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Comparison between SAGE II and ISCCP high-level clouds
2. Locating cloud tops

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Abstract. A comparison is made of the vertical distribution of high-level cloud tops derived from the Stratospheric Aerosol and Gas Experiment II (SAGE II) occultation measurements and from the International Satellite Cloud Climatology Project (ISCCP) for all Julys and Januarys in 1985 to 1990. The results suggest that ISCCP overestimates the pressure of high-level clouds by up to 50-150 mbar, particularly at low latitudes. This is caused by the frequent presence of clouds with diffuse tops (>50% time when cloudy events are observed). The averaged vertical extent of the diffuse top is about 1.5 km. At midlatitudes where the SAGE II and ISCCP cloud top pressure agree best, clouds with distinct tops reach a maximum relative proportion of the total level cloud amount (about 30-40%), and diffuse-topped clouds are reduced to their minimum (30-40%). The ISCCP-defined cloud top pressure should be regarded not as the material physical height of the clouds but as the level which emits the same infrared radiance as observed. SAGE II and ISCCP cloud top pressures agree for clouds with distinct tops. There is also an indication that the cloud top pressures of optically thin clouds not overlying thicker clouds are poorly estimated by ISCCP at middle latitudes. The average vertical extent of these thin clouds is about 2.5 km.

1. Introduction

The most common method for determining cloud top locations (given as pressures) from satellite observations is to infer the cloud top temperature from infrared radiances and then, using information about the atmospheric vertical temperature profile, locate the cloud top at the level with the corresponding physical temperature (see review by *Rossow et al.* [1989]). The most extensive results of this kind are available from the International Satellite Cloud Climatology Project (ISCCP) [*Rossow and Schiffer,* 1991]. The accuracy of this approach depends on the vertical profile of optical thickness in the uppermost portion of the cloud, since most of the infrared radiation is emitted by the layer over which longwave ($\approx$11 μm) optical thickness decreases from about 4 to zero. If this layer has a small (<0.5 km) vertical extent ("sharp top"), then the effective temperature of the radiation will be within a few degrees of the physical temperature of the atmosphere at cloud top. However, if this layer has a larger vertical extent ("diffuse top"), then the effective temperature of the radiation will be larger than that at the physical top of the cloud. If the total optical thickness of the cloud layer is <4, then transmitted radiation from below adds to the radiation emitted by the cloud, making the cloud top temperature appear too large. This effect can be accounted for, however, if the cloud optical thickness and the amount of radiation from below are known.

Another method for determining cloud top locations uses satellite-measured ratios of infrared radiation at nearby wavelengths that are influenced by differing amounts of atmospheric absorption (the "CO_2 slicing" method) [e.g., *Smith and Platt,* 1978; *Menzel et al.,* 1983]. Determining cloud top location with this method does not depend directly on the measured intensity of the infrared radiation (i.e., cloud top temperature); however, it still depends on the vertical distribution of cloud optical thickness. Consequently, a diffuse cloud top would also affect the accuracy of this determination. Other ways to infer cloud top location are stereoscopic imagery [*Shenk et al.,* 1975] and use of differential absorption methods, such as with reflected sunlight in the oxygen *A* band [*Fischer and Grassl,* 1991; *Fisher et al.,* 1991], that determine cloud top pressure more directly.

The most extreme case of a diffuse cloud top is an optically thin cloud in the upper atmosphere that overlies a thicker, lower-level cloud. This situation causes the largest error for both analysis methods because they both model the observed radiation, using a single cloud layer that (implicitly) has small vertical extent. For the first method, where optical thickness is obtained from satellite-measured visible radiances, the optical thickness of both cloud layers is attributed to the upper layer, thereby underestimating the amount of transmitted infrared radiation from below. This error is partially offset by the fact that the lower cloud decreases the magnitude of the radiation coming from below. Available statistics suggest that cirrus clouds overlie boundary layer cloud types at least 50% of the time [*Warren et al.,* 1985], but what fraction of these clouds are optically thin enough to cause large retrieval errors is not known.

The Stratospheric Aerosol and Gas Experiment II (SAGE II) measures vertical profiles of the extinction of sunlight when viewed through the atmosphere parallel to the surface. The high sensitivity of SAGE II observations to the presence of particle scattering [cf., *Kent et al.,* 1993] with relatively high vertical resolution (1 km)

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provides a more direct estimate of the location of the physical cloud top that can be contrasted with radiometric determinations to assess the importance of the issues raised above. However, comparisons of cloud amounts inferred from SAGE-like (limb-viewing) observations and ISCCP-like (nadir-viewing) observations have always indicated differences of at least a factor of 2 [*Barton*, 1983; *Woodbury and McCormick*, 1986]. Such large differences have prevented a comparison of cloud top locations by raising the possibility that significant differences in average cloud top pressure are also caused by different detection frequencies as a function of pressure level.

By matching individual observations, we have found that monthly zonal mean high-level cloud amounts from SAGE II and ISCCP agree to within ±0.05 if the SAGE II data are analyzed with a threshold extinction coefficient, $K = 0.008$ km^{-1}, and an effective cloud horizontal size, $l = 75$ km, is assumed [*Liao et al.*, this issue, henceforth paper 1]. High-level clouds are defined by cloud top pressures of <440 mbar. To avoid confusion, all cloud amounts will be stated as fractions from 0 to 1.0, whereas frequencies of occurrence or fractional populations will be given as a percentage of the total number of observations. The optimum value of K is about 10 times larger than the cloud detection threshold suggested by *Kent et al.* [1993], which indicates a greater inherent detection sensitivity of SAGE II observations for optically thin clouds as compared with the ISCCP analysis. The SAGE II results indicate a relatively uniform coverage of Earth (amount = 0.09) by high-level clouds with optical thicknesses of <0.1 that are too thin to be detected by ISCCP. However, the largest difference between SAGE II and ISCCP is caused by the interpretation of the SAGE II frequencies of cloud occurrence as cloud cover fractions, equivalent to assuming that all clouds are about 200 km in size. The optimum effective cloud size is determined by comparison with ISCCP and represents the average fraction of the 200 km atmospheric path length observed by SAGE II that is actually occupied by clouds. That this size is much smaller than the total path length explains most of the difference between cloud amounts determined from limb-viewing and nadir-viewing satellite observations [cf., *Woodbury and McCormick*, 1986]. Use of a single global number reduces regional differences in SAGE II and ISCCP monthly mean cloud amounts to <20%; however, these systematic regional differences indicate variations of the effective cloud sizes over a range of at least 50–110 km.

By explaining the apparent differences in high-level cloud amounts between SAGE II and ISCCP, the study in paper 1 sets the stage for exploiting the relatively high vertical resolution of SAGE II extinction profiles to investigate the vertical structure of the uppermost portions of clouds that affect radiometric determinations of cloud top location. Monthly mean cloud top pressures for high-level clouds are obtained by averaging over the vertical distributions of matched individual measurements of cloud top pressure from SAGE II and ISCCP. The shape of these distributions can differ for two reasons: differences in cloud detection frequencies as a function of pressure and differences in the cloud top pressure assigned when observing the same cloud. In our analysis, we separate these two effects and show that the latter is the more important.

