

**CLOUD TOP PROPERTIES AND CLOUD PHASE  
ALGORITHM THEORETICAL BASIS DOCUMENT**

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## 1.0 Introduction

Cloud top properties (height, temperature, and effective emissivity) will be generated using the CO<sub>2</sub> slicing algorithm that corrects for possible cloud semi-transparency. The MODIS infrared CO<sub>2</sub> channels will be used to investigate clouds at 5 x 5 pixel resolution (Level 2) and to generate a global cloud climatology at 1.0 degree resolution (Level 3). At nadir one pixel has one km resolution. Additionally, cloud phase will be obtained by MODIS 8, 11 and 12 micron brightness temperature differencing at 5 x 5 pixel resolution (Level 2), and temporally averaged at 1.0 degree resolution (Level 3). This infrared technique will eventually be supplemented during daytime by the visible reflection function technique (King et al., ATBD-MOD-05) to result in a single MODIS cloud phase product. This document describes both algorithms, details the MODIS applications, and sizes the possible errors. Several references are available for further reading; for cloud top properties they are

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## 2.0 Overview

Cirrus clouds are crucially important to global radiative processes and the heat balance of the Earth; they allow solar heating while reducing infrared radiation to space. Models of climate changes will have to correctly simulate these clouds to have the proper radiative terms for the Earth's heat budget. Past estimates of the variation of cloud cover and the Earth's outgoing longwave radiation have been derived primarily from the longwave infrared window (10-12 microns) radiances observed from polar orbiting and geostationary satellites (Rossow and Lacis, 1990; Gruber and Chen, 1988). The occurrence of semi-transparent clouds is often underestimated in these single channel approaches. Recently, multispectral techniques have been used to better detect cirrus in global (Wylie et al., 1994; Wu and Susskind, 1990) and North American (Wylie and Menzel, 1989) cloud studies.

Cloud phase also plays a role in regulating the Earth's energy budget; ice and water clouds react differently to similar incident radiation. For example, more absorption takes place in ice clouds between 10 and 12 microns than in water clouds of equal water content based on the indices of refraction. Therefore, changes in cloud phase will affect climate feedback mechanisms and must be included in global climate models. In the infrared window region, changes in microphysical properties from 8 to 11 microns and 11 to 12 microns allow three carefully chosen bands to differentiate cloud phase. Past infrared single band and bi-spectral split window cloud detection techniques (Booth, 1978; Inoue, 1987; Inoue, 1989) cannot fully take advantage of these properties; to date, no single operational satellite contains three bands within these spectral ranges. Visible channel cloud phase detection techniques exist (Pilewskie and Twomey, 1987; King, 1992), but do not provide complete temporal coverage.

MODIS offers the opportunity to investigate seasonal and annual changes in the cirrus or semi-transparent global cloud cover and cloud phase with multispectral observations at high spatial resolution (one km rather than the current operational 17 km). Transmissive clouds that

are partially transparent to terrestrial radiation can be separated from opaque clouds in the statistics of cloud cover (Wylie and Menzel, 1989). To date semi-transparent or cirrus clouds have been found in roughly 40% of all HIRS observations (Wylie et al., 1994).

### 3.0 Algorithm Description

The theoretical basis of the algorithms and practical considerations are contained in this section.

#### 3.1 Theoretical Description

This section discusses the physics of deriving cloud height and amount, and cloud phase from multispectral infrared radiances from a given field of view, presents the application with MODIS data, and estimates different sources of error.

##### 3.1.1.a Atmospheric Physics of Cloud Top Properties Algorithm

The CO<sub>2</sub> slicing technique is founded in the calculation of radiative transfer in an atmosphere with a single cloud layer. For a given cloud element in a field of view (FOV) the radiance observed,  $R(\nu)$ , in spectral band  $\nu$  can be written

$$R(\nu) = (1 - NE)R_{clr}(\nu) + NE * R_{bcd}(\nu, P_c) \quad (1)$$

where  $R_{clr}(\nu)$  is the corresponding clear sky radiance,  $R_{bcd}(\nu, P_c)$  is the corresponding radiance if the field of view were completely covered with an opaque or "black" cloud at pressure level  $P_c$ ,  $N$  is the fraction of the field of view covered with cloud, and  $E$  is the cloud emissivity. It is apparent from this expression that for a given observed radiance, if the emissivity is

overestimated, then the cloud top pressure is also overestimated (putting it too low in the atmosphere).

The opaque cloud radiance can be calculated

$$R_{bcd}(\nu, P_c) = R_{clr}(\nu) - \int_{P_c}^{P_s} \tau(\nu, p) \frac{dB[\nu, T(p)]}{dp} dp \quad (2)$$

where  $P_s$  is the surface pressure,  $P_c$  is the cloud pressure,  $\tau(\nu, p)$  is the fractional transmittance of radiation of frequency  $\nu$  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  $\nu$  for temperature  $T(p)$ . The second term on the right represents the decrease in radiation from clear conditions introduced by the opaque cloud.

Following the work of Chahine (1974) and Smith and Platt (1978), to assign a cloud top pressure to a given cloud element, the ratio of the deviations in observed radiances,  $R(\nu)$ , and the corresponding clear air radiances,  $R_{clr}(\nu)$ , for two spectral channels of frequency  $\nu_1$  and  $\nu_2$  viewing the same FOV can be written as

$$\frac{R(\nu_1) - R_{clr}(\nu_1)}{R(\nu_2) - R_{clr}(\nu_2)} = \frac{NE_1 \int_{P_c}^{P_s} \tau(\nu_1, p) \frac{dB[\nu_1, T(p)]}{dp} dp}{NE_2 \int_{P_c}^{P_s} \tau(\nu_2, p) \frac{dB[\nu_2, T(p)]}{dp} dp} \quad (3)$$

If the frequencies are close enough together, then  $E_1$  approximates  $E_2$ , and one has an expression by which the pressure of the cloud within the FOV can be specified. The atmospheric temperature and transmittance profiles for the two spectral bands must be known or estimated.



Alternately, if clear sky radiances are unavailable, one can write a modified version of Equation (3) where the cloud top pressure is inferred from the radiance gradients in two CO2 slicing spectral bands within the area of interest (eg. 5 x 5 pixels).

$$\frac{R_{\min}(\nu_1) - R_{\max}(\nu_1)}{R_{\min}(\nu_2) - R_{\max}(\nu_2)} = \frac{(NE_{\min} - NE_{\max}) \int_{P_c}^{P_s} \tau(\nu_1, p) \frac{dB[\nu_1, T(p)]}{dp} dp}{(NE_{\min} - NE_{\max}) \int_{P_c}^{P_s} \tau(\nu_2, p) \frac{dB[\nu_2, T(p)]}{dp} dp} \quad (3')$$

where  $R_{\min}$  ( $R_{\max}$ ) is the cloudiest (clearest) pixel and  $NE_{\min}$  ( $NE_{\max}$ ) is the associated effective emissivity. Similar to before, one assumes that the gradients in the effective emissivities for the clearest and cloudiest pixels in the two spectrally close channels are the same, and one can solve for the cloud top pressure of cloud. This mitigates the dependence on finding or forward calculating clear sky radiances (the former being prone to errors from undetected cloud and the latter suffering from radiance bias corrections). One assumes that the radiance gradients are due to changes in effective emissivity and not change in cloud top pressure.

Once a cloud height has been determined, an effective cloud amount (also referred to as effective emissivity) can be evaluated from the infrared window channel data using the relation

$$NE = \frac{R(w) - R_{clr}(w)}{B[w, T(P_c)] - R_{clr}(w)} \quad (4)$$

Here  $N$  is the fractional cloud cover within the FOV,  $NE$  the effective cloud amount,  $w$  represents the window channel frequency, and  $B[w, T(P_c)]$  is the opaque cloud radiance. Effective emissivity cannot be calculated without an estimate of the window channel clear sky radiance.

Effective emissivity refers to the product of the fractional cloud cover,  $N$ , and the cloud emissivity,  $E$ , for each observational area ( $5 \times 5$  pixels). When  $NE$  is less than unity, MODIS may be observing broken cloud ( $N < 1, E = 1$ ), overcast transmissive cloud ( $N = 1, E < 1$ ), or broken transmissive cloud ( $N < 1, E < 1$ ). With an observational area of roughly five kilometer resolution, the semi-transparency for a given field of view is more often due to cloud emissivity being less than one than due to the cloud not completely covering the field of view; for most synoptic regimes, especially in the tropics and subtropics, this is found to be true (Wylie et al., 1994).

#### 3.1.1.b Physical Basis of Cloud Phase Algorithm

The intent of the cloud phase discrimination method is to implement an infrared-only based technique that works independently of solar illumination conditions. Originally, it was thought that a tri-spectral technique would be adequate for application to global data. The methodology improvements we report here stem primarily from the availability of more realistic cirrus scattering models than were reported previously and also operational application to global MODIS data. Originally, Strabala et al. (1994) discussed the development and application of a trispectral IR technique that used bands located at 8.5, 11, and 12  $\mu\text{m}$ . As much of the theoretical basis is still applicable, we will present that here. Modifications will be discussed subsequently.

The use of the IR bands to infer cloud phase has its roots in the calculation of radiative transfer in the atmosphere. Single scattering processes can be parameterized in the cloud emissivity  $E(\lambda)$  in Equation (1) (Parol et al., 1991). The bulk single scattering properties are defined by the index of refraction, the cloud particle size distribution and the particle shape distribution. This section discusses the underlying physical principles that determine the capabilities and channel bandwidths of the IR cloud phase technique.

Absorption and emission by clouds are dependent upon the index of refraction of the cloud particles and their size. The index of refraction ( $m$ ) of the particle is given by

$$m = n_r - in_i, \quad (5)$$

where  $n_r$ , the real portion, is an indication of the strength of scattering by the particle, and  $n_i$ , the complex portion, is an indication of absorptive properties of the material. Figure 1 depicts the real and imaginary portions of the index of refraction at wavelengths between 8 and 13  $\mu\text{m}$  for both ice and liquid water. *Warren* (1984) provide the most recent measured data of the ice refractive index in the IR. The water refractive indices are from *Downing and Williams* (1975). The magnitude of  $n_i$  for ice and water are nearly equal between 8.5 and 10  $\mu\text{m}$  but diverge between 10 and 13  $\mu\text{m}$ . Differences in the values of the indices for water versus ice will result in distinctive reactions to similar incident radiation. If water and ice clouds were to have the same temperature (i.e., exist at the same altitude), and have similar microphysical size and shape distributions, the 8.5- $\mu\text{m}$  cloud radiance would not depend greatly on thermodynamic phase. However, one might expect differences in the measured radiances between the ice and water cloud at 11 and 12  $\mu\text{m}$  as ice has greater values of  $n_i$  than water.

The divergence in  $m_i$  at wavelengths greater than 9.5  $\mu\text{m}$  formed the basis for the trispectral technique (*Ackerman et al.*, 1990; *Strabala et al.*, 1994; and *Menzel and Strabala*, 1997) to infer particle thermodynamic phase. *Strabala et al.* (1994) demonstrated that radiances of ice clouds and water clouds tended to separate when brightness temperature differences (BTD) between 8.5  $\mu\text{m}$  and 11  $\mu\text{m}$  (BTD[8.5-11]) and 11  $\mu\text{m}$  and 12  $\mu\text{m}$  (BTD[11-12]) are compared. Ice clouds tended to have greater values of BTD[8.5-11] than BTD[11-12] whereas water clouds tend to have greater BTD[11-12] than BTD[8.5-11] values. For the case studies considered, the water and ice clouds were well separated in height, so differences between water and ice clouds were maximized. But as will be shown below, this is only part of the story – other considerations

need to be taken into account for operational application.

The behavior of the IR radiances at these wavelengths for both ice and water clouds is dependent on the following parameters:

- a. atmospheric absorption by gases such as water vapor,
- b. the scattering properties of ice and water clouds, which are in turn based on particle size distributions and for ice clouds, particle habit distributions,
- c. surface emissivity, and
- d. cloud height.

Each of these parameters will be discussed briefly.

#### *Atmospheric Absorption*

The abundance of trace gases in the column above the cloud will affect the upwelling radiance. For a cloud-free atmosphere, scattering is negligible in the infrared region since the wavelengths are much greater than the size of gaseous molecules. The 8.5- $\mu\text{m}$  band is sensitive to  $\text{H}_2\text{O}$ ,  $\text{O}_3$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$ , while the 11- and 12- $\mu\text{m}$  bands are primarily affected by  $\text{H}_2\text{O}$  and  $\text{CO}_2$ .

