errors. In order to compare these results with those computed using the methods of Wielicki and Coakley (1981), however, we need some way of viewing these instantaneous results as an ensemble error. For illustrative purposes, we assume that half of the mid- to high-level semitransparent oceanic cirrus cloud contains underlying low cloud following Hahn et al. (1982). We take an ensemble of midlatitude oceanic HIRS pixels, with 50% of the pixels containing cirrus alone and the other 50% of the pixels containing cirrus over overcast, black stratiform cloud, and further assume that the pressure of the stratiform cloud is constant at 850 mb. For this case, both the bias and the standard deviation of the cloud pressure retrieval errors would be half the magnitude of the bias errors shown in Fig. 3.

The methods of Wielicki and Coakley (1981) are implemented to compute standard deviations of retrieved cloud-top pressure errors caused by instrument noise. The instrument noise is assumed Gaussian with a zero mean and a standard deviation equal to the noise-equivalent radiance shown in Table 1 for the HIRS/2 channels. The instrument noise errors are calculated assuming exact knowledge of the temperature and humidity profiles. Exact knowledge of the temperature and humidity profiles implies exact knowledge of the derived quantities I_{clr} [Eq. (1)], I_{ob} [Eq. (2)], and $G(P_c)$ [Eq. (6)]. Measured radiances are simulated for a range of cloud amounts between 0.1 and 1 and cloud pressures between 920 and 200 mb. A total of 1000 samples are constructed for each combination of cloud amount and pressure to derive statistical properties of the retrieved cloud-top pressures. The top row of frames in Fig. 7 shows the standard deviation in cloud pressure obtained by applying the ratio method to the HIRS 4/5, 5/6, and 6/7 channel combinations assuming instrument noise only. We note that as $\epsilon A_c \rightarrow 0$ and $P_c \rightarrow 1000$ mb, the retrieved cloud pressure errors become large as a result of the cloud signal becoming comparable to instrument noise. For the 4/5 channel combination, cloud-top pressure retrievals are difficult to obtain for low-level clouds and conditions of low cloud amount because the cloud signal for the lower channel often drops below our threshold limit of two times signal noise, in which case the FOV is classified as clear.

The standard deviation of cloud-top pressure error caused by instrument noise is shown in the top row of Fig. 7. However, there is also an instrument noise bias error between the retrieved mean cloud pressure and

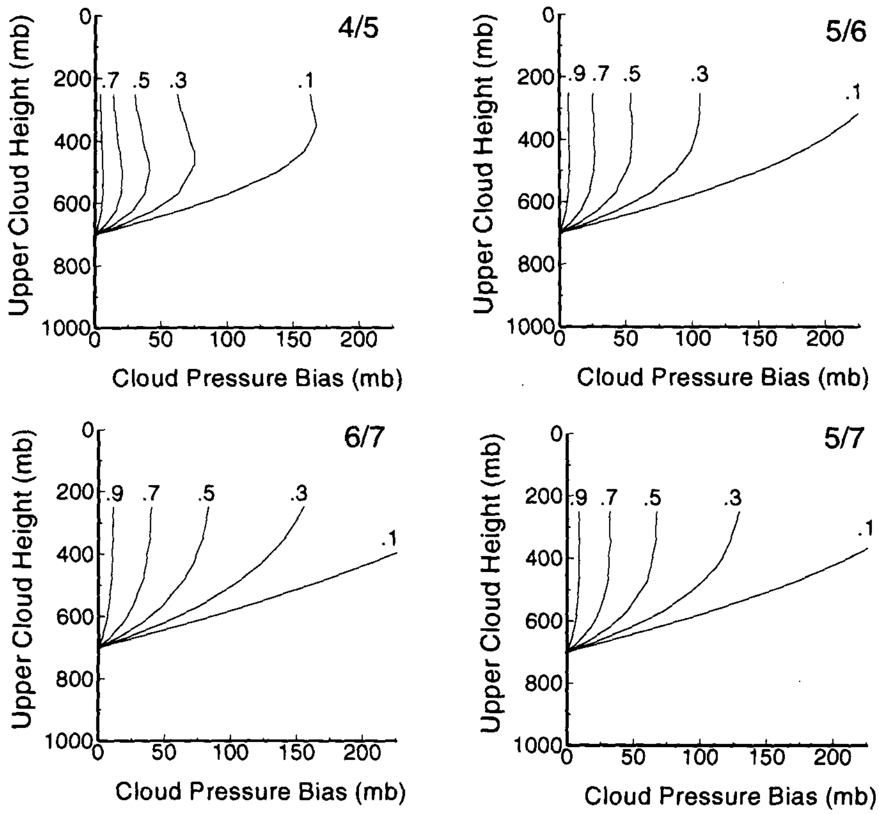

FIG. 6. Similar to Fig. 3 except the lower cloud layer is fixed at 700 mb.