2. Data Sets and Analysis Methods

2.1. SAGE II and ISCCP

SAGE II on the Earth Radiation Budget Satellite (ERBS) views the Sun at seven wavelengths through a 200 km atmospheric path length and measures vertical profiles of extinction from 150 km altitude down to the level where all signal is lost [*McCormick et al.*, 1979; *Rind et al.*, 1993]. Since scattering by submicron background aerosol particles is much weaker than scattering by larger cloud particles at longer wavelengths [*Kent et al.*, 1993], we use extinction measurements at 1.02 µm to detect the presence of clouds. Clouds are present wherever the layer extinction coefficient $k_i > 0.0008$ km^{-1} [cf., *Kent et al.*, 1993; paper 1]. Note that each layer is viewed through all the higher layers, so that the extinction at each level is the difference between the total value and the sum of the higher layer values [see *Chu and McCormick*, 1979]. We also include as cloud detections those profiles with sudden loss of signal above the 440 mbar level [see paper 1 for more details], even though only a lower limit on k_i can be set. Since October 1984, about 30 locations per day have been observed to accumulate coverage from about 79°S to 79°N over periods of a few months, though the number of observations declines poleward of 55°.

ISCCP has collected measurements of infrared (≈11 µm) and visible (≈0.6 µm) radiances from the operational polar orbiting and geostationary weather satellite imaging radiometers since July 1983. Clouds are detected in individual image pixels, about 4–7 km in size, by deviations of the measured radiances from the inferred clear sky values by more than some threshold amount [*Rossow and Garder*, 1993a]. Cloud amount is determined every 3 hours for regions about 280 km in size as the fraction of the total number of pixels that are cloudy [*Rossow and Schiffer*, 1991]. Even though the data set is spatially sampled to intervals of about 30 km, providing about 50–100 samples per region, monthly average results are statistically equivalent to the full resolution data set [*Seze and Rossow*, 1991; *Rossow et al.*, 1993]. The radiance thresholds used by ISCCP for high-level cloud detection are equivalent to a lower limit on visible optical thickness, $\tau > 0.1$-0.3 [*Wielicki and Parker*, 1992; *Rossow and Garder*, 1993b]. For typical cloud vertical and horizontal extents of 2.5 km and 75 km, this would be approximately the same as a limit on the SAGE II layer extinction coefficient, $k_i > 0.008$ km^{-1} (see paper 1)

Because the SAGE II sampling is much less dense than that of ISCCP, we match individual SAGE II profiles with individual ISCCP (stage C1) observations for all six years. The match-up criteria are that the SAGE II profile, taken to represent a region about 200 km in size, have its path length midpoint located within an ISCCP equal area map grid cell and that the time difference between the SAGE II and ISCCP observations be <9 hours. All reported statistics below come from these matched data sets unless otherwise stated. Results from 1985-1990 are combined into a composite January and July, each with about 4500 observations.

2.2. Determining Cloud Top Pressure

In the SAGE II analysis, cloud top is defined as the highest level at which the layer extinction coefficient $k_i > K$, the set threshold value, and represents the boundary separating the "clear" atmosphere with background aerosol from the cloudy atmosphere [cf., *Kent et al.*, 1993]. For multiple-layer clouds, the SAGE II cloud top pressure is the top of the uppermost cloud layer. The SAGE II data set reports values of k_i as a function of altitude above the mean surface; but we use profiles of atmospheric temperature and pressure, obtained from the National Meteorological Center (NMC) analysis [*Rind et al.*, 1993] and included in the SAGE II data set, to convert cloud top heights to cloud top pressures, P_c. High-level clouds are defined by $P_c < 440$ mbar to be consistent with the ISCCP definition. With a vertical resolution of 1 km, the precision of SAGE II cloud top pressure values varies from 30 to 80 mbar, depending on altitude; but with more than 100 observations in each 2.5° latitude zone, the precision of average cloud top pressures should be better than 10 mbar.

In the ISCCP analysis, cloud top pressure is determined in two ways. If only infrared radiance measurements are available (nighttime), then all clouds are assumed to be opaque (all radiation is emitted from cloud top with no radiation transmitted from below) and (implicitly) to have a sharp top. The cloud top temperature, T_c, is then determined from the satellite-measured 11 μm brightness temperature for cloudy locations, T_{obs}, by correcting for the effects of absorption and emission by atmospheric water vapor [*Rossow et al.,* 1991]. A brightness temperature gives the temperature of a blackbody that radiates the same amount of energy as measured by a radiometer over the wavelength range to which the radiometer is sensitive. Cloud top pressure is determined by the level in the atmosphere that has the same physical temperature using the TIROS Operational Vertical Sounder data set [*Rossow et al.,* 1991].

If visible radiances are available to determine cloud visible optical thicknesses (daytime) and the value is sufficiently low ($\tau_{ir}/\mu < 9$, where μ is cosine of the satellite view angle), then the infrared radiation emitted from cloud top, $B(T_c)$, is calculated as by *Rossow et al.* [1991],

$$B(T_c) = \frac{B(T_{obs}) - Trans \times B(T_s)}{1 - Trans} \qquad (1)$$

where $Trans = \exp(-\tau_{ir}/\mu)$, the infrared optical thickness $\tau_{ir} = \tau_{vis}/2$ [*Rossow et al.,* 1991], and T_s is the surface temperature. The function $B(T)$ gives the amount of radiation emitted by a blackbody with temperature, T, in the wavelength range to which the satellite radiometers are sensitive. This expression subtracts from the observed radiation, $B(T_{obs})$, the radiation that is transmitted through the cloud from the atmosphere below, which is assumed to be clear so that this radiation is from the surface, attenuated by water vapor, $B(T_s)$. The remainder is the infrared radiation emitted from the cloud top, $(1-Trans) \times B(T_c)$. The value of T_c is then obtained from $B(T_c)$ [*Rossow et al.,* 1991] and is smaller than the value obtained by the first method. For larger values of τ, the cloud is treated as opaque, and no adjustment is made to the value of T_c obtained by the first method. Comparison of the daytime ISCCP results obtained with and without this correction shows that the correction increases the amount of high-level cloud by about 0.05 and decreases the average cloud top pressure of the other high-level clouds by about 55 mbar. We use only daytime ISCCP results in our comparison with SAGE II.

The ISCCP temperature measurements have a precision of 0.5–2.0 K for high-level clouds, which gives a precision of cloud top pressures of better than 20 mbar. Uncertainties in the calibration of the satellite radiometers for colder temperatures are as much as 4 K [*Brest and Rossow,* 1992], equivalent to an uncertainty of cloud top pressures 20–40 mbar, which may appear as a bias.