#### *Cloud Single Scattering Properties*

Cloud single scattering properties depend on the assumed size distribution of the cloud particles. While water clouds are assumed to be composed entirely of spherical particles, ice clouds are generally composed of a variety of habits. The Version 1 cirrus scattering models, currently used in operational processing to retrieve optical thickness and particle size, are based on mixtures of randomly-oriented hexagonal plates and columns, two-dimensional bullet rosettes, and aggregates. Work is ongoing to update these models.

Tables 1 and 2 show the values of the single scattering albedo ( $\omega_0$ ) as a function of particle size for water and ice clouds, respectively. Further details on their derivation may be

found in Baum et al. (2000a). Examination of the last three columns of Table 1 shows that  $\omega_o$  is much larger at 8.52  $\mu\text{m}$  than at 11 or 12  $\mu\text{m}$  until values of  $r_{eff}$  become large.

**Table 1: IRW Water droplet single scattering albedo  $\omega_o$  as a function of effective size.**

$r_{eff}$	$\omega_o$ (8.52 $\mu\text{m}$ )	$\omega_o$ (11 $\mu\text{m}$ )	$\omega_o$ (12 $\mu\text{m}$ )
4	0.7459	0.2914	0.2218
8	0.7768	0.4400	0.3524
10	0.7550	0.4747	0.3871
16	0.6501	0.5151	0.4410
32	0.5348	0.5051	0.4815

**Table 2: IRW cirrus single scattering albedo  $\omega_o$ .**

$\lambda$ ( $\mu\text{m}$ )	$\omega_o$ Cs	$\omega_o$ Ci Uncinus	$\omega_o$ Ci (Cold)	$\omega_o$ Ci (Warm)	$\omega_o$ Ci (T=-40°C)	$\omega_o$ Ci (T=-60°C)
8.52	0.6966	0.5737	0.7574	0.6867	0.6473	0.7344
11.01	0.4822	0.5373	0.4124	0.4761	0.5044	0.4409
12.01	0.5412	0.5678	0.5021	0.5339	0.5501	0.5170

*Cloud Height Effects: Radiative Transfer Simulations*

The RT calculations shown in Figure 2 are based on a temperature and humidity rawinsonde profile recorded on April 21, 1996 during SUCCESS (Baum et al., 2000a). This profile is very similar to a midlatitude summer regime. The low-level water cloud resides at a

temperature of 284K while the cirrus is at 235K. These RT calculations indicate that the brightness temperature difference between the 8.5- and 11- $\mu\text{m}$  bands (hereafter denoted as  $\text{BTD}[8.5-11]$ ) tends to be positive in sign for ice clouds that have an infrared optical thickness greater than approximately 0.5. Water clouds of relatively high optical thickness tend to exhibit highly negative  $\text{BTD}[8.5-11]$  values of less than -2K. The  $\text{BTD}[8.5-11]$  values are quite sensitive to atmospheric absorption, especially by water vapor, and also to the surface emittance properties. Clear-sky  $\text{BTD}[8.5-11]$  values tend to be negative because the surface emittance at 8.5- $\mu\text{m}$  tends to be much lower than at 11  $\mu\text{m}$ , especially over non-vegetated surfaces. The  $\text{BTD}$  value for low-level water clouds tends to become more negative as the water vapor loading increases. While a relatively small effect, multiple scattering is included in radiative transfer simulations of the  $\text{BTD}[8.5-11]$ . Small particles tend to increase the  $\text{BTD}[8.5-11]$  values relative to large particles because of increased scattering. The  $\text{BTD}[11-12]$  values for water (Fig. 2b) and ice (Fig. 2d) clouds are similar in magnitude and sign; investigations into how best to utilize this additional information are still underway.

The difficulty encountered with midlevel clouds may be seen in the  $\text{BTD}[8.5-11]$  behavior shown in Figure 3. When ice and water clouds are well separated in height, the  $\text{BTD}[8.5-11]$  values, in conjunction with the 11- $\mu\text{m}$  BT, are adequate for phase discrimination. As the water and ice cloud top temperatures approach 260K, as in this example, one may note that the  $\text{BTD}[8.5-11]$  values are very similar for both the ice and water RT simulations. Therein lies the problem. Without additional information, perhaps with the use of a NIR band, unambiguous midlevel cloud phase discrimination is problematic.

### 3.1.2.a Mathematical Application of Cloud Top Properties Algorithm

The MODIS radiometer senses infrared radiation in seventeen spectral bands that lie between 3.75 and 14.24 microns at 1 km resolution (depending upon viewing angle) in addition to visible reflections at the same or better resolution. The four channels in the  $\text{CO}_2$  absorption band (ch 33 at 13.34, ch 34 at 13.64, ch 35 at 13.94, and ch 36 at 14.24 microns) are used to

differentiate cloud altitudes and the longwave infrared window channel (ch 31 at 11.03 microns) identifies the effective emissivity of the cloud in the MODIS field of view (FOV). Figure 4 indicates the weighting functions for the CO<sub>2</sub> absorption channels on MODIS.

Equation (3) will nominally be used to determine the mean cloud properties from a 5 x 5 FOV. On the left side of Equation (3), cloud radiances are determined by averaging the radiances for those FOVs designated to be probably cloudy or cloudy by the cloud mask (at least 4 must be flagged); this enables signal to noise ratio enhancement. Clear radiances are calculated in a radiative transfer calculation of the MODIS spectral band radiances using a transmittance model called Pressure layer Fast Algorithm for Atmospheric Transmittances (PFAAST) (Hannon et al. 1996); this model has 101 pressure level vertical coordinates from 0.05 to 1100 hPa. 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. The global analyses of temperature and moisture fields from the National Center of Environmental Prediction (NCEP) is used to define the fields of temperature and moisture used in the forward calculation.

The right side of Equation (3) 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 (the integration through the atmosphere is accomplished at discrete 50 mb intervals and the best pressure level interpolated to 10 mb). Again, the NCEP global analyses of temperature and moisture fields are used. A radiance bias adjustment of measured versus calculated clear sky radiances will be incorporated when the eight day clear sky radiance composite is available for processing; this adjustment is necessary to assure that the right and left sides of Equation (3) are balanced.

Assuming that the emissivity of the clouds are the same for the two spectral channels, the desired solution is the  $P_c$  that best matches measured and calculated ratios; the search is restricted between the surface pressure (or the top of the inversion layer) and the tropopause.

Alternately, Equation (3') can be used. The left side of Equation (3') could be determined from the MODIS observed radiance gradients with the 5 x 5 FOV area. This version of the CO<sub>2</sub> slicing algorithm has been tested but is not used routinely.

Using the ratios of radiances of the four CO<sub>2</sub> spectral channels and the infrared window channel, five separate cloud top pressures can be determined (14.24/13.94, 13.94/13.64, 13.94/13.34, 13.64/13.34, and 13.34/11.03). From theoretical considerations it is found that a 5% adjustment in the emissivity of ice clouds is advisable for the spectrally close CO<sub>2</sub> channels (e.g. the emissivity in the 14.24 micron channel is about 5% less than the emissivity in the 13.94); that adjustment in Equation (3) has been tested (Zhang and Menzel, 2002) but has not yet been incorporated.

Whenever  $(R - R_{clr})$  or  $(R_{max} - R_{min})$  is within the instrument noise (conservatively estimated at roughly .5 mW/m<sup>2</sup>/ster/cm<sup>-1</sup>),  $P_c$  cannot be determined reliably. Using the five cloud top pressures, as many as five effective cloud amount determinations can be made using Equation (4). 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<sub>2</sub> channels and the infrared window.

Once NE is determined, then E can be estimated. Using the cloud mask generated for all MODIS pixels (Ackerman et al., ATBD-MOD-06), an estimate of the cloud cover, N, for the 5 x 5 pixel array is made, and in turn E is inferred. The cloud top temperature is also readily estimated using a representative temperature profile (Menzel and Gumley, ATBD-MOD-07).



If no ratio of radiances can be reliably calculated because  $(R - R_{clr})$  or  $(R_{max} - R_{min})$  is within the instrument noise level, then a cloud top pressure is calculated directly from the infrared window channel (assuming it has adequate signal to noise). The MODIS observed 11.03 micron infrared window channel brightness temperature is compared with an in situ temperature profile to infer a cloud top pressure and the cloud cover,  $N$ , and the cloud emissivity,  $E$ , are assumed to be unity. In this way, all clouds are assigned a cloud top pressure either by CO<sub>2</sub> or infrared window calculations. Very thin high cloud are sometimes mistaken for low level opaque clouds; Wylie and Menzel (1989) found that this occurred for about half of the very thin clouds with  $NE$  less than 10%.

In summary, the calibrated and navigated MODIS data will be processed for 5 X 5 pixel areas. Fields of view are determined to be clear or cloudy from the cloud mask (Ackerman et al. ATBD-MOD-06). In the case where all 21 to 25 of the 1 km FOV's are clear, no cloud parameters are calculated. The data also will be corrected for zenith angle, to minimize any problems caused by the increased path length through the atmosphere of radiation upwelling to the satellite. Global coverage is expected every two days with one satellite.

(1) In Equation (3), the LHS (left hand side) is determined using the measured cloud radiance minus a forward calculated clear radiance (the cloud forcing) for the CO<sub>2</sub> slicing channels in the 5 x 5 pixel area. The NCEP global model is used to calculate the clear radiances; these forward calculated radiances must still be adjusted for radiance bias (calculated - measured clear radiance) inferred for clear FOVs from the previous weeks. The same global model is used to calculate the RHS (right hand side) for a distribution of cloud top pressures; this calculation will be performed only at the grid spacing of the model.

(1') Or the algorithm can chose to proceed with measured only radiances to calculate the LHS of Equation (3'). In this approach, the measured radiance gradients in the 5 x 5 pixel area for the CO<sub>2</sub> slicing channels are used to determine the cloud forcing. The RHS is calculated as in step (1).

(2) For a given  $P_C$ , NE is calculated from the longwave infrared window channel cloud forcing using Equation (4), where clear radiance is inferred from the calculated value in step (1).

(2') Alternately, the algorithm can choose to use the measured cloud forcing inferred from the difference of the average of clear fovs within the 5 x 5 pixel area minus the average of the cloudy fovs, as designated by the cloud mask (if no clear FOVs, then check nearest neighbor boxes and borrow that value).

(3)  $P_C$  and NE, that best satisfy RTE for CO<sub>2</sub> and IRW channels, are selected.

(4) Given NE, N is calculated by counting the number of cloudy FOVs in the cloud mask and dividing by 25; E is then inferred from NE/N.

(5) If radiance gradients or cloud forcing are too small (within instrument noise), infrared window channel solution for an opaque cloud is used.

### 3.1.2.b Mathematical Application of the Cloud Phase Algorithm

While the original MODIS IR phase approach was based on the use of the 8.5, 11, and 12- $\mu$ m bands, the results obtained from operational testing uncovered some problems. The essence of the tri-spectral method consisted of interpreting a scatter diagram of BTD[8.5-11] versus BTD[11-12] values. To obtain a scatter plot of such values, an entire MODIS scan line was processed at one time. Much of the testing prior to the launch of MODIS involved the use of MODIS Airborne Simulator (MAS) data, or with case studies using the lower spatial resolution HIRS-10 instrument, which was the only satellite that contained all three IR bands. The MAS data was collected primarily in the midlatitude region in the Northern Hemisphere and did not tend to include midlevel, mixed phase clouds. When working with MAS data, at 50-m pixel resolution, certain problems were never encountered such as scenes that contain clouds at multiple levels. When applied to MODIS scan lines, with a much greater swath width, data from low clouds over water in one part of the scan were mixed with data from high clouds over land in another part of the same scan line.

Another problem encountered during initial operational application of the trispectral algorithm was that the slopes between the BTD[8.5-11] and BTD[11-12] values were often close to zero, thereby confusing the algorithm. This problem was noted for clouds at temperatures between approximately 250K and 270K. One topic that hadn't been adequately addressed during the testing phase was the ability to discriminate between ice and water particles at cloud top when the clouds may contain primarily supercooled water droplets or perhaps a mixture of both ice and water (i.e., mixed phase). Single-layered clouds of wide spatial extent having cloud-top temperatures in the range between 250K and 270K are prevalent in the storm tracks in both the Northern and Southern Hemispheres. These clouds are extremely difficult to discriminate phase for unambiguously. Current efforts are to improve cloud phase discrimination for clouds at temperatures between 233K and 273K, the range over which the presence of supercooled water is possible.