the actual cloud pressures. The instrument noise bias in retrieved cloud pressures is shown in the middle row of frames in Fig. 7 for the HIRS 4/5, 5/6, and 6/7 channel combinations, respectively. These frames show that low- and midlevel cloud retrievals are biased lower in pressure than the actual pressure (i.e., clouds appear higher in altitude), while clouds retrieved near the tropopause are biased higher than the actual pressure (i.e., clouds appear lower in altitude). Wielicki and Coakley (1981) showed that this bias is caused by the imposed physical limitations on cloud amount to the range (0.0, 1.0) and limiting cloud pressures to the range between the surface and the tropopause. In addition to the above standard deviation and bias results in cloud pressure due to instrument noise, we also consider errors due to the presence of overlapping cloud layers. The bottom row of frames in Fig. 7 shows the standard deviation of retrieved upper cloud-top pressure (mb) for the 4/5, 5/6, and 6/7 channel combinations assuming that an opaque lower-level cloud at 850 mb underlies the upper cloud for half of the total number of oceanic midlatitude HIRS FOVs as discussed earlier in this section. For the special case considered here of an ensemble of HIRS pixels in which half of the total pixels are single layered and half are two layered, the standard deviation of the cloud pressure retrieval error is equal in magnitude to the bias error.

Since anticipated MODIS instrument noise as listed in Table 1 is less than that for the same HIRS channels, the standard deviation of retrieved cloud-top pressure should be less than that for the same HIRS channel combinations. We find in our calculations that the standard deviation in retrieved cloud pressure scales approximately linearly with instrument noise; that is, the standard deviations in retrieved cloud pressure for MODIS are about 75% of those found for HIRS for the same channel combinations. The only way to decrease instrument noise for the HIRS instrument is to average the radiances from more than one FOV. This would increase the observation area and would decrease the chances of viewing a homogeneous cloud or clear scene. However, if one considers the higher-resolution (1 km) MODIS radiometric data for the 15-μm channels, the process of averaging four pixels together, for example, would decrease the error by a factor of 2.

From the above discussion it becomes apparent that noise due to the instrument can introduce significant errors in the computation of cloud-top pressure relative to the presence of an opaque lower-level cloud. However, since the errors due to the presence of a lower opaque cloud layer increase cloud pressure retrieval errors more for the 6/7 ratio than for the 5/6 or the 4/5 ratios, the optimal channel choice is no longer as straightforward as in Wielicki and Coakley (1981). In