3. Cloud Top Locations

3.1. Vertical Distribution of Cloud Amount

Using a threshold extinction coefficient, $K = 0.008$ km^{-1} (and an effective cloud size, $l = 75$ km), which produces the best match of SAGE II and ISCCP monthly, zonal mean high-level cloud amounts (paper 1), we calculate monthly, zonal mean cloud top pressures from the individually matched observations for July and January 1985–1990 (Figure 1). Note that only matched observations where both SAGE II and ISCCP report the presence of a high-level cloud are included in Figure 1 (see next section). In contrast to the good agreement of cloud amounts (paper 1), there are systematic differences between the two sets of average cloud top pressures. The SAGE II cloud top pressures are generally 100–150 mbar lower than the ISCCP values at low latitudes, about 50 mbar lower in summer midlatitudes, and <20 mbar lower in winter midlatitudes.

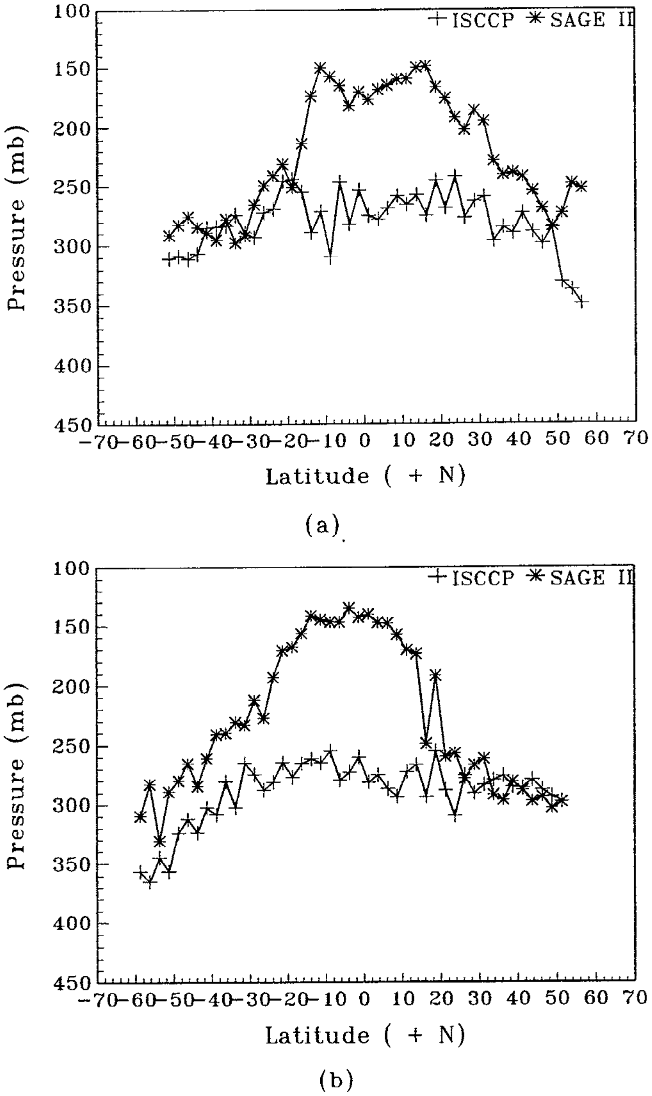


Figure 1. Zonal monthly mean cloud top pressures **(in millibars)** for all high-level clouds ($K = 0.008$ km^{-1}) from SAGE II and ISCCP in cases where both report clouds present: (a) July 1985–1990 and (b) January 1985–1990.

The differences in average cloud top pressures arise from differences in the vertical distributions of SAGE II and ISCCP cloud amounts. To show this, we collect the SAGE II values into the same three pressure intervals used to report the ISCCP high-level cloud results: 50–180 mbar, 180–310 mbar, and 310–440 mbar. The top of the uppermost layer (50 mbar) is actually defined by the location of the tropopause, which has a pressure that varies with latitude and season but typically is 100–150 mbar. Figure 2 displays the SAGE II and ISCCP cloud amounts in each of these three layers for July and January 1985–1990 in three latitude zones: 50°S–20°S, 20°S–20°N and 20°N–50°N. ISCCP has fewer clouds in the 50 to 180 mbar and 180 to 310 mbar layers but more clouds in the 310 to 440 mbar layer relative to SAGE II (there is little difference in total amounts). In the tropics, where the largest difference in the average SAGE II and ISCCP cloud top pressures occurs, SAGE II has many more clouds in the highest layer than ISCCP. However, at winter