Furthermore, optically thin cirrus is very difficult to detect, the estimation of phase is often ambiguous. To ameliorate these and other problems, the approach was distilled and simplified so that it could be applied to any individual pixel or averaged group of radiances. Currently, cloud phase is inferred from analysis of the 8.5- and 11- $\mu\text{m}$  brightness temperatures.

The MODIS 8.5- and 11- $\mu\text{m}$  bands are used to determine cloud phase over a 5 pixel x 5 pixel area. The MODIS cloud mask (MOD35) provides a pixel-level product that identifies pixels which are unobstructed (i.e., clear sky). The brightness temperatures for each band for a given FOV are averaged over each 5 by 5 pixel box. As the implementation now being used does not rely on analyses of scatter plots, as did the original code, the method may easily be applied to each pixel if desired.

### 3.1.3.a Estimate of Errors of Cloud Top Properties Algorithm

In the study of Wylie and Menzel (1989), the CO<sub>2</sub> cloud heights derived from VAS (VISSR Atmospheric Sounder) data over North America were found to be of good quality when compared to three other independent sources of cloud height information. Results showed: (a) for about thirty different clouds, the CO<sub>2</sub> heights were within 40 mb rms of cloud heights inferred from radiosonde moisture profiles; (b) in 100 comparisons with lidar scans of clouds, the CO<sub>2</sub> heights were 70 mb lower on the average and were within 80 mb rms; (c) satellite stereo parallax measurements in 100 clouds compared to within 40 mb rms. The CO<sub>2</sub> heights appeared to be consistent with other measurements within 50 mb and the effective fractional cloud cover within 0.20 in most cloud types. The CO<sub>2</sub> slicing technique works best for middle and high clouds, but has trouble with very low clouds.

#### 3.1.3.a.1 Errors Associated with the Assumption of Constant Emissivity

Spectrally close channels are used to minimize differences in the cloud emissivity between the two spectral channels. Calculations by Jacobowitz (1970) indicate that negligible error occurs in the cloud top pressure estimation using the assumption of constant emissivity for the CO<sub>2</sub> channels between 13.3 and 14.2 microns.

#### 3.1.3.a.2 Errors Associated with the Assumption of a Thin Cloud Layer

The CO<sub>2</sub> slicing algorithm assumes that all of the radiative effects of the cloud occur in the top thin layer. This makes the mathematics tractable. If the radiative transfer integral of Equation (3) were to include a cloud term where the cloud has finite depth, then a knowledge of the vertical structure of the cloud would be required. There are an infinite variety of combinations of cloud depths and vertical combinations that could produce the same integrated

radiative signature; a unique solution is not possible. Any initial assumption of cloud structure biases the cloud top and bottom solution derived in the radiative transfer formulation.

The thin layer cloud approximation is investigated in Smith and Platt (1978). They found that errors in the height assignment approaching one-half (one-quarter) the thickness of the cloud were introduced for optically thin (thick) clouds where the integrated emissivity is less than (greater than) .6. The largest errors will be associated with physically thick but optically thin cirrus clouds. For optically thin (very transparent) cirrus with 100 mb depth the error in the height estimate is roughly 50 mb.

Wielicki and Coakley (1981) also discussed the consequences of the thin layer cloud approximation. They concluded that the algorithm solution ( $P_c$ ) would be near the center of the cloud for optically thin clouds and near the top of the cloud for optically thick clouds. This is similar to a center of mass concept. The algorithm solution will thus be close to the "radiative center" of the cloud. Thus,  $P_c$  is somewhere between the cloud top and its center varying with the density of the cloud.

Cirrus height errors are also discussed in Wylie and Menzel (1989) where VAS cloud top pressure estimates were compared to cloud tops measured by lidars and by the stereo parallax observed from the images of two satellites at two different viewing angles. VAS CO<sub>2</sub> channels (14.25, 14.01, and 13.33 microns) are similar to three of the four on MODIS. In the lidar comparison, the VAS inferred cloud top pressure over an observation area was compared to the highest lidar observation in the same area; these clouds had to be radiatively thin for the lidars to see through to the tops. Definition of a single cloud top was often difficult within a cloud layer; the lidar heights varied considerably (by more than 50 mb) from one cloud element to another in the same cloud layer. On the average, the VAS  $P_c$  was found to be 70 mb larger (lower cloud altitude) than the tops seen on the lidars. The CO<sub>2</sub> slicing technique was sensing the mean height; the VAS heights were comparable to the lidar top heights to within half the cloud

thickness. In the comparisons to stereo parallax measurements for thin transmissive clouds, the VAS heights showed little bias. It was often difficult to measure parallax for thin transmissive clouds, as they appeared fuzzy with poorly defined boundaries in the images. Since the image of the clouds is more indicative of the center of the diffuse cloud mass than its outer boundaries, the parallax method is also sensitive to the radiative center of mass rather than the physical tops of these clouds. Thus, in these intercomparisons of actual measurements, the CO<sub>2</sub> cloud top pressures were found to be within the accuracy suggested by theoretical considerations.

### 3.1.3.a.3 Errors Associated with the Presence of a Lower Cloud Layer

The algorithm assumes that there is only one cloud layer. However, for over 50% of satellite reports of upper tropospheric opaque cloud, the ground observer indicates additional cloud layers below (Menzel and Strabala, 1989). To understand the effects of lower cloud layers, consider the radiation sensed in a cloudy field of view. For a semi-transparent or cirrus cloud layer, the radiation reaching the satellite,  $R$ , is given by

$$R = R_a + E * R_c + (1 - E) * R_b \quad (10)$$

where  $R_a$  is the radiation coming from above the cloud,  $R_c$  is the radiation coming from the cloud itself,  $R_b$  is the radiation coming from below the cloud, and  $E$  is the cloud emissivity. When a lower cloud layer is present under the semi-transparent or cirrus cloud,  $R_b$  is smaller (i.e., some of the warmer surface is obscured by the colder cloud). If prime indicates a two layer cloud situation of high semi-transparent cloud over lower cloud, and no prime indicates a single layer high semi-transparent cloud, then

$$R_b' < R_b, \quad (11)$$

which implies

$$R' < R. \quad (12)$$

Thus the difference of cloud and clear radiance is greater for the two layer situation,

$$[R_{clr} - R'] > [R_{clr} - R]. \quad (13)$$

The effect of two cloud layers is greater for the 13.3 micron channel than for the other CO<sub>2</sub> micron channels, because the 13.3 micron channel "sees" lower into the atmosphere (Figure 4 shows the weighting functions where the 13.3 peaks lower in the atmosphere than the other CO<sub>2</sub> channels). So using the 13.9/13.3 ratio as an example

$$[R_{clr}(13.3) - R'(13.3)] > [R_{clr}(13.9) - R'(13.9)] \quad (14)$$

This reduces the ratio of the clear minus cloud radiance deviation in Equation (3) because the denominator is affected more than the numerator (when the less transmissive channel is in the numerator),

$$\frac{[R_{clr}(13.9) - R'(13.9)]}{[R_{clr}(13.3) - R'(13.3)]} < \frac{[R_{clr}(13.9) - R(13.9)]}{[R_{clr}(13.3) - R(13.3)]}, \quad (15)$$

or Left' < Left, where Left refers to the left side of Equation (3). An example plot of  $P_c$  versus Right (where Right refers to the right side of Equation (3)), shown in Figure 5, indicates that Left' < Left implies  $P_c' > P_c$ . Thus, when calculating a cloud pressure for the upper semi-transparent cloud layer in a two cloud layer situation, the CO<sub>2</sub> slicing algorithm places the upper cloud layer too low in the atmosphere.

An example from 25 October 1990 using VISSR Atmospheric Sounder (VAS) data is presented to illustrate further the magnitude of the errors that can be induced by lower level clouds (results for other days and other situations were found to be comparable). Ground observers in Omaha, Nebraska reported thin cirrus clouds with no other underlying clouds present. The ratio of the 13.9 to 13.3 micron satellite observed radiance differences between clear and cloudy FOVs (the left side of Equation (3)) is 0.36 on 25 October. This implies single layer cloud at 300 mb (solving the right side of Equation (3) for  $P_c$  as shown in Figure 5).

$R'$  has been modeled for a semi-transparent cloud at 300 mb with an underlying opaque cloud layer at 920, 780, 670, 500, and 400 mb (each configuration produces a different ratio in the left side of Equation (3), Left'). The different Left' suggest different  $P_c'$  solutions as Left' is matched to Right, the right side of Equation (3). In the absence of any knowledge of a lower layer, the CO<sub>2</sub> algorithm integrates the right side of Equation (3) from the surface to an incorrect  $P_c'$ . Figure 5 shows Right as a function of  $P_c$  for the situation of 25 October. The errors in calculated cloud top pressure from the original 300 mb solution,  $P_c' - P_c$ , are shown as a function of height of the underlying opaque cloud layer in Figure 6a for 25 October.

In the two cloud layer situation, the position of the lower cloud layer affects the accuracy of the estimate of the height of the upper cloud layer. Opaque clouds in the lower troposphere underneath high cirrus have little affect on the cirrus  $P_c$ . Inspection of the spectral transmittance show that neither the 14.2 or the 13.9 micron channels are very sensitive to radiation from low in the troposphere, while the 13.3 micron channel senses only about half of the radiation from below 800 mb. Opaque clouds in the middle troposphere, between 400 and 800 mb, underneath high cirrus, cause the cirrus  $P_c$  to be overestimated (lower in the atmosphere) by up to 220 mb (this extreme occurs for the very thin high cirrus cloud with NE of 0.10). The decreases in  $R_b$  produce smaller ratios for the left side of Equation (3) which in turn produces larger estimates of



$P_c$ . Opaque clouds high in the atmosphere, underneath higher cirrus, have little effect on the cirrus  $P_c$ , since the height of the lower opaque layer approaches the height of the semi-transparent upper cloud layer and the CO<sub>2</sub> algorithm is going to estimate a height in between the two layers.

The errors in  $P_c$  were also examined for different emissivities of transmissive clouds (see Figure 6b). This was modeled by varying the emissivity and forming new ratios on the left side of Equation (3). The maximum cloud top pressure error of roughly 220 mb occurred in very thin cloud with emissivity of 0.10. The error in  $P_c$  reduced as the emissivity of the transmissive clouds increased. For a cloud with emissivity of 0.5, the maximum error in  $P_c$  is about 100 mb. For more dense clouds with emissivity of 0.9, the maximum error in  $P_c$  is less than 20 mb. The VAS data have shown a nearly uniform population of emissivity center around 0.5 (Wylie and Menzel, 1989), so one can conclude that the errors in the cloud top pressure caused by underlying clouds should average under 100 mb.

Multi-layer cloud situations (transmissive over opaque cloud) cause the height estimate of the upper cloud to be about 100 mb too low in the atmosphere on the average. The error in transmissive cloud height is largest when the underlying opaque layer is in the middle troposphere (400- 700 mb) and small to negligible when the opaque layer is near the surface or close to the transmissive layer. The error in effective emissivity increases as the opaque layer approaches the transmissive layer; when they are coincident, the effective emissivity is assumed to be one. In summary the cloud forcing from two layers is greater than the cloud forcing from one layer; assuming only one cloud layer when two exist causes the CO<sub>2</sub> solution to put the cloud between the two layers with larger effective emissivity. This suggests that, overall, global cloud parameter estimates will be a little low in the atmosphere and with an effective emissivity a little too high.

Recent work has suggested that the radiative transfer equation in a two layer cloud situation can be solved from the CO<sub>2</sub> radiance observations. The two layer cloud forcing can be written, where  $u$  is the upper cloud layer and  $l$  is the lower cloud layer,

$$R - R_{clr} = N_l E_l \left[ 1 - N_u E_u \right] \int_{P_s}^{P_{cl}} \tau dB + N_u E_u \int_{P_s}^{P_{cu}} \tau dB \quad (16)$$

Thus the two layer cloud forcing is characterized by four unknowns  $N_l E_l$ ,  $N_u E_u$ ,  $P_{cl}$ , and  $P_{cu}$ . Using the measured cloud forcing in the CO<sub>2</sub> channels, a solution for upper and lower cloud pressures and effective cloud amounts is calculated. The algorithm selects spectrally close pairs of CO<sub>2</sub> channels. For each pair of cloud forcing measurements, all possible  $N_l E_l$ ,  $N_u E_u$  are calculated as a function of  $P_{cl}$ ,  $P_{cu}$ . From this array of possible solutions, the selected solution best satisfies the radiative transfer equation for all spectral channels. Since four unknowns offer more degrees of freedom than two unknowns, the two layer solution is preferred over the one layer solution. Indication of when to use the two layer solution is sought through inspection of 4.0 micron versus 11.0 micron radiance scatter plots for the 5 x 5 pixel area (when radiances for the two spectral channels lie on two or more straight lines then the presence of two or more cloud layers is suggested). More development work remains, before the two layer solution can be incorporated into the cloud parameter algorithm.