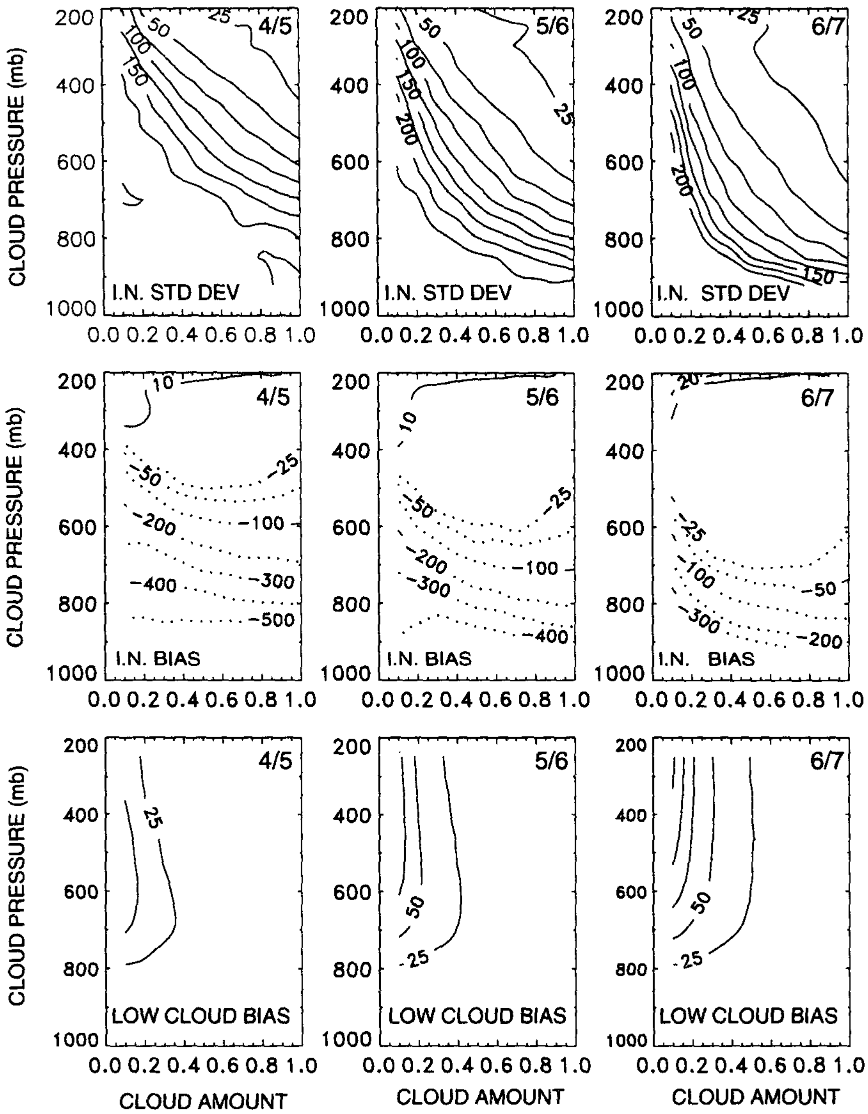

FIG. 7. The frames in the top row show the standard deviation (STD DEV) in cloud pressure error (mb) caused by instrument noise (IN) only for the HIRS 4/5, 5/6, and 6/7 channel combinations. The middle row of frames shows the corresponding cloud pressure bias error (mb) caused by instrument noise only for the HIRS 4/5, 5/6, and 6/7 channel combinations. Negative IN bias error (pressure lower than actual) is shown as dotted line, and positive IN bias error (pressure higher than actual) is shown as solid line. The bottom row of frames shows the cloud pressure retrieval bias errors (mb) in retrieved upper-layer cloud-top pressure caused by a 50% probability of an opaque lower cloud at 850 mb for HIRS 4/5, 5/6, and 6/7 channel combinations, respectively. For this case, bias and standard deviation errors are equal (see section 4a).

an effort to determine the channel combination that provides the minimum standard deviation and bias errors, we combine the error results presented in Fig. 7 for each of the three channel combinations. Figure 8a shows the channel combination that provides the minimum in the standard deviation of the retrieved cloud pressures, taking into account the standard deviation errors caused by instrument noise and mixed single-layer and double-layer cloud cases. Figure 8a shows that the 6/7 ratio provides the lowest standard deviations for clouds below approximately 300 mb. For clouds higher than 300 mb, the 4/5 or 5/6 ratios provide lower errors. These results are relevant for studies in which minimizing the instantaneous error is important. For global climate studies, minimizing the bias errors is important. Figure 8b shows the channel ratio that provides the minimum bias, which was derived from the results of Fig. 7. Figure 8b shows that in order to minimize bias errors, there are three regimes that should be considered. The 4/5 ratio minimizes bias