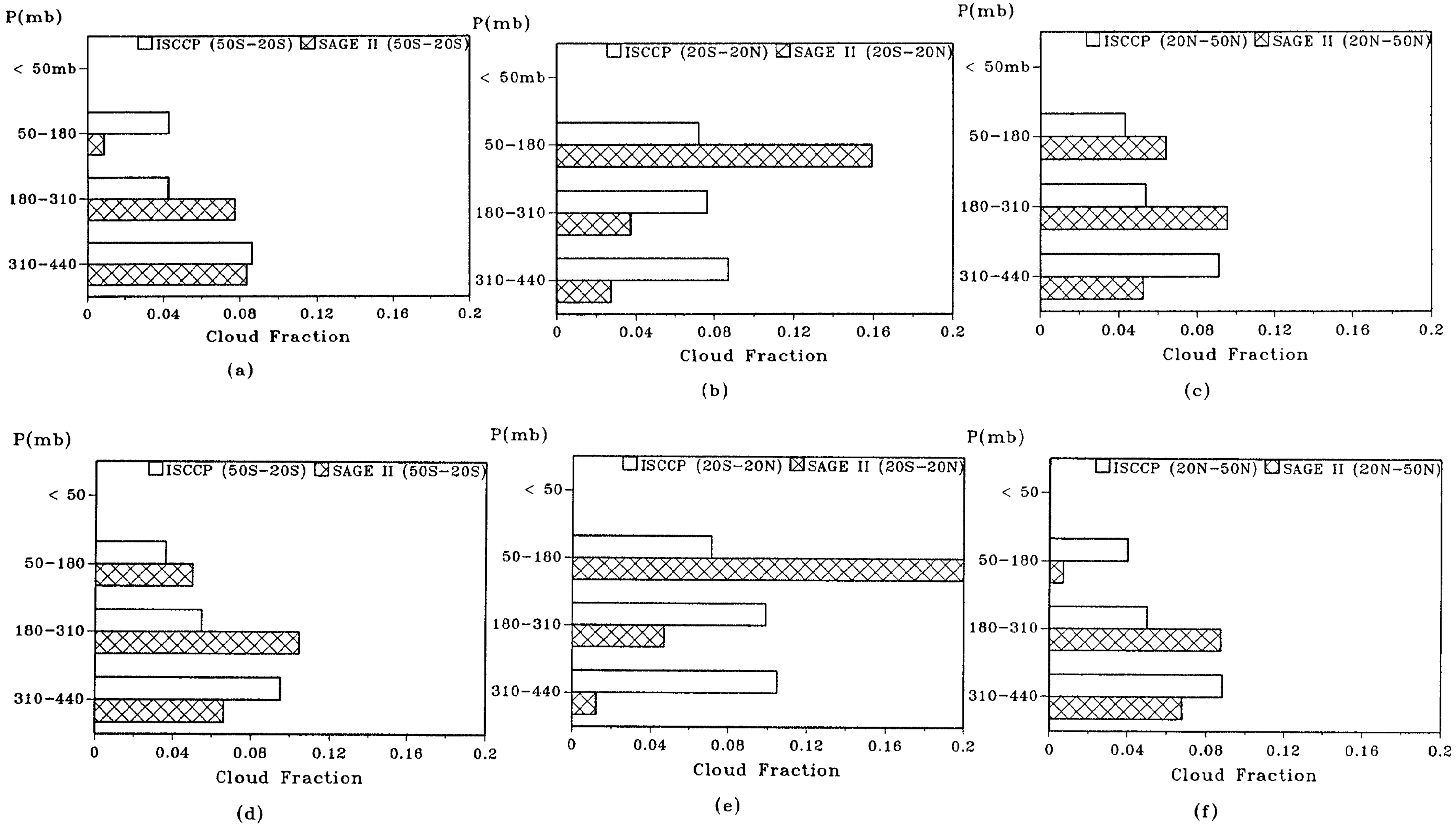


Figure 2. Vertical distributions of cloud amounts (category 4 in Table 1) from SAGE II and ISCCP for 1985–1990: (a) 50°S to 20°S for July, (b) 20°S to 20°N for July, (c) 20°N to 50°N for July, (d) 50°S to 20°S for January, (e) 20°S to 20°N for January, and (f) 20°N to 50°N for January.

hemisphere higher latitudes where the agreement of average cloud top pressures is better, there are slightly more ISCCP clouds in the highest layer than SAGE II clouds, which is offset by more SAGE II clouds in the lower layer than ISCCP clouds. The results in Figure 2 suggest that the explanation for the differences in average cloud top pressures shown in Figure 1 varies with latitude and season.

Two factors can explain the differences in cloud top pressures shown in Figures 1 and 2: (1) the detection frequency of high-level clouds by SAGE II and ISCCP differs systematically with pressure and/or (2) the cloud top pressure determined by SAGE II and ISCCP differs when viewing the same cloud because of the radiometric effects of the vertical distribution of cloud optical thickness in the uppermost part of the clouds.

In order to examine these possible reasons, the matched cloud data are classified into four categories: Category 1: both SAGE II and ISCCP detect no clouds; category 2: SAGE II detects no clouds but ISCCP does; category 3: SAGE II detects clouds but not ISCCP; and category 4: both SAGE II and ISCCP detect clouds.

The contributions of factors 1 and 2 are investigated in the next two sections.

3.2. Differences in Cloud Detection Frequency

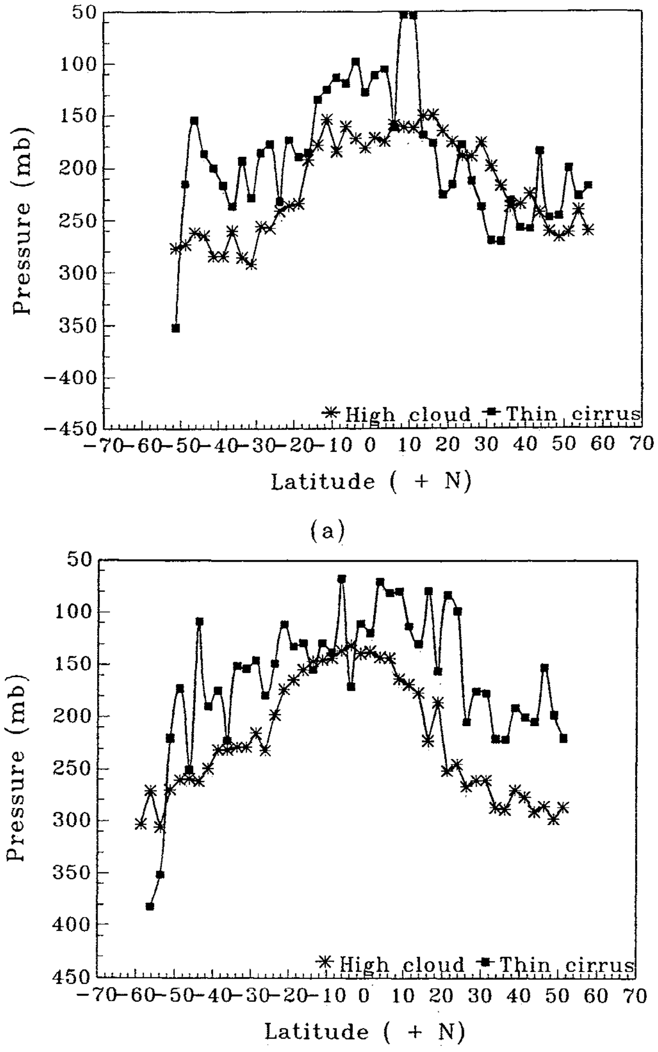
Table 1 classifies each individually matched SAGE II and ISCCP observation by whether a cloud is present or not. Using the value of the threshold extinction coefficient (K_{high} = 0.008 km^{-1}) in the SAGE II analysis, which produces the best match of total cloudiness, there is agreement (category 1 or 4) in 67% of the cases. In 33% of the cases, SAGE II and ISCCP disagree as to whether a high-level cloud is present. These disagreements can arise for three reasons (see paper 1): (1) ISCCP detects the same cloud as SAGE II does but assigns a cloud top pressure >440 mbar so that it is excluded as a high-level cloud (category 3), (2) SAGE II fails to detect clouds that are broken and widely scattered (category 2), or (3) SAGE II detects the presence of a cloud that is too optically thin for ISCCP to detect (category 3).

The first problem can account for only 7% of the cases, at most, and cannot contribute to the systematic difference of average cloud top pressures because we have excluded these cases from the comparison in Figure 1. Note, however, also that these clouds are generally at higher pressures than the majority of high-level clouds (average cloud top pressure measured by SAGE II is about 25 mbar larger; see next section). Even with the most sensitive SAGE II analysis (using K_{low} = 0.0008 km^{-1}), the second problem still accounts for 16% of the cases, where, as shown in paper 1, all of these cases are associated with ISCCP cloud amounts of <0.25. However, the average ISCCP cloud top pressure for these cases is within <10 mbar of the average for the category 4 cases, so that these cases do not contribute to the bias shown in Figure 1.