#### 3.1.3.a.4 Errors from an Inaccurate Estimate of the Surface Temperature

The CO<sub>2</sub> slicing algorithm has little sensitivity to surface temperature. The weighting functions for the CO<sub>2</sub> channels indicate that very little radiation from the Earth surface is detected by the satellite radiometer in these spectral bands (14.2 and 13.9 micron observations don't even see the ground). Table 3 indicates the changes in cloud top pressure associated with changes in estimates of surface temperature inferred from a recalculation of the right side of Equation (3); the atmospheric profile of 25 October was used as an example (other situations

yield similar results). When the surface temperature  $T_{sfc}$  is assumed to be 5 C too warm, the cloud top pressure  $P_c$  is 32 mb smaller (higher in the atmosphere); when  $T_{sfc}$  is assumed to be 5 C too cold,  $P_c$  is 26 mb larger (lower in the atmosphere). In other words, when the surface temperature guess doesn't track surface warming (cooling), then the cloud layer is calculated to be too low (high).

Table 3 also indicates an additional effect that arises when the surface temperature is assumed to be too cold. In the cloud screening process, some cloudy FOVs are inferred to be clear and  $R_{clr}$  is reduced for all spectral channels. Thus the left side of Equation (3) is reduced (when the less transmissive channel is in the numerator) and  $P_c$  goes even larger (lower in the atmosphere). The last four columns of Table 3 show the total error when 25% of the FOVs are incorrectly inferred to be clear for a guess that is 5 C too cold; when high clouds at 300 mb contaminate the clear radiance determination,  $P_c$  is 39 mb larger (representing an additional error of 13 mb), and when low clouds at 700 mb contaminate the clear radiance determination,  $P_c$  is 20 mb larger (representing an offsetting error of 6 mb).

**Table 3. The changes in cloud top pressures ( $P_c$ ) and effective emissivities determined from the CO<sub>2</sub> slicing algorithm after changes to the estimated temperature profile and surface temperature (using the data of 25 October 1990).**

		Guess Error (guess - truth)		Cloud Top Pressure and Effective Emissivity Error					
								with additional errors from faulty cloud screening for contaminating clouds at	
met	sfc	atm			300mb		700mb		
cond	$DT_s$	$DT_{(p)}$	$DP_c$	$D(NE)$	$DP_c$	$D(NE)$	$DP_c$	$D(NE)$	
a	+5 K	0 K	-32 mb	-.09					
b	-5	0	+26	+.13	+39 mb	+.13	+20 mb	+.09	
d	0	+2	+10	+.03					

c	0	-2	-13	-.03				
ad	+5	+2	-20	-.07				
ac	+5	-2	-44	-.11				
bd	-5	+2	+37	+.19	+50	+.19	+31	+.14
bc	-5	2	+16	+.09	+28	+.09	+09	+.06

Possible meteorological conditions that could cause indicated errors in the guess

a indicates nocturnal cooling

b indicates solar heating

c indicates warm frontal passage

d indicates cold frontal passage

The surface temperatures are monitored hourly with the SVCA conventional observations; errors of 5 C are unusual, but do occur in the western mountains where surface observations are too sparse to accurately represent the varying altitude conditions. We conclude that nominal diurnal changes in surface temperature will not affect the CO<sub>2</sub> slicing solutions of  $P_c$  by more than 50 mb.

Furthermore, fictitious reports of transmissive clouds cannot be produced by changes in the ground surface temperature, since two of the three channels do not see the ground. As witnessed in Table 3, effective emissivity estimates are relatively insensitive to surface temperature excursions of 5 C; NE changes of about 0.10 are found.

The preceding discussion also implies that the CO<sub>2</sub> algorithm is insensitive to surface emissivity changes since 5% changes in surface temperature can be equated with roughly 7% changes in surface emissivity for the long wavelength channels.

### 3.1.3.a.5 Errors from an Inaccurate Estimate of the Temperature Profile

Table 3 also shows the changes in cloud top pressure associated with changes in estimates of temperature profile as well as surface temperature for the example of 25 October. When the entire temperature profile was changed by +/- 2 K in the calculation of the right side of Equation (3), the resulting changes were very small; about 10 mb for  $P_c$  and 0.03 for  $NE$ . These errors are roughly inversely proportional to the lapse rate at the altitude of the cloud. When the surface temperature and the atmospheric temperature were adjusted by 5 and 2 K respectively, maximum errors of roughly 40 mb in  $P_c$  and 0.20 in  $NE$  were found for the situation where the surface temperature was underestimated and the atmospheric temperature was overestimated (perhaps possible in nearly clear sky with strong solar heating producing a very large lapse rate in the lower atmosphere). Where the surface temperature and the atmospheric temperature were both underestimated (possible in a warm frontal passage), the cloud was estimated to be too low in the atmosphere by 20 mb in  $P_c$  and too opaque by 0.10 in  $NE$ .

Experiments were also conducted simulating errors localized to only one level of the temperature profile. The results (not shown) were modified minimally. Little sensitivity is apparent for temperature errors low in the atmosphere ( $P_c > 700$ ), as expected from inspecting the transmittances of the MODIS CO<sub>2</sub> channels. An error of 2 C for a level between 700 and 300 mb can produce a shift of up to 30 mb in the cloud top pressure. This should be viewed in conjunction with the lapse rate of 5 C per 50 mb for the example of 25 October. Here and in other situations inspected, the errors in the CO<sub>2</sub> slicing cloud top pressure estimate,  $DP_c$ , caused by sounding errors,  $DT$ , in layers where the CO<sub>2</sub> spectral channels have sensitivity, are found to be roughly inversely proportional to the lapse rate at the level of the cloud,  $L$ ; this can be expressed as  $DP_c = DT/L$ .

### 3.1.3.a.6 Errors Associated with Instrument Noise

The VAS radiometer is accurate to better than  $1 \text{ mW/m}^2/\text{ster/cm}_1$ . This corresponds to less than 1 K in the  $\text{CO}_2$  channels for temperatures ranging from 220 to 320 K. Noise affects the ability of the VAS to detect thin cirrus. Noise of 1 K implies that effective cloud emissivities of less than 10% cannot be resolved for high clouds (using  $D(NE) = \frac{DR}{(R - R_{clr})}$ ). In our earlier work of 1989, it was found that about half of the very thin clouds with  $NE$  less than 0.10 were classified incorrectly as low opaque cloud observations (this represented about 5% of all observations); it was also found that about half of these very thin clouds were correctly classified by the  $\text{CO}_2$  slicing algorithm.

The  $\text{CO}_2$  slicing technique cannot measure the properties of clouds where the contrast of radiation from cloud free and cloud obscured observations is too small for reliable discrimination in the satellite  $\text{CO}_2$  spectral radiances (when radiance differences are less than  $.5 \text{ mW/m}^2/\text{ster/cm}^{-1}$  cloud properties are not calculated). This occurs for very thin cirrus (as discussed in the previous paragraph) and for some low clouds below 700 mb. Clouds below 700 mb were assumed to have an effective emissivity of one, thus preventing the interpretation of low broken cloud as cirrus. Occasionally, low clouds were also reported in situations of clear sky with tropospheric temperature inversions; this created problems in early morning statistics during the winter months.

When noise is introduced in one channel of the  $\text{CO}_2$  radiance ratio, the left side of Equation (3) changes. Using the example of 25 October once again, Figure 5 shows the noise induced changes in the ratio. The extremes produce a  $P_c$  that is 50 mb lower or make it impossible to have a solution in the atmosphere. This example is representative of further noise investigations in the  $\text{CO}_2$  slicing algorithm; the effect of sensor noise is typically less than 50 mb.

### 3.1.3.a.7 Conclusions of the Cloud Top Pressure and Emissivity Error Studies

(i) Errors associated with the assumption of constant emissivity for the CO<sub>2</sub> channels are negligible.

(ii) The CO<sub>2</sub> slicing algorithm determines the height of the radiative center of the cloud; for optically thick clouds this is near the cloud top while for optically thin clouds it is near the cloud middle.

(iii) Multi-layer cloud situations where an opaque cloud underlies a transmissive cloud cause errors in the height of the transmissive cloud of about 100 mb for most cases (the cloud is determined to be too low in the atmosphere). The error in transmissive cloud height is largest when the underlying opaque layer is in the middle troposphere (400- 700 mb) and small to negligible when the opaque layer is near the surface or close to the transmissive layer.

(iv) When the surface temperature guess doesn't track surface warming (cooling), then the cloud layer is calculated to be too low (high). Nominal diurnal changes in the ground temperature are typically tracked to better than 5 C in the CO<sub>2</sub> slicing algorithm, so that they have little effect on the ability to detect transmissive clouds or to determine their heights.

(v) The CO<sub>2</sub> solution is largely insensitive to errors in the temperature sounding in the lower troposphere. There are often compensating effects in the integration of the atmospheric column. The errors in the CO<sub>2</sub> slicing cloud top pressure estimate caused by sounding errors in layers where the CO<sub>2</sub> spectral channels have sensitivity are roughly inversely proportional to the lapse rate at the level of the cloud.

(vi) Instrument noise causes the CO<sub>2</sub> slicing algorithm to miss roughly half of the thin cirrus with effective emissivity less than 0.10; this represents about 5% of all observations.

#### 3.1.3.b Error Estimates of Cloud Phase Algorithm

Modeled results and observations of the infrared cloud phase determination suggest it is very reliable in the determination of low-level water clouds and high-level ice clouds with optical thicknesses above approximately 0.5. The most difficulty pertains to (a) midlevel clouds for which unambiguous cloud phase discrimination is problematic, (b) extremely optically thin cirrus, and (c) when thin cirrus overlies a lower-level cloud (i.e., multilayered clouds). Verification of cloud phase will be made through comparison of ER-2 based Cloud Lidar System (CLS) depolarization lidar with both MAS and MODIS data. Known sources of error are discussed below.

#### 3.1.3.b.1 Errors Due to Mixed Phase Cloud Scenes

Single-layered clouds of wide spatial extent having cloud-top temperatures in the range between 250K and 270K are prevalent in the storm tracks in both the Northern and Southern Hemispheres. Unambiguous phase discrimination for these clouds is extremely difficult. Current efforts are to improve cloud phase discrimination for clouds at temperatures between 233K and 273K, the range over which the presence of supercooled water is possible.

#### 3.1.3.b.2 Errors Due to Non-uniform Surface Emissivities

The current version of the bispectral technique assumes a uniform surface emissivity for both IR bands. This is certainly not the case for many different ground surface types, including bare soils and deserts. Gao and Wiscombe 1994 modeled the effects of different surface types on the BTDR[8 – 11] values based on laboratory surface emissivity measurements. Their results suggest that certain types of bare rock, and dry vegetation will lead to misidentification of cloud phase by the tri-spectral technique due the resultant location of the brightness temperatures differences on the scatter diagram. Many different MODIS and MAS data sets over numerous surface types have been investigated to date.



### 3.1.3.b.3 Errors Due to Instrument Noise

An investigation into the effects of MAS pixel averaging on brightness temperature differencing was conducted, with distinct cloud signals becoming apparent after averaging over a 5 x 5 pixel box. This lowers the NEDT values for the 8, 11 and 12 micron channels (as evaluated for MAS 5 December 1993 data) to 0.13, 0.09 and 0.15 K respectively. The MODIS NEDT specifications of these infrared bands at 300 K is 0.05 K, suggesting that the noise will be within the limits for cloud phase delineation.

## 3.2 Practical Considerations

### 3.2.1.a Radiance Biases and Numerical Considerations of Cloud Top Properties Algorithm

The MODIS measured radiances will have biases with respect to the forward calculated radiances using model estimates of the temperature and moisture profile for a given field of view. There are several possible causes for this bias: these include calibration errors, spectral response uncertainty, undetected cloud in the FOV, and model uncertainty. Solution of Equation (3) and (4) uses measured and calculated cloud forcing (clear minus cloudy FOV radiances) and thus requires that this bias be minimized. Techniques developed at the European Centre for Medium range Weather Forecast to characterize the HIRS radiance bias with respect to the ECMWF model (Eyre, 1992) will be employed in the MODIS cloud algorithm. In order to reduce systematic biases from being introduced into the cloud height calculations, simulated MODIS spectral radiances from clear-sky FOVs will be compared to the corresponding observed radiances for several days at the beginning of each month processed. A regression relationship will be developed for a correction to the simulated radiances during subsequent reprocessing of the data. One relationship will be derived for all ocean regions. (In a continuous operational

setting, this could be done automatically, with the radiances stored in a rotating file containing data from several previous days.)