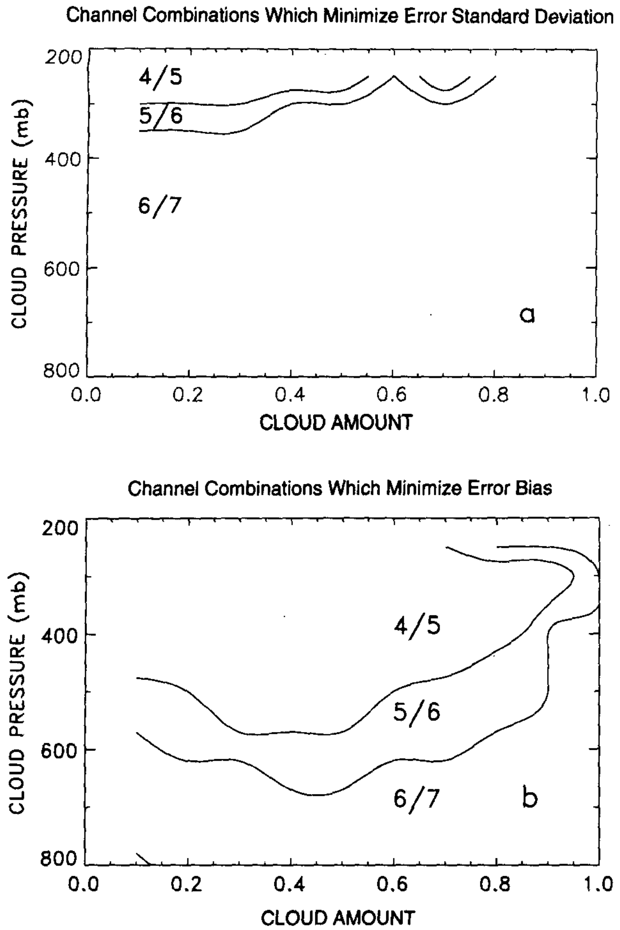

FIG. 8. Optimal channel combinations for cloud-pressure retrieval when considering both instrument noise and the 50% probability of two-layer cloud occurrences for (a) error standard deviation and (b) error bias.

error for high clouds (generally above 450 mb), the 5/6 ratio minimizes bias error for midlevel clouds (between perhaps 600 and 450 mb), and the 6/7 ratio minimizes bias for lower-level clouds. The optimal choice of HIRS channels for the midlatitude, oceanic scenario presented in this section thus depends on the type of study being performed with the infrared sounder data.

b. Identification of lower-cloud presence

Since the effect of neglecting a lower-level cloud may lead to significant errors in cloud pressure retrieval using the conventional sounding channel methods outlined in this study, it would be of use to determine first whether low clouds exist. If low clouds exist and the lower-level cloud-top pressure could be determined, then the low-cloud height could be incorporated in subsequent analyses of the HIRS data. A possible method would be to analyze the HIRS data in conjunction with the Advanced Very High Resolution Radiometer (AVHRR) instrument, as proposed by Baum et al. (1992). The AVHRR instrument is flown with the HIRS instrument on the NOAA platforms and has five narrow spectral bands with a nadir resolution of 1.1 km. The authors are currently extending this previous study to incorporate the spatial coherence method developed by Coakley and Bretherton (1982) and Coakley (1983). This method, when applied to the AVHRR imaging data, provides a means for determining the presence and the radiance of the underlying low cloud. Preliminary results from this approach as applied to a nighttime oceanic multilevel cloud scene are presented in Baum and Wielicki (1992). The AVHRR data were used to estimate P_{lc}, whereupon the HIRS 6/7 ratio was used in turn to derive upper-layer cloud pressure.

5. Conclusions

We have shown that bias errors in cloud pressure retrieval may result through the use of conventional sounding channel methods if a lower opaque stratiform cloud layer is present in a HIRS FOV. Our results for the HIRS 15-μm channels are similar to those presented by Menzel et al. (1992) and by Wielicki and Coakley (1981). Our results point to several issues that must be considered when using the sounding channel methods. We have shown that the largest biases result from the use of the lowest sounding channels. However, the lowest sounding channels have the smallest errors due to random instrument noise. In addition, the bias errors are greatest for the sounding channels whose weighting functions peak between 700 and 1000 mb. The biases in retrieved upper-cloud pressure also increase with increasing lapse rate between the lower-level cloud-top pressure and the surface. This last result indicates that we need the best possible information regarding the input temperature profile.

The conclusions from this study may be summarized as follows.