Table 1. Cloud Detection Match-Up Statistics for SAGE II and ISCCP Cloud Observations

Population Category	SAGE II	ISCCP	K_{low}	K_{high}
1	Clear	Clear	18	26
2	Clear	Cloudy	16	26
3	Cloudy	Clear	15	7
4	Cloudy	Cloudy	51	41

The total population of observations from six Januarys and Julys in 1985-1990 is about 9000; populations in each category are given as a fraction in percent. K is the SAGE II extinction coefficient threshold, where K_{low} = 0.0008 km^{-1} and K_{high} = 0.008 km^{-1}.



(a)

(b)

Figure 3. Zonal monthly mean cloud top pressure (in milibars) from SAGE II for optically thicker high-level clouds (K = 0.008 km^{-1}, lines with asterisks) and for optically thin clouds (0.008 km^{-1} > k_i > 0.0008 km^{-1}, lines with solid squares): (a) July 1985–1990 and (b) January 1985–1990.

Using the more sensitive SAGE II analysis shifts about 18% of the category 1 and 2 cases to categories 3 and 4 (Table 1). In 10% of the cases, the extra cloud detected by SAGE II is associated with other clouds that ISCCP has already detected. Only in 8% of the cases does ISCCP detect no cloud when SAGE II detects very thin cloud. Overall, the SAGE II results (with $K = K_{low}$) contain about 0.09 more high-level cloud fraction than does ISCCP, but these clouds can contribute to a bias of SAGE II cloud top pressures relative to ISCCP values only if they have a vertical distribution very different from tat of the other clouds. Figure 3 compares the monthly, zonal mean cloud top pressures from SAGE II for the thinner clouds with the average for the thicker clouds ($K = K_{high}$): generally, the average cloud top pressures of the clouds missed by ISCCP are less than the thicker cloud top pressures by about 50 mbar.

Thus although there is a small systematic difference in cloud detection frequencies between SAGE II and ISCCP associated with very thin clouds, the small average difference in the cloud top pressures of these thinner clouds, together with their small amount, means that including them in the SAGE II results would not change very much (<15 mbar) the values shown in Figure 1. By using an extinction threshold of 0.008 km^{-1}, we have already excluded these clouds (as well as categories 2 and 3) from the SAGE II results shown in Figures 1 and 2. In other words, the differences in SAGE II and ISCCP cloud top pressures shown, which are solely due to differences in methods by which cloud top pressure is determined for individual observations, would not be changed significantly by the different cloud detection frequencies as a function of pressure.

3.3. Vertical Profiles of Extinction Coefficient at Cloud Top

We explore the reasons for a difference of cloud top pressures between SAGE II and ISCCP by using individually matched observations where both data sets agree that high-level clouds are present (category 4 in Table 1). We use the vertical profiling capability of SAGE II to determine the characteristics of the uppermost portion of the clouds that might account for the systematically higher cloud top pressures reported by ISCCP.

Figure 4 presents schematics of four types of cloud top vertical extinction profiles observed by SAGE II: (1) a "sharp-topped" thick cloud (Figure 4a), (2) a "diffuse-topped" thick cloud (Figure 4b), (3) an isolated thin layer (Figure 4c) and (4) a thin cloud layer overlying a thicker high-level cloud layer (Figure 4d). A thin cloud is one that has layer extinction coefficients above the threshold value, K = 0.008 km^{-1}, but never reaches saturation within the defined cloud top pressure range. A thick cloud is one that produces complete loss of signal (saturation) at some level. A sharp-topped cloud profile is defined by the extinction changing from below the threshold value at one level to the saturated value in the next lower level. A diffuse-topped cloud profile is defined by having at least one level with an extinction coefficient above the threshold value, but less than the saturation value, immediately above the saturated level. The distinction between the two thin cloud types depends on whether a second cloud layer is detected within the high-level cloud top pressure range (<440 mbar).

Figure 5 summarizes the frequencies of occurrence of these four cloud types as a function of latitude for July and January. Figure 6 summarizes the distribution of differences in individual cloud top pressures between SAGE II and ISCCP for the four cloud types, and Table 2 gives the average cloud top pressures for each type.

3.3.1. Type A: Thick cloud layer with sharp top. The total horizontal extinction measured by SAGE II at 1.02 μm saturates at about 0.04 km^{-1} (this value assumes a 200 km path length), which is very roughly equivalent to a visible (0.6 μm) optical thickness of 0.2–0.3 for a 2.5 km deep cloud layer. Thus all saturated clouds in