The measured and the calculated radiance gradient ratios in Equation (3) or (3') do not always converge within the allowable pressure bounds (between the tropopause and the top of the inversion layer or the surface). Solutions are not accepted if found at the boundaries, even though there may be a good meteorological reason to accept these values. In these cases the opaque cloud solution from the window channel is used.

Evaluation of the integrals in the right side of Equation (3) or (3') are performed at 50 mb increments (the integration through the atmosphere is accomplished at discrete 50 mb intervals and the best pressure level interpolated to 10 mb). When the slope in Figure 5 increases, instrument noise causes more error in the cloud top pressure determination. It has been found that mid-latitudes have greater slopes than the tropics, thus cloud top pressures in the tropics might be slightly less error prone.

#### 3.2.1.b Numerical Considerations of Cloud Phase Algorithm

The implementation of the cloud phase algorithm is very straightforward, and requires that the cloud mask product (MOD35) be available as well as the 8.5 and 11- $\mu\text{m}$  BT's for each cloudy pixel.

#### 3.2.2.a Programming Considerations of Cloud Top Properties Algorithm

Processing will be accomplished for every 5 x 5 pixel area (5 km resolution at nadir). The clear sky radiances come from a spatial analyses of the pixels designated clear by the cloud mask. Spatial registration of the channels must occur, so that FOVs can be collocated with ancillary data.

The CO<sub>2</sub> slicing algorithm has been used for the past nine years on VAS data over North America and for the past seven years on global HIRS data. It is a robust algorithm. The census of cirrus clouds derived from both of these efforts has been published in refereed literature.

Processing time for the MOD06CT algorithm are derived from using the direct broadcast version on a Sun solarix x86 machine. To process 5000 lines (~10 minutes) requires ~ 15 minutes.

The product Level 2 MOD06CT-5km volume per granule (5 minutes of data) is 14 MB. A full day of MODIS processing will then result in a volume load of 14 MB/granule \* 288 granules/day = 4.0 GB/day for the parameters listed in Table 5. It should be noted that product MOD06 also includes particle radius and optical thickness retrievals at 1km during the daytime. This increase the size of daytime granules to 60 MB.

### 3.2.3. Validation

Validation will be approached in several ways: (i) collocation with higher resolution aircraft data, (ii) ground-based and aircraft in situ observations, and (iii) intercomparisons with other AM-1 platform instruments. Our validation approach relies heavily on the sources of the data that were used in the algorithm development, which consisted primarily of the MAS, a fifty channel visible, near-infrared, and thermal infrared imaging spectrometer with 50 m resolution at nadir (cf. King et al. 1996), HIS, a 2 km resolution nadir-viewing Michelson interferometer with 0.5 cm<sup>-1</sup> spectral resolution from 4 to 15 μm (Revercomb et al. 1988), and AVIRIS, a 224 band imaging spectrometer from 0.4-2.5 μm with 20 m resolution at nadir.

Well-calibrated radiances are essential for the development of accurate algorithms. The calibration of the HIS is such that it serves as a reference for line-by-line radiative transfer

models. The MAS infrared channels are calibrated through two onboard blackbody sources that are viewed once every scan. Calibration of the shortwave infrared and thermal infrared channels will be routinely assessed through vicarious calibration and intercomparisons with the HIS flying on the same aircraft. The MAS solar channels are calibrated in the field, using a 30" integrating sphere before and after each ER-2 deployment, as well as a 20" integrating hemisphere shipped to the field deployment site for periodic calibrations during a mission. A comprehensive description of both the shortwave and longwave calibration procedures, signal-to-noise characteristics, and thermal vacuum characterization of the MAS can be found in King et al. (1996).

Several field campaigns are planned with the ER-2 aircraft carrying the MAS and HIS over various scenes and ecosystems. In addition to the major national and international activities outlined above, we envision the following focused and short field deployments:

- winter deployment over the Great Lakes, Hudson Bay, sea ice, and lake ice (based in Madison, WI);
- summer deployment over the ocean, mountains, and desert (based in Mountain View, CA).

A ground campaign with the ER-2 over the Atmospheric Radiation Measurement (ARM) CART (Clouds And Radiation Testbed) site in Oklahoma would entail:

- post-launch deployment of the MAS and HIS on the ER-2 aircraft to coincide with a MODIS overflight and to collect simultaneous ground-based class-sondes, AERI (a ground-based Michelson interferometer), tower measurements of temperature and moisture at various elevations, microwave moisture measurements, lidar and radar cloud observations, and whole sky camera images.

A ground campaign with all sky cameras (from the University of Chicago, Dr. Ted Fujita) would coincide with

- winter and summer in the upper Midwest.

Comparisons with products from other platforms are also planned. Cloud masks will be compared with those from AVHRR and HIRS/2 data, ASTER and MISR (also on the AM-1 platform), and CERES. Atmospheric profiles will be compared with those from HIRS, GOES, and AIRS (also on the PM-1 platform). Cloud properties will be intercompared with those derived from HIRS, GOES, CERES, MISR and AIRS, as well as from in situ aircraft (see below). Timing, coverage and resolution will vary from one instrument to another; for example with ASTER, comparisons will be possible for selected swaths (60 km wide with 30 m resolution) that are available for different (and selected) ecosystems no more than once every 16 days.

**Table 4. MODIS Field Campaigns used in Cloud Properties Validation**

<i>Mission</i>	<i>Dates</i>	<i>Responsible Team Members</i>	<i>Primary Purpose</i>
SUCCESS	April-May 1996	Si-Chee Tsay, Steve Ackerman, Steve Platnick	cirrus cloud properties with MAS and HIS
WINCE	February 1997	Paul Menzel, Steve Ackerman, Dorothy Hall	cloud detection and properties over snow/ice covered land and lakes with MAS and HIS
FIRE III	April-June 1998 August 1998	Michael King Si-Chee Tsay	arctic stratus clouds over sea ice
ARM-1	August- September 1998	Paul Menzel, Steve Ackerman, Dan LaPorte, Bill Smith	periodic flights over the Oklahoma ARM site with MAS & HIS & NAST
MOBY	December 1998	Paul Menzel, Steve Ackerman	cirrus clouds and atmospheric corrections over the ocean with MAS and NAST

ARM-2	April-May 1999	Paul Menzel, Steve Ackerman, Dan LaPorte, Bill Smith	periodic flights over the Oklahoma ARM site with MAS & HIS & NAST
LBA	September 1999	?	tropical clouds and biomass burning
California	July 1999 December 1999	Michael King, Steve Platnick, Si-Chee Tsay	marine stratocumulus and valley fog

Several field programs have already offered opportunities for pre-launch and post-launch MODIS validation through collection and analysis of observations obtained from the MODIS Airborne Simulator (MAS; King et al. 1996) and High-spectral resolution Interferometer Sounder (HIS; Revercomb et al. 1988). Those field campaigns relating primarily to cloud top properties and cloud phase are found in Table 4.

The Subsonic Aircraft Contrail and Cloud Effects Special Study (SUCCESS) field experiment in April-May 1996 had the goal of determining the radiative properties of cirrus contrails, and to contrast them with naturally occurring cirrus. To assess the radiative impact of these clouds requires a well-calibrated set of radiation measurements and “ground (or in situ) truth” observations. During SUCCESS several MAS and HIS multispectral observations from the NASA ER-2 aircraft were coordinated with in situ aircraft and ground based measurements. The MAS and HIS measurements address the very important relationship between cirrus radiative properties and the thermodynamic environment (atmospheric temperature and moisture conditions) wherein cirrus clouds form and are maintained. The HIS provides accurate measurements of the atmospheric thermodynamical properties supporting the cirrus life cycle and the MAS measures the cirrus areal extent and radiative properties. Special emphasis has been placed on developing and validating methods of detecting upper tropospheric clouds and defining their areal extent with infrared (e.g. 13.9  $\mu\text{m}$ ) and near infrared (e.g. 1.88  $\mu\text{m}$ ) channels; these are similar to the MODIS channels and MAS cirrus detection has direct relevance to the MODIS cloud mask algorithm.

Several studies have demonstrated the sensitivity of spectral radiances to cloud particle size and shape distributions. The MAS and HIS instruments provide accurate spectral measurements that can be used to assess differences in the radiative signatures between contrails and naturally occurring cirrus clouds. One difficulty in assessing the impact of high-altitude subsonic aircraft on cirrus formation and modification is the natural variability of the atmosphere and the potentially small signal of the radiative perturbation. Variations in the atmospheric spectral properties for contrail and natural cirrus conditions will be assessed with the two ER-2 instruments in conjunction with in situ and ground-based observations.

The Winter Cloud Experiment (WINCE January-February 1997) will investigate the difficulties in detecting cloud and estimating their properties in winter conditions. Cirrus and thin clouds over frozen tundra and lakes in the northern USA and Canada will be measured with the MAS and HIS (along with the GOES-8 and AVHRR). At least one of the missions will investigate the product stability in the transition from day (visible plus infrared) to night (infrared only) and then nighttime only. In addition two ground sites in New England will be instrumented for snow and ice cover measurements and MAS/HIS flights will be made in clear sky condition (in collaboration with Dorothy Hall and George Riggs working on the MODIS snow/ice product). The field campaign will be centered in Madison. Examples of the MAS cloud mask will be distributed to science team members so that they can determine its effect on their MODIS products.

FIRE, the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment, has previously conducted four successful field missions focused on cloud remote sensing and modeling studies as they relate to climate. FIRE Phase III will be conducted in the Arctic in two phases, phase I to be conducted over a 7 week period or longer with a serial deployment of low- to mid-level aircraft, together with a 4 week period of high-altitude ER-2 overflights. During this component of FIRE III, it is anticipated that the University of

Washington CV-580 and, to a lesser extent, the NCAR C-130Q will be utilized. Both of these aircraft will be equipped with an extensive set of PMS cloud microphysics probes, a Gerber PVM-100A liquid water content and effective radius probe, Johnson-Williams and King hot wire probes, a Nd:YAG lidar, thermodynamic state variable measurements, and selected chemistry instrumentation. In addition, the ER-2 will participate as the upper level aircraft from May 18-June 9, with the MAS, CLS, radiation measurement system for radiative fluxes, a multispectral along-track scanning radiometer, a microwave imaging radiometer. The primary sensors of interest to Goddard Space Flight Center (Michael King, Si-Chee Tsay, Steve Platnick, Robert Pincus) are the MAS on the ER-2, the CAR on the CV-580, and numerous in situ microphysics probes that will be invaluable in accessing the accuracy of cloud retrievals of the microphysical and radiative properties of Arctic stratus clouds over a bright (sea ice) surface. This valuable data set will also be of interest to the University of Wisconsin for testing the cloud mask algorithm, cloud phase and cloud top properties.

The first EOS-targeted campaign after the MODIS launch were coordinated with measurements taken at the ARM site in Oklahoma. The ER-2 with MAS and HIS are being deployed to synchronize with the MODIS overflight; the ARM site suite of ground-based measurements (class-sonde, AERI, tower measurements of temperature and moisture at various elevations, microwave moisture measurements, lidar and radar observations, whole sky images) will be collected simultaneously. These combined air and ground measurements are being used to validate MODIS radiance measurements. Results are being used to adjust the infrared calibration coefficients as necessary. In addition, the ARM ground-based measurements can be used to validate geophysical parameters as well. Lidar and radar observations of cloud boundaries over the ARM sites are being used to validate the presence of a cloud as well as its cloud top pressure altitude. Whole sky imagers are also available at the site, and can be used to compare satellite and ground-based estimates of cloud amount. Finally, optical depth measurements derived from lidar will aid in specifying the limit of thin cirrus detection in the cloud mask algorithm and for cloud properties.



An independent ground validation campaign of MODIS cloud heights is being undertaken through comparisons with stereo determinations of cloud heights (using the MISR over Great Britain and two GOES satellites over the U. S.), aircraft reports of cirrus cloud heights (from the ACARS), and lidar estimates of cirrus heights (using the University of Wisconsin lidar). These intercomparisons are being conducted in concert with a field campaign of the MAS on the ER-2 after the MODIS launch (probably at the time of the ARM overflights described above). Validation of the MODIS cloud emissivity is being attempted through comparison with the lidar determinations. Pre-launch validations came from cloud top property determinations with MAS data from several field campaigns which included lidar measurements.