- The errors in cloud pressure and effective cloud amount due to the presence of a lower overcast, black cloud layer are greatest for the CO_2 slicing techniques that use the lowest sounding channel and least for those channels whose weighting functions peak higher in the atmosphere.
- The choice of the optimal HIRS channel selection depends on the type of study being performed. We find that while the HIRS channels whose weighting functions peak between 700 and 1000 mb minimize random errors, the use of the sounding channels whose weighting functions peak at 300–500 mb minimize bias errors. For a cloud climatology, the bias errors are most critical.
- The errors in cloud pressure and effective cloud amount depend upon the temperature lapse rate between the low-level cloud top and the surface. The re-

trieved upper-cloud pressure bias increases with increasing lapse rate between the low cloud and the surface.

Acknowledgments. The authors would like to thank H. Woolf for providing the HIRS upwelling radiance code. In addition, we would like to thank the two anonymous reviewers for their insightful comments that have helped to improve this paper.

REFERENCES

Baum, B. A., and B. A. Wielicki, 1992: On the retrieval and analysis of multilevel clouds. *Proc. 11th Int. Conf. on Clouds and Precipitation,* Montreal, Amer. Meteor. Soc., 1061–1064.

——, ——, P. Minnis, and L. Parker, 1992: Cloud property retrieval using merged HIRS and AVHRR data. *J. Appl. Meteor.,* **31,** 351–369.

CESA (Committee on Extension to the Standard Atmosphere), 1966: *U.S. Standard Atmosphere Supplements.* Government Printing Office, 278 pp.

Chahine, M. T., 1974: Remote sounding of cloudy atmospheres. I. The single cloud layer. *J. Atmos. Sci.,* **31,** 233–243.

Coakley, J. A., Jr., 1983: Properties of multilayered cloud systems from satellite imagery. *J. Geophys. Res.,* **88,** 10 818–10 828.

——, and F. P. Bretherton, 1982: Cloud cover from high resolution scanner data: Detecting and allowing for partially filled fields of view. *J. Geophys. Res.,* **87,** 4917–4932.

Hahn, C. J., S. G. Warren, J. London, R. M. Cherrin, and R. Jenne, 1982: Atlas of simultaneous occurrence of different cloud types over the ocean. NCAR Tech. Note, TN-201 + STR, 211 pp.

Kidwell, K. B., 1991: *NOAA Polar Orbiter Data Users Guide.* NOAA National Climatic Data Center, Satellite Data Services Division, 294 pp.

King, M. D., Y. J. Kaufman, W. P. Menzel, and D. Tanre, 1992: Remote sensing of cloud, aerosol, and water vapor properties from the Moderate Resolution Imaging Spectrometer (MODIS). *IEEE Trans. Geosci. Remote Sens.,* **30,** 2–27.

McCleese, D. J., and L. S. Wilson, 1976: Cloud top heights from temperature sounding instruments. *Quart. J. Roy. Meteor. Soc.,* **102,** 781–790.

Menzel, W. P., W. L. Smith, and T. R. Stewart, 1983: Improved cloud motion wind vector and altitude assignment using VAS. *J. Climate Appl. Meteor.,* **22,** 377–384.

——, D. P. Wylie, and K. I. Strabala, 1992: Seasonal and diurnal changes in cirrus clouds as seen in four years of observations with the VAS. *J. Appl. Meteor.,* **31,** 370–385.

Salomonson, V. V., W. L. Barnes, P. W. Maymon, H. E. Montgomery, and H. Ostrow, 1989: MODIS: Advanced facility instrument for studies of the earth as a system. *IEEE Trans. Geosci. Remote Sens.,* **27,** 145–153.

Smith, W. L., and C. M. R. Platt, 1978: Comparison of satellite-deduced cloud heights with indications from radiosonde and ground-based laser measurements. *J. Appl. Meteor.,* **17,** 1796–1802.

——, and R. Frey, 1990: On cloud altitude determinations from high resolution interferometer sounder (HIS) observations. *J. Appl. Meteor.,* **29,** 658–662.

Weinreb, M. P., H. E. Fleming, L. M. McMillin, and A. C. Neuendorffer, 1981: Transmittances for the TIROS operational sounder. NOAA Tech. Rep. NESS 85, U.S. Department of Commerce, 60 pp.

Wielicki, B. A., and J. A. Coakley, Jr., 1981: Cloud retrieval using infrared sounder data: Error analysis. *J. Appl. Meteor.,* **20,** 157–169.

Wylie, D. P., and W. P. Menzel, 1989: Two years of cloud cover statistics using VAS. *J. Climate,* **2,** 380–392.