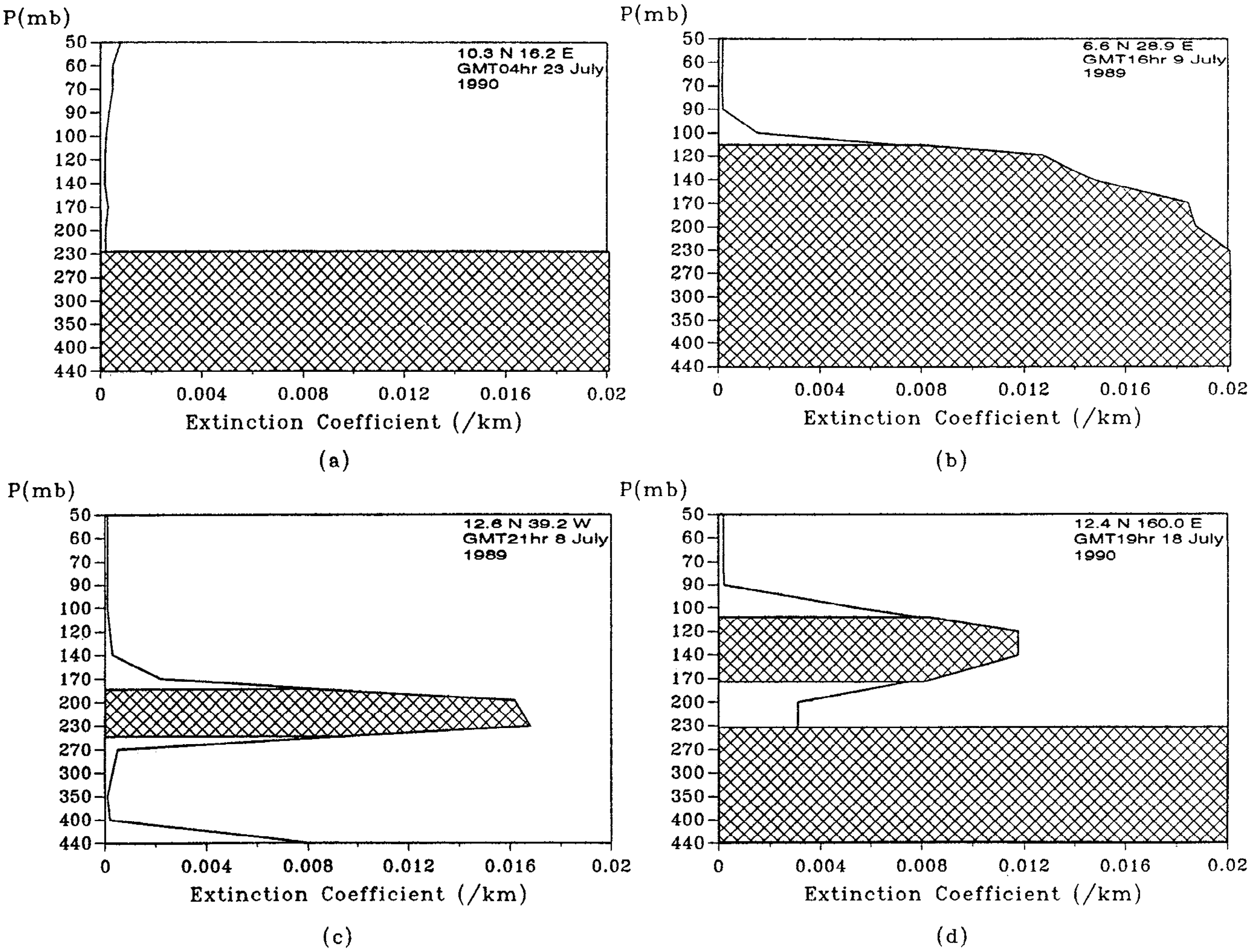


Figure 4. Four types of cloud extinction profiles from SAGE II: (a) sharp-topped thick cloud, (b) diffuse-topped thick cloud, (c) isolated thin cloud; and (d) thin high cloud overlying a thicker high-level cloud. Hatched areas indicates extinction greater than the cloud threshold.

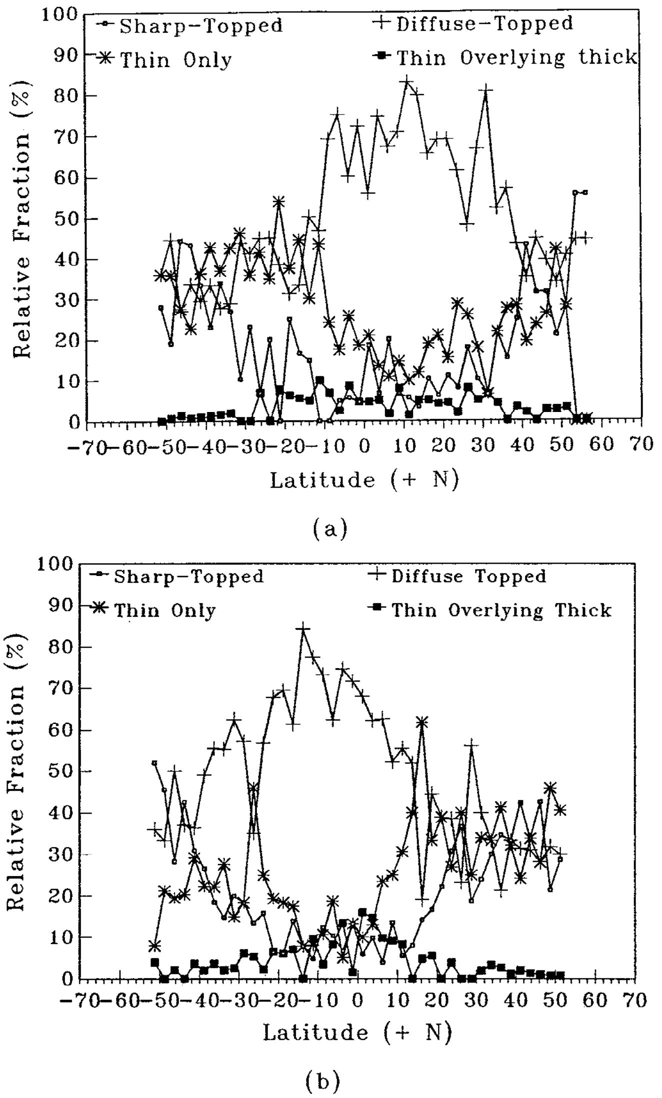


Figure 5. Relative fraction of occurrence of the four types of high-level clouds ($K = 0.008\ \mathrm{km}^{-1}$) in each latitude zone from SAGE II: (a) July 1985–1990 and (b) January 1985–1990.

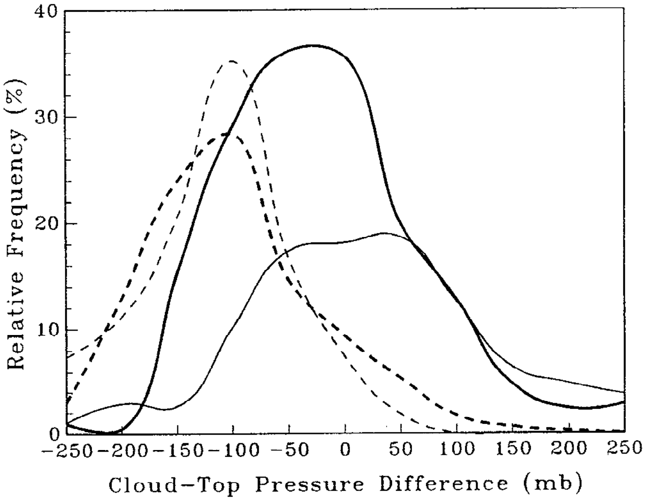


Figure 6. Frequency distribution of differences between individually matched SAGE II and ISCCP measurements of cloud top pressure for the four types of high-level clouds.

the SAGE II results most likely have visible optical thicknesses of >0.2–0.3 (see paper 1); however, this limit can still include some clouds that transmit infrared radiation from below. Indeed, in about 1.5% of the cases (category 3 in Table 1), SAGE II indicates the presence of a type A cloud, but ISCCP does not detect any high-level cloud, as would occur if the SAGE II value of P_c were just below 440 mbar and the ISCCP value were too large.

If the profile of extinction coefficient indicates a sharp top (Figure 4a) and the total visible optical thickness is >4, then the infrared radiation observed by a nadir-viewing satellite will be emitted from very near the upper edge of the cloud (within the first one to two optical depths). Note that the profile below the saturation level shown in Figures 4a and 4b are for illustration only, since SAGE II cannot detect the presence of scattering below the saturation level. This cloud type represents about 18% of all high-level clouds in the global mean (equivalent to a cloud amount of 0.038), in the tropics, type A clouds are only about 10% of the total, but they are about 40% of the total at higher latitudes, especially in winter (Figure 5). The average cloud top pressure for this cloud type is significantly below the tropopause level (Table 2). The SAGE II and ISCCP cloud top pressures, P_c, should agree well for these cases: The average difference in cloud top pressures is 13 mbar (Table 2), and the standard deviation of the difference is 89 mbar. Figure 6 shows that the distribution of individual differences in P_c for this type of cloud is monomodal (mode value ≈ -25 mbar). The standard deviation does not change significantly with latitude or season and is roughly consistent with the estimated precisions of the SAGE II and ISCCP values of P_c, which are limited by their vertical resolution.