The MOBY (Marine Optical Buoy) positioned near Lanai, Hawaii will be used in February 2003 to investigate MAS infrared-derived sea surface temperatures, visible/near-infrared water-leaving radiances, and radiometric calibration of the MAS measurements. The SST and water-leaving radiance data will aid in evaluating the results of several cloud mask spectral tests by providing accurate information on background radiance conditions. The effect of elevated water leaving radiances (caused by suspended materials or sub-aqueous bottom reflectance) on the cloud mask results will be investigated using MAS cloud mask results with MOBY water leaving radiances. MOBY data will also help assess temporal variability of water leaving radiance. MAS visible/near infrared calibration will be assessed by combining MOBY data with model-generated atmospheric scattered radiance. Well calibrated data are important for setting meaningful cloud mask test thresholds. Cloud investigation will be a by-product.

With the MODIS in orbit and returning regular data, several focused periods of ER-2 under-flights have been and are being coordinated with the Terra and Aqua orbits. Table 5 shows some of these. This indicates the intention for an ongoing Cal / Val activity.

**Table 5: Calibration and Validation Field Campaigns**

<u>Name</u>	<u>Reference URL</u>	<u>Principal Airborne Sensors</u>	<u>Primary Purpose</u>
SAFARI-2000	safari.gecp.virginia.edu	MAS, MQUALS,	Biophysical validation, LST, VI, Albedo, Aerosol, Fire
BOREAS	boreas.gsfc.nasa.gov/html_pages/boreas_home.html		Biophysical validation, LST, VI, Albedo, Aerosol, Fire
LBA	www-eosdis.ornl.gov/lba_cpTec/indexi.html	MAS	Biophysical validation, LST, VI, Albedo, Aerosol, Fire
CLAMS	snowdog.larc.nasa.gov/cave/cave2.0/C LAMS.dir/index.html	NAST-I, NAST-M, MAS	
TRACE			
CRYSTAL			
THORPEX	<a href="http://www.nrlmry.navy.mil/~langland/THORPEX_document/Thorpex_plan.htm">www.nrlmry.navy.mil/~langland/THORPEX_document/Thorpex_plan.htm</a>		
WINTEX	cimss.ssec.wisc.edu/wintex/wintex.html		
CAMEX	ghrc.msfc.nasa.gov/camex3/instruments/lase.html		
ARMCAS	ltpwww.gsfc.nasa.gov/MODIS/MAS/armcashome.html		Detect and differentiate between clouds, ice, and snow. Determine the scattering albedo of clouds
ACE-1 ACE-2	saga.pmel.noaa.gov/ace1.html www.ei.jrc.it/ace2		

3.2.3.a Validation of Cloud Top Properties Algorithm

The CO<sub>2</sub> slicing algorithm uses calibrated radiances that will be bias adjusted with respect to the NCEP forward calculations of clear sky radiances. Also the algorithm depends on the spectral radiance gradients or cloud forcing (clear minus cloudy fov radiances). These two considerations mitigate the algorithm dependence on extremely accurate calibration, although it is highly desirable.

As outlined in section 3.2.3 above, validation of the MODIS cloud heights will be undertaken through comparisons with stereo determinations of cloud heights (using the two GOES satellites over the U. S. and the University of Chicago ground all sky cameras), estimates

of cloud height from cloud shadows, (using aircraft MAS, NOAA AVHRR, and GOES data), reports of cirrus cloud heights (from the ACARS), and lidar estimates of cirrus heights (using the University of Wisconsin lidar). These intercomparisons will be conducted in concert with field campaigns of the MAS on the ER-2 after MODIS launch. Validation of the MODIS cloud emissivity will be attempted through comparison with the lidar determinations. Pre-launch validations will come from cloud top property determinations with MAS data from several field campaigns which will include stereo and lidar measurements also.

Post-launch validation will be made by comparing the cloud top properties product with CERES single sample footprint (SSF) and single satellite gridded (SSG) products that include cloud top pressure and temperature. CERES is heavily dependent on MODIS observations for cloud detection, so it will be important to ensure that the MODIS and CERES-derived cloud products are consistent. MISR altitude binned cloud fraction and stereo heights will be compared with the MODIS effective emissivity and cloud top heights to geometrically validate the MODIS radiometrically derived cloud height data.

#### 3.2.3.b Validation for Cloud Phase Algorithm

The cloud phase algorithm uses calibrated radiances which will be converted into brightness temperatures, and averaged over a 5 x 5 pixel box. The use of temperature differences between the 8, 11, and 12 micron channels averaging also stresses the algorithm dependence on very accurate relative calibration between channels.

Validation of the infrared cloud thermodynamic phase product will be made primarily through comparisons with cloud lidar determinations (CLS onboard the ER-2) and cloud microphysical data (collected on instruments onboard the CV-580 and NCAR C-130Q) collected during field campaigns outlined in section 3.2.3 above. Limited pre- and post-launch validation will also be carried out using collocated HIRS/AVHRR data sets, focusing on surface emissivity

effects. This data set has the advantage of its global coverage, but the spatial scale is far removed from that of MODIS, and the spectral bandwidths are wider and off center from those of MODIS. Post-launch validation will also consist of close inspection of sections of data representing differing cloud regimes and surface types, including cross checks during the day mode with the visible reflection function technique of King et al. (ATBD-MOD-05) and consistency with the cloud top properties results. Finally, post-launch validation will also include intercomparisons with other EOS instrument products such as the CERES SSF and SSG cloud phase product, and the ASTER polar cloud mask product, which includes a cloud phase bit.

#### 3.2.4.a Quality Control of Cloud Top Properties Algorithm

As indicated in section 3.1.3.a., the accuracy of the cloud top pressures have been found to be 50 mb root mean square with respect to radiosonde, stereo, and lidar estimates; the effective emissivity determinations have been found to be correlate within 20% root mean square of lidar visible estimates of optical thickness.

Quality control within the software checks for cloud forcing greater than the instrument noise and cloud top pressure within the atmospheric layer where temperature and pressure enjoy a one to one relationship. Additionally, cloud top pressures will be stratified as a function of satellite viewing angle to make sure that the atmospheric transmittance corrections for viewing angle are not introducing a bias.

Beyond these simple tests, quality control is accomplished by manual and automated inspection of the data and comparison to other sources of cloud information. MODIS cloud top pressures and effective emissivities will be compared to those determined from the NOAA HIRS and the GOES sounder. Additional data from field experiments using the MODIS Airborne Simulator on the ER2 will assist with quality assessment of the MODIS cloud parameter determinations.

Global mean distributions of cloud height and emissivity will be compared from one week to the next; thresholds will be set to flag unrealistic changes. Trend analyses of global cloud properties will be compared with trends in OLR; a strong correlation between the two will be expected. Additionally comparisons with ISSCP will be made. These comparisons will all be done with the gridded 1.0 degree resolution MODIS cloud properties (determined from averaging of the 5 x 5 pixel cloud properties).

The cloud top properties and cloud phase product (the 5 km resolution part of MOD06) will carry 10 bytes of quality analysis information for each pixel. The information contained in this byte array include a confidence in the usefulness of each individual parameter, input data resource flags and processing path flags. Please refer to the MODIS Atmosphere QA Plan for exact details.

### 3.2.4.b Quality Control of Cloud Phase Algorithm

Quality control will consist of consistency checks with previous days resultant statistics, including the global cloud phase determination consistency and known cloud area persistence consistency (marine stratus regions, etc.).

The cloud top properties and cloud phase product (the 5 km resolution part of MOD06) will carry 10 bytes of quality analysis information for each pixel. The information contained in this byte array include a confidence in the usefulness of each individual parameter, input data resource flags and processing path flags. Please refer to the MODIS Atmosphere QA Plan for exact details.

### 3.2.5 Exception Handling

If the required radiance data is not available, then the algorithm will record the cloud products missing for that 5 x 5 pixel area.

### 3.2.6. Data Dependencies

#### 3.2.6.a Data Dependencies of Cloud Top Properties Algorithm

The CO<sub>2</sub> slicing algorithm needs calibrated, navigated, coregistered one km FOV radiances from channels 29 (8.6 micron for moisture correction), 31 (11.03 micron infrared window), 32 (12.02 micron for moisture correction), 33-36 (13.335, 13.635, 13.935, and 14.235 microns CO<sub>2</sub> absorption band channels). Navigation implies knowledge of the surface terrain including height (DEM) and whether land or sea. The MODIS viewing angle for a given FOV must be known. The cloud mask from visible and infrared radiance considerations will be used as an indicator for cloud cover within a given one km FOV. The NCEP GDAS Final Run global model analysis of

surface temperature and pressure as well as profiles of temperature and moisture will be initially used in the calculation of the cloud forcing as a function of pressure and effective emissivity (in Equation (3)); as the AIRS/AMSU profiles become available, they will be used also. The Reynolds blended SST will also be used over the ocean. The algorithm also requires knowledge of the clear radiances for evaluation of the cloud forcing for each channel used in the ratio tests. This information will be provided in the form of clear radiance maps created and updated daily by the cloud mask production software. Table 6 summarizes the input data dependencies.

There has been some consideration for using the short wavelength CO<sub>2</sub> spectral bands 22 through 25 in parallel with the long wavelength CO<sub>2</sub> bands in a composite CO<sub>2</sub> slicing algorithm. The shortwave CO<sub>2</sub> algorithm has problems with reflected solar contributions during daylight hours, but is useful additional information at night. Current plans do not include these bands, but future versions of the software might.

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**Table 6. MODIS Cloud Parameter Input Data Dependencies**

MODIS data channels	29, 31-36
Navigation	lat, lon, land, sea
MODIS viewing angle	lin, ele, ang
Cloud mask	yes, no, type
Surface data	SST, model analysis of temperature, dewpoint and pressure,
	topography (DEM)
Model profiles	temp (12 levels), moisture (6 levels)
Clear Radiance Base Maps	Channels 31, 33-36.

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### 3.2.6.a Data Dependencies of Cloud Phase Algorithm

The bispectral cloud phase algorithm needs calibrated, navigated, coregistered one km FOV radiances (for FOV uniformity screening and conversion to brightness temperatures) from channels 29 (8.6 micron) and 31 (11.03 micron). The MODIS viewing angle for a given FOV

must be known. The MODIS cloud mask product will be used to screen areas where the probability of cloud is high. As the algorithm develops, a global surface emissivity map (related to surface cover) will be needed to adjust ice/water thresholds. Table 7 is a summary of the input data dependencies.

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**Table 7. MODIS Cloud Phase Input Data Dependencies**

MODIS data channels	29, 31
MODIS cloud mask	cloud or clear
Navigation	lat, lon, land, sea
MODIS viewing angle	lin, ele, ang
Surface data	surface emissivity

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3.2.7. Output Products

3.2.7.a Level 2 Output Product of Cloud Top Properties and Cloud Phase Algorithm

The Level 2 output file for each 5 x 5 pixel area (when cloud is present) is summarized in Table 8. The combined MODIS cloud properties, cloud phase and cloud retrieval product number is MOD06.

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**Table 8. MODIS cloud product (MOD06 - 5 km) Output File Contents**

parameter type	Bytes	content
double	8	Scan Start Time
float	4	location latitude
float	4	location longitude
short	2	Solar Zenith Angle
short	2	Solar Azimuth Angle
short	2	Sensor Zenith Angle



short	2	Sensor Azimuth Angle
short	14	brightness temperature of bands 29,31-36
short	2	surface temperature
short	2	surface pressure
byte	1	processing flag
byte	1	cloud height method (CO <sub>2</sub> slicing or IR window)
short	2	cloud top pressure
short	2	cloud top pressure day
short	2	cloud top pressure night
short	2	cloud top temperature
short	2	cloud top temperature day
short	2	cloud top temperature night
short	2	tropopause height
byte	1	cloud fraction
byte	1	cloud fraction day
byte	1	cloud fraction night
byte	1	cloud effective emissivity
byte	1	cloud effective emissivity day
byte	1	cloud effective emissivity night
short	2	cloud top pressure from IR window
short	2	spectral cloud forcing
short	10	cloud top pressure from ratios (33/31, 34/33, 35/33, 35/34, 36/35)
short	2	surface type
short	14	radiance variance (7 channels)
short	4	brightness temperature difference (8-11, 11-12)
byte	1	cloud phase infrared
byte	1	cloud phase infrared day
byte	1	cloud phase infrared night
byte	10	quality assurance at 5x5 km resolution

Total: 111 bytes/pixel

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### 3.2.7.b Level 3 Output Product of Cloud Top Properties and Cloud Phase Algorithm

The Level 3 cloud top properties and cloud phase products will be included as part of a joint atmosphere discipline group product (MOD44). The products will be produced on a daily bases from the Level 2 files, on an 8 day basis from the daily files and a monthly bases from the daily Level 3 files. The Level 3 daily files will be produced at 1.0 degree equal area only, while

the 8 day and monthly Level 3 product files are produced for both 1.0 degree equal area and 1.0 degree equal angle grids. The cloud top properties and cloud phase contribution to the joint product is shown in Table 9. An example of the probability of cirrus equal angle Level 3 product derived from HIRS data is provided in Figure 7.

**Table 9. Cloud Top Property and Cloud Phase Level 3 Output File Contribution to Joint Atmosphere Level 3 Products**

parameter number	content
1	thermodynamic phase (coded 0-6)
2	thermodynamic phase (coded 0-6) day
3	thermodynamic phase (coded 0-6) night
4	cloud top temperature
5	cloud top temperature day
6	cloud top temperature night
7	cloud top pressure
8	cloud top pressure day
9	cloud top pressure night
10	cloud top effective emissivity
11	cloud top effective emissivity day
12	cloud top effective emissivity night
13	probability of cirrus
14	probability of high cloud

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## 4.0 Assumptions

### 4.0.a Assumptions of Cloud Top Properties Algorithm

The data is assumed to be calibrated (within the instrument noise), navigated (within one FOV), and coregistered (within two tenths of a FOV). The algorithm assumes the presence of only one cloud layer of infinitesimal thickness; adjustments for the presence of multiple cloud layers are under investigation. The cloud need not cover the entire FOV. Spectral cloud forcing must be greater than the instrument noise.

### 4.0.b Assumptions of Cloud Phase Algorithm

Assumptions are discussed in the estimate of error section 3.1.3.b.

## Figures

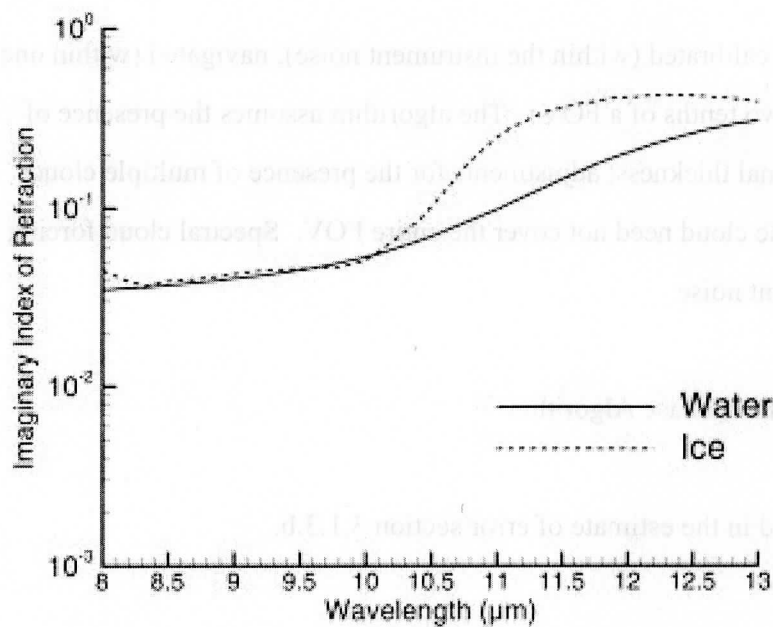


Figure 1: Imaginary index of refraction for water and ice between 8 and 13  $\mu\text{m}$ .



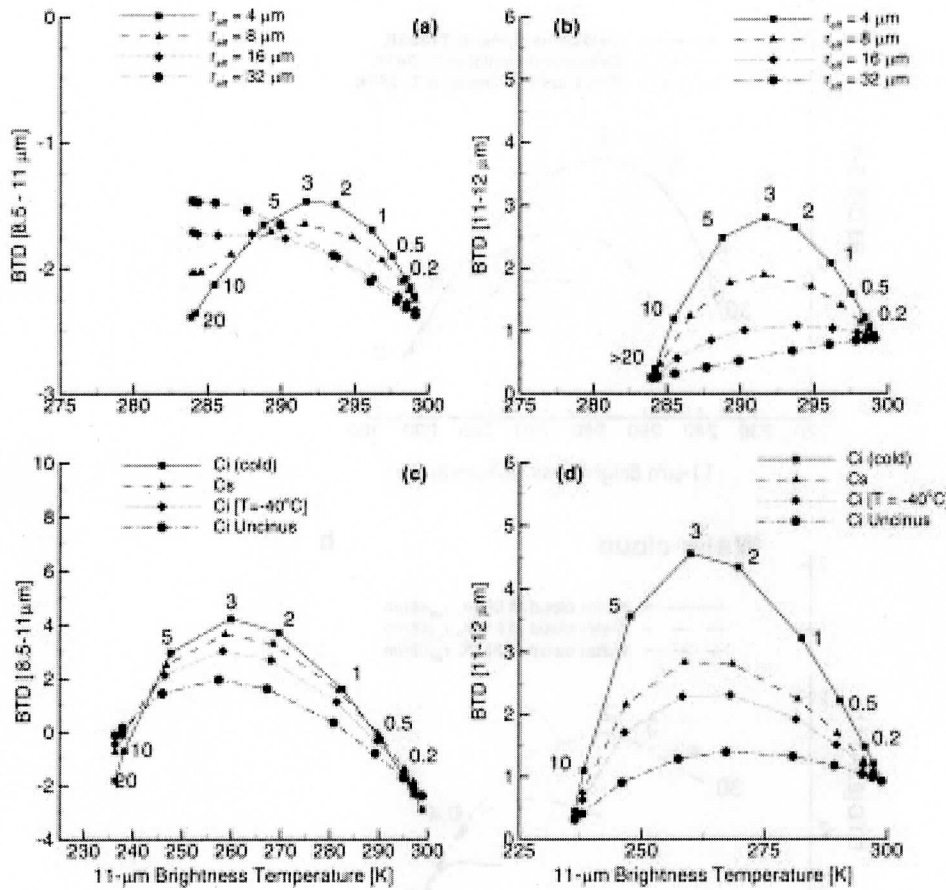


Figure 2: RT calculations for a. BTD[8.5-11] for water cloud, b. BTD[11-12] for water cloud, c. BTD[8.5-11] for ice cloud, d. BTD[11-12] for ice cloud.

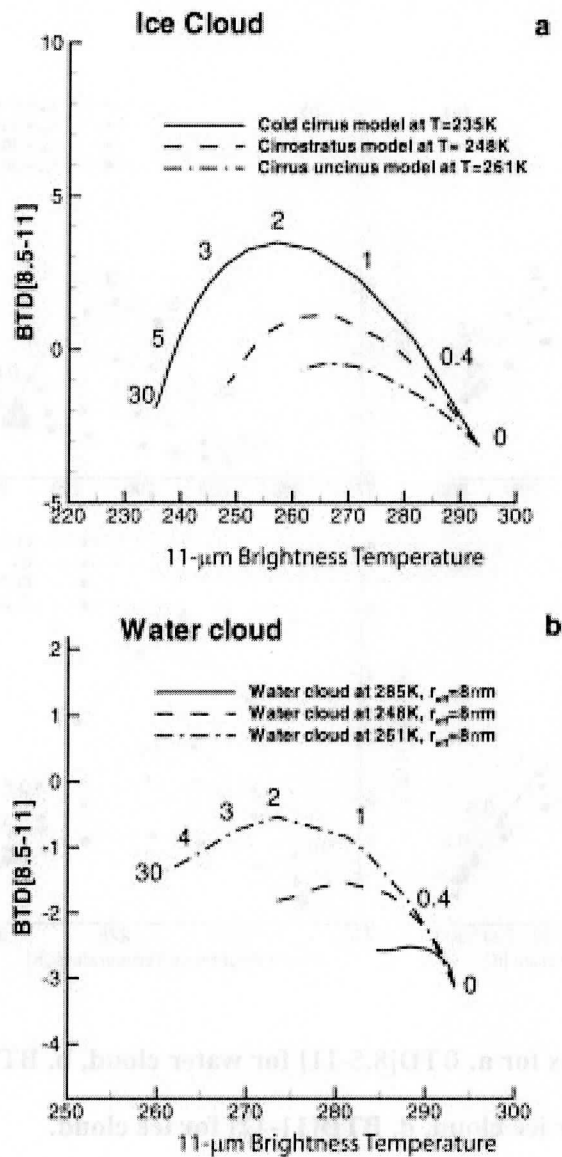
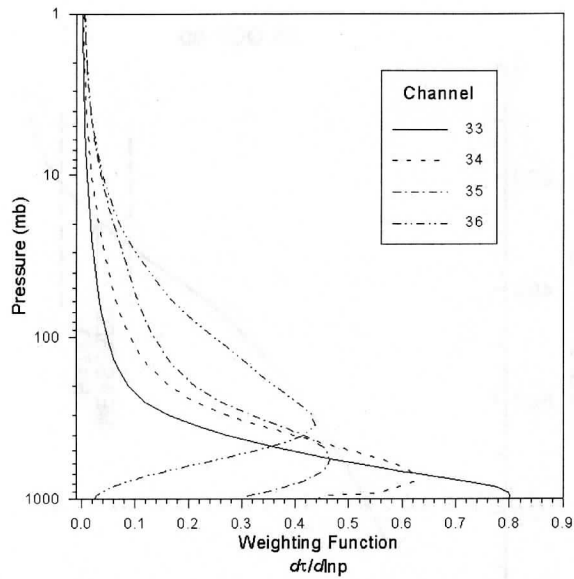


Figure 3: RT calculations to show effect of cloud temperature on BTD[8.5-11] for ice and water clouds.



**Figure 4. Weighting functions for the four MODIS channels in the CO<sub>2</sub> absorption band**

Figure 4. The weighting ratio from the right side of Equation 7 as a function of cloud top pressure for the four MODIS channels in the CO<sub>2</sub> absorption band. The measured ratio from the left side of Equation 7 is indicated. The cloud top pressure is indicated to be 300 mb.

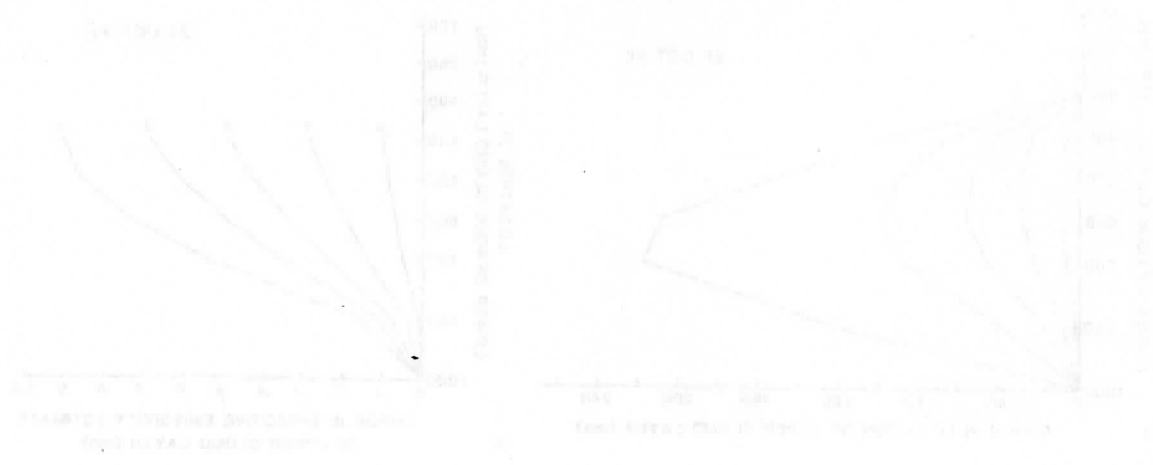


Figure 5. (a) The weighting ratio from the right side of Equation 7 as a function of height of the underlying opaque cloud for channel 33. (b) The weighting ratio from the right side of Equation 7 as a function of height of the underlying opaque cloud for channel 34. The measured ratio from the left side of Equation 7 is indicated. The cloud top pressure is indicated to be 300 mb.