Table 2. Relative Fraction of All High-Level Clouds

Four Types of Clouds	SAGE II global cloud amount	SAGE II relative fraction (in %)	SAGE II cloud top pressure (in mbar)	ISCCP cloud top pressure (in mbar)
Sharp-topped	0.04	18	275	288
Diffuse	0.10	52	174	284
Isolated thin	0.05	26	301	274
Overlying	0.01	4	162	320
All	0.20	100	224	284

Category 4 in Table 1 with $K = K_{high}$, with one of four types of SAGE II extinction profiles and the global mean values of cloud top pressure determined by SAGE II and ISCCP for each type.

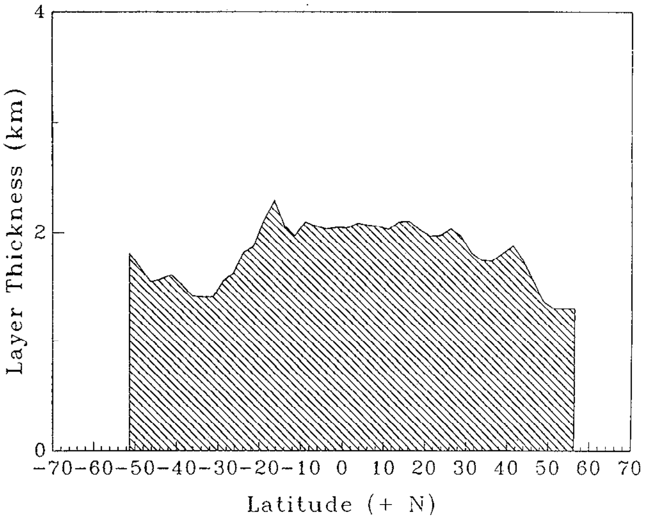


Figure 7. Zonal monthly mean vertical extent (in kilometers) of the diffuse layer for diffuse-topped clouds from SAGE II for July 1985–1990. Thick solid line: SAGE-ISCCP sharp-topped; thin solid line: SAGE-ISCCP isolated; thicker dashed line: SAGE-ISCCP diffuse; thin dashed line: SAGE-ISCCP overlying.

3.3.2. Type B: Thick cloud layer with diffuse top. Another type of thick cloud appears with a diffuse top (Figure 4b), where the extinction coefficient gradually increases over a substantial vertical extent. In this case the infrared radiation observed by a nadir-viewing satellite arises from a level below and warmer than the actual cloud top, so that the ISCCP cloud top pressure would be larger than that obtained by SAGE II. About one third of the category 3 clouds in Table 1 are also of this type. The globally averaged SAGE-ISCCP difference in P_c for this cloud type is -110 mbar detected by ISCCP (Table 2); the distribution of individual differences is monomodal with a mode at about -110 mbar (Figure 6). In the global mean, this type of cloud represents more than half of all high-level clouds (Table 2), equivalent to a cloud amount of 0.11. Figure 5 shows that this cloud type is the dominant one in the tropics, representing about 70% of all clouds there (cloud amount = 0.22); the average ISCCP cloud top pressure is 122 mbar larger than the average SAGE II value for type B clouds in the tropics. At middle latitudes, where this type of cloud represents about 30-40% of the total in winter and about 40-50% in summer, the average pressure difference is about 100 mbar.

The cloud top defined by ISCCP represents the effective height at which the equivalent infrared radiance is emitted. This effective height does represent some aspects of the effect of clouds on radiation, but the material height detected by SAGE II is important to understanding cloud and heterogeneous chemical processes. The physical cloud top for this type of cloud is usually located near the tropopause, as evidenced by an average $P_c = 174$ mbar (Table 2). We use the matched SAGE II and ISCCP results to determine a lower limit on the depth of this diffuse layer (Figure 7): The average diffuse depth inferred for this type of cloud is about 1.5–2.0 km and does not vary significantly with latitude. This value is only a little larger than the vertical resolution of the SAGE II observations, so the lack of variations with latitude may indicate that this determination is limited by instrument resolution. Note also that because the SAGE II measurements would saturate at a visible optical thickness of about 0.2-0.3, the actual depth of an optically thin layer may be 2 or 3 times larger than this estimate.