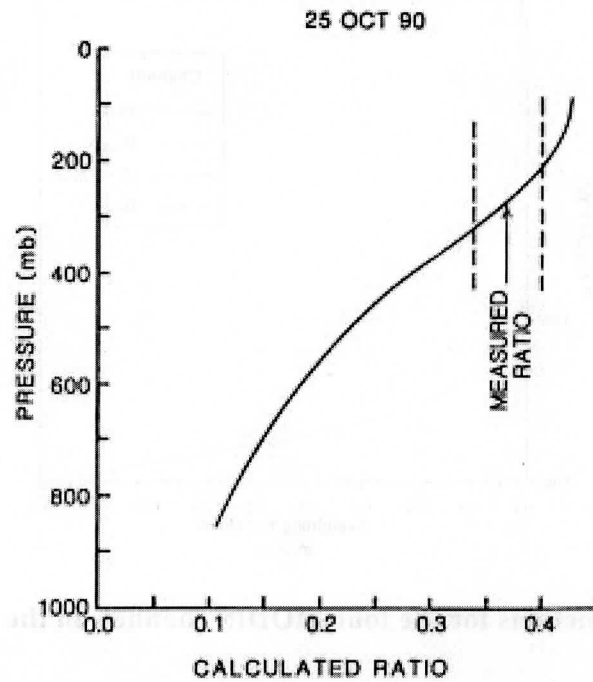


Figure 5. The calculated ratio from the right side of Equation 3 as a function of cloud top pressure from the sounding of 25 October 1990. The measured ratio from the left side of Equation 3 is indicated. The cloud top pressure is inferred to be 300 mb.

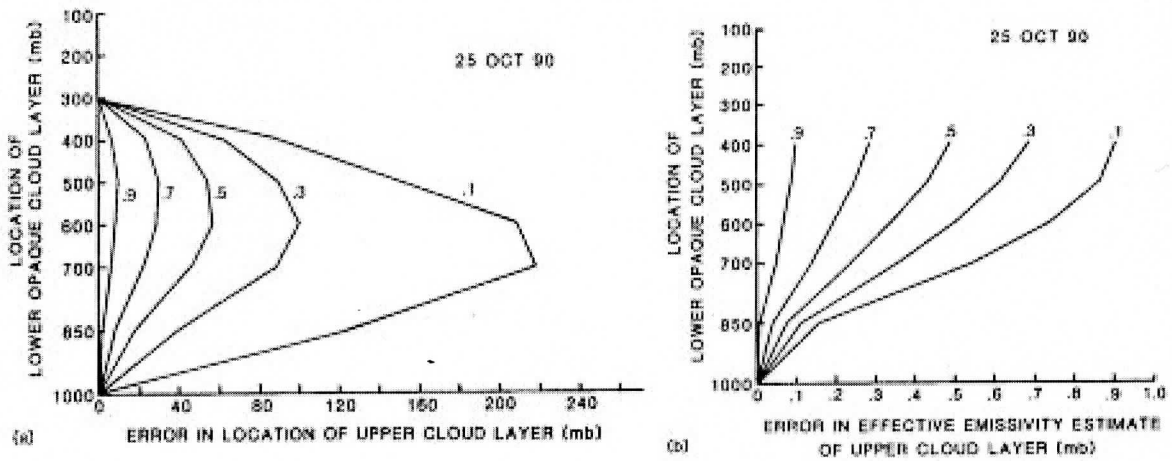
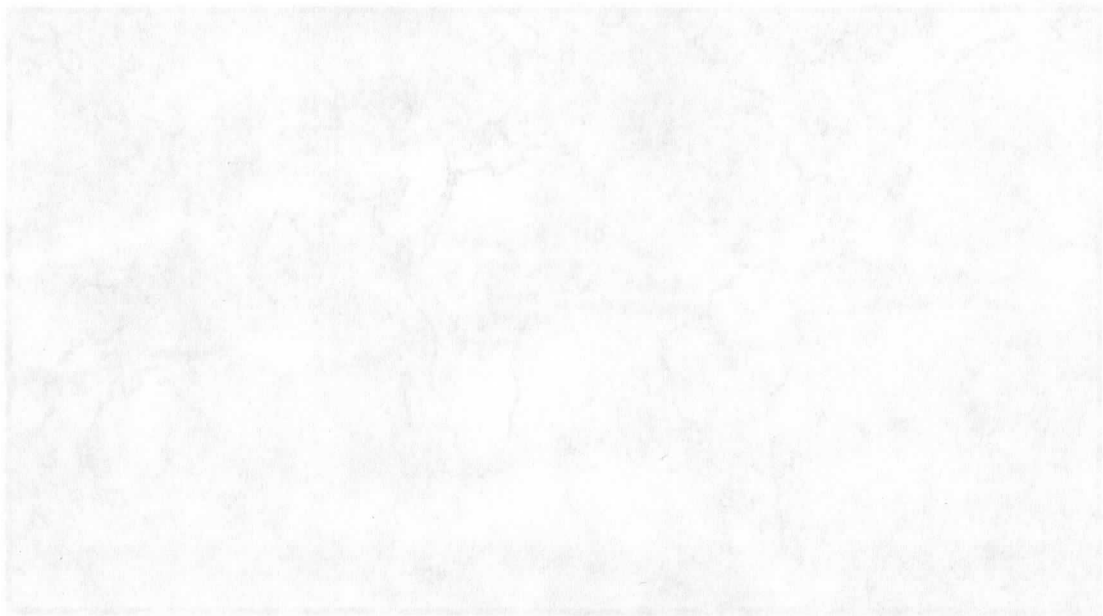
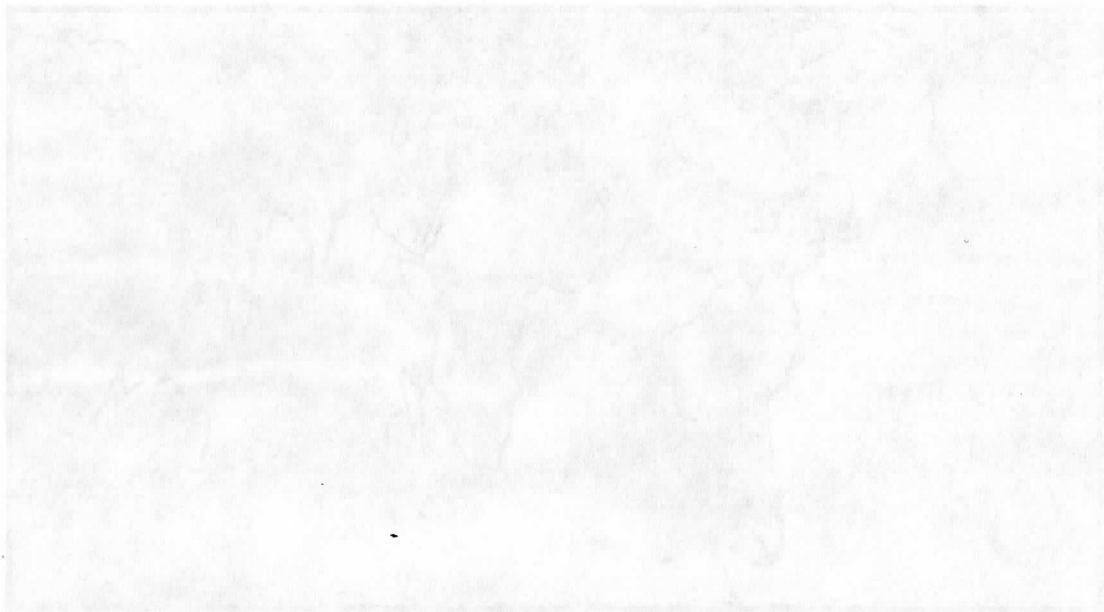


Figure 6. (a) The errors in calculated cloud top pressure (from the original 300 mb solution) for several different NE as a function of height of the underlying opaque cloud layer. (b) The associated errors in effective emissivity (from the original solution of NE).



FIRST PROBABILITY OF CIRRUS JUL-AUG

1900 - 1909 7 SEASON AVERAGE



FIRST PROBABILITY OF CIRRUS DEC-MAR

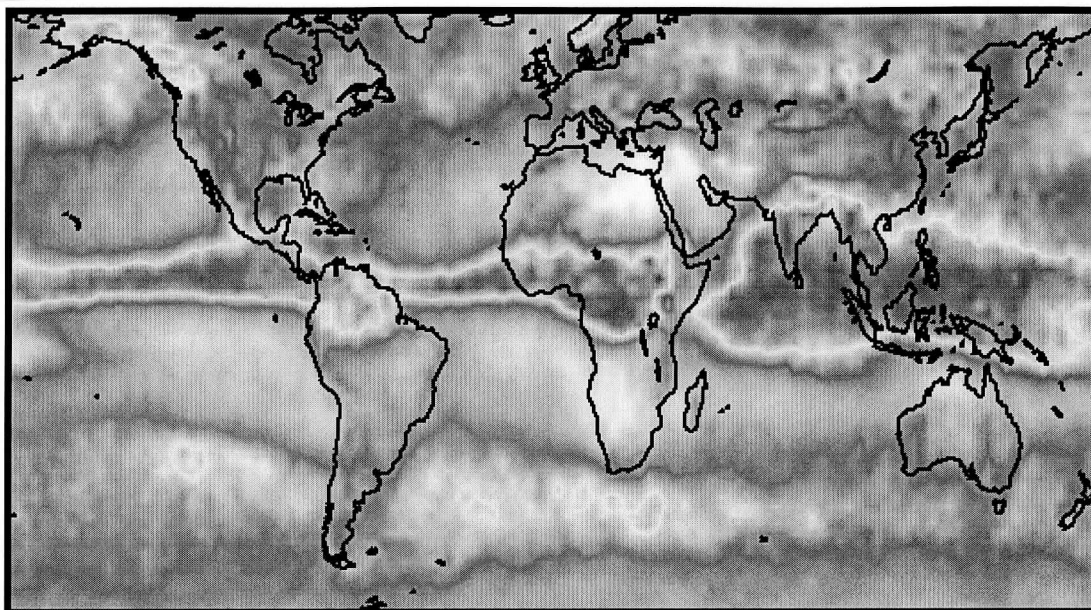
1880-1909 7 SEASON AVERAGE

These maps are based on a 10-year period from 1880-1909. The data is derived from the reports of the United States Weather Bureau.

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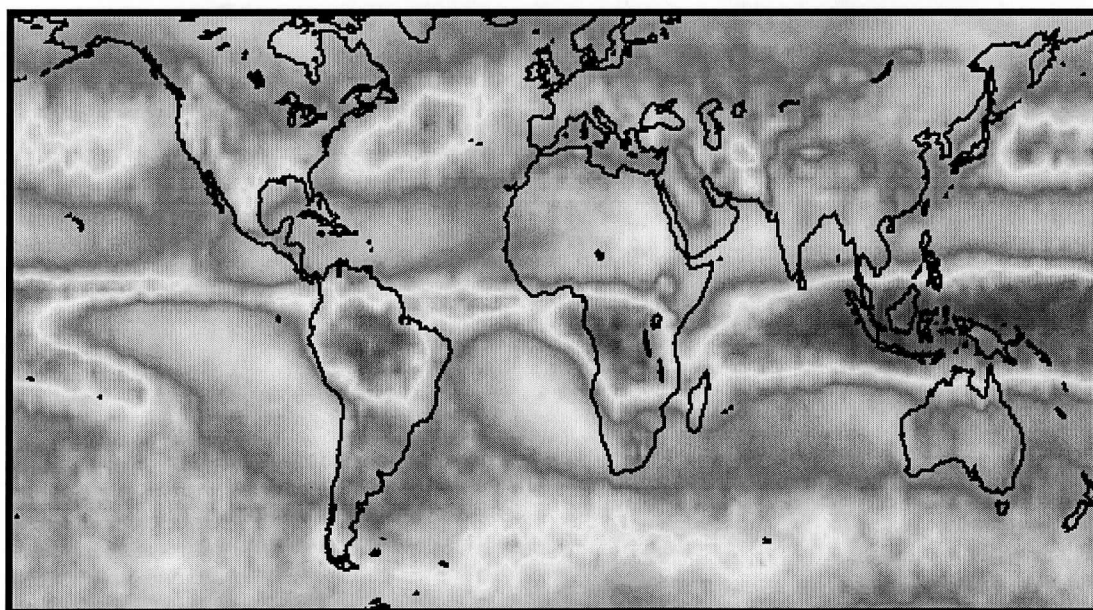
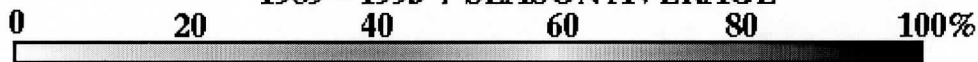


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**HIRS PROBABILITY OF CIRRUS JUN-AUG**

1989 - 1995 7 SEASON AVERAGE



**HIRS PROBABILITY OF CIRRUS DEC-FEB**

1989-1995 7 SEASON AVERAGE

UW/CIMSS

Figure 7. Example of a Level 3 equal angle cloud top property product as derived from HIRS data on a 2 degree latitude by 3 degree longitude grid.