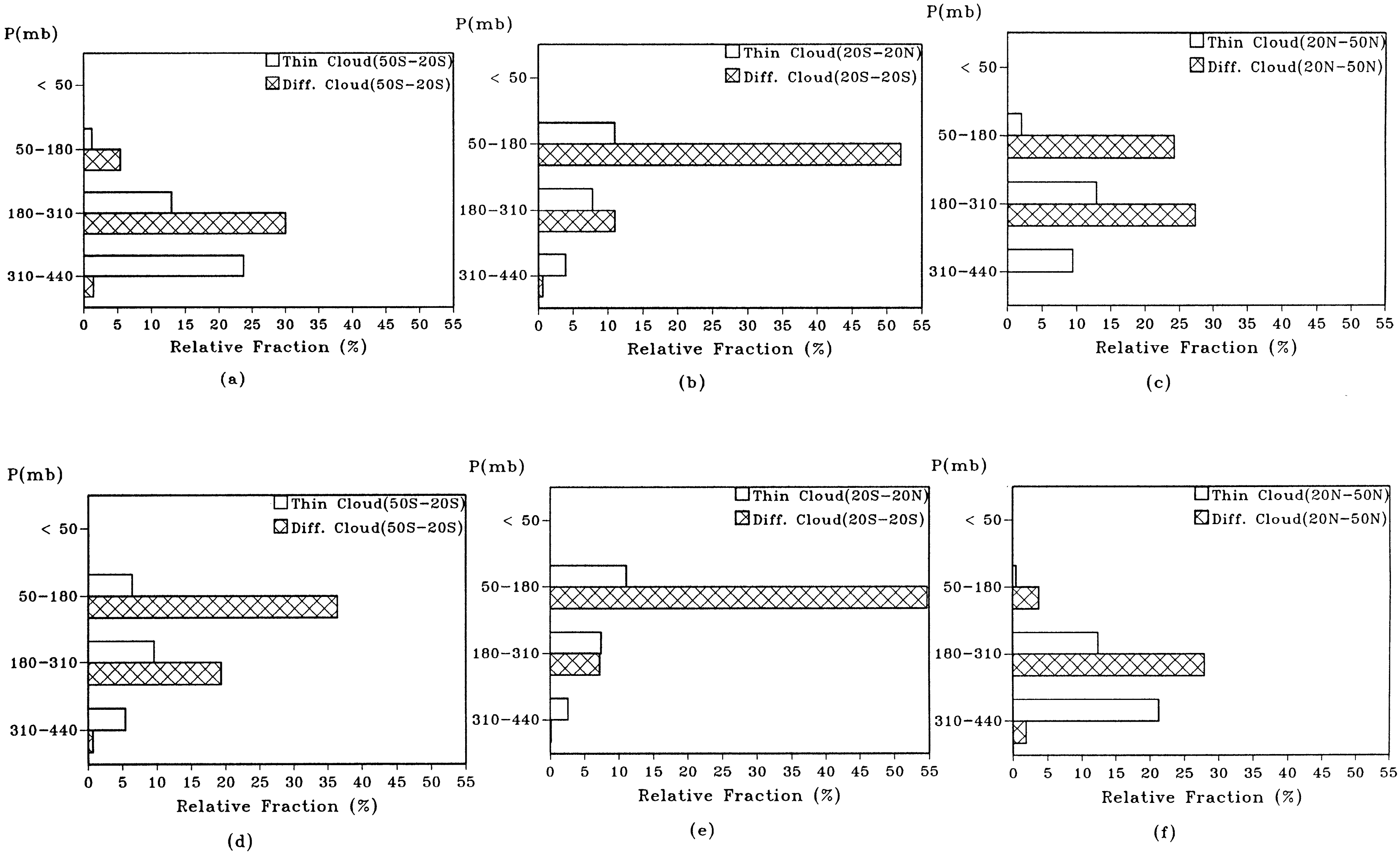
3.3.3. Type C: Isolated thin cloud layers. This type of cloud has a total optical thickness that never exceeds the saturation value, 0.2-0.3 (Figure 4c), assuming an average cloud horizontal size of 75 km (see paper 1) and an average vertical extent of ≈2.0–2.5 km (see end of this section). Globally, about 26% of all high-level clouds are of this type (equivalent to a cloud amount of 0.055); this fraction decreases to 10-15% in the tropics and increases to over 30% at colder latitudes, particularly winter midlatitudes (Figure 5). The additional very thin clouds, detected by SAGE II but not by ISCCP, are also of this type, giving a total fractional cover of more than 0.13 by optically thin cloud layers (about 3% of this type of clouds also appear in category 3 in Table 1). The distribution of individual P_c differences indicates three different groups (Figure 6): the majority of cases exhibit a distribution of P_c differences distributed about 0 ± 75 mbar, where the standard deviation is consistent with the SAGE II and ISCCP precisions. There are also two small groups of cases with SAGE II values of P_c much smaller than ISCCP values and much larger than the ISCCP values, respectively.

The ISCCP cloud detection is sensitive enough to detect the thickest versions of type C clouds [*Rossow and Garder,* 1993b]; however, the radiative model used in the ISCCP analysis assumes that all clouds are composed of 10 μm water spheres when it is more likely that these high-level clouds are composed of ice crystals. For some viewing geometries, this assumption results in an overestimate of cloud optical thicknesses (underestimate of *Trans* in equation (1)) and, consequently, an overestimate of cloud top temperature and pressure in the correction step [*Minnis,* 1993]. This effect could account for the group of cases where the ISCCP values of P_c are as much as 200 mbar larger than the SAGE II values.

In the ISCCP analysis, some of the thinner type C clouds are detected by the infrared radiance threshold test, but not by the visible radiance threshold test. In this circumstance, the attempt to reconcile the observed infrared radiance with a cloud top temperature within the range of tropospheric temperatures and with the retrieved optical thickness sometimes fails because (1) the retrieved optical thickness is inaccurate enough to be inconsistent with the observed infrared radiances for any tropospheric temperature or (2) the optical thickness retrieval fails altogether because the visible radiance is equal to or less than the clear sky value due to errors in the measured visible radiance, cloud shadows, or errors in determining the clear sky radiances. In the ISCCP analysis, such cases are treated as clouds with very low optical thicknesses, and in order to obtain a solution the cloud is assumed to be located at the tropopause, and the infrared measurement is used to retrieve an optical thickness. This procedure can account for the group of cases where the ISCCP values of P_c are as much as 150–200 mbar lower than the SAGE II values.

For population category 4 in Table 1, the SAGE II results show that type C clouds occur about two thirds of the time in the 310 to 440 mbar layer in winter midlatitudes, well below the tropopause (Figures 8a and 8f). Therefore in this case the ISCCP procedure overestimates the altitude of the cloud tops. In summer midlatitudes (Figures 8c and 8d), the SAGE II results show that slightly more than half the type C clouds occur in the 180 to 310 mbar layer, nearer the tropopause. In the tropics (Figures 8b and 8e), most of the type C clouds occur in the topmost level (50-180 mbar) at the tropopause. Thus the ISCCP procedure for this cloud type is more accurate in summer midlatitudes and at lower latitudes.

Surface observations have suggested that about half of all high-level clouds overlie lower-level clouds, particularly boundary layer clouds [*Warren et al.,* 1985]. This fact does not affect the analysis of the optically thicker type A and B cloud, but could be a significant source of error for type C clouds. However, the generally good comparison in a global sense between SAGE II and ISCCP for type C clouds suggests either that this particular type of cloud does not



(a) (b) (c)

(d) (e) (f)

Figure 8. Vertical distribution of relative occurrence of clouds (in percent) for single thin layers and clouds with diffuse tops from SAGE II: (a) 50°S to 20°S for July, (b) 20°S to 20°N for July, (c) 20°N to 50°N for July, (d) 50°S to 20°S for January, (e) 20°S to 20°N for January and (f) 20°N to 50°N for January.

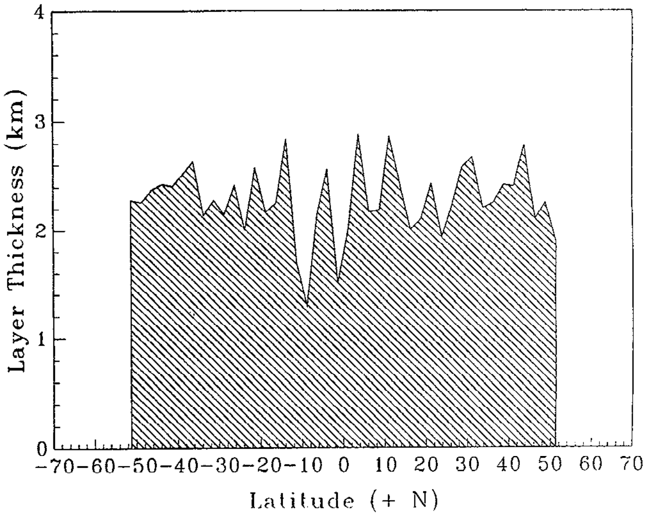


Figure 9. Zonal monthly mean vertical extent (in kilometers) of single thin layer clouds from SAGE II for July 1985–1990.

occur frequently over lower-level clouds or that their optical thickness is still large enough to minimize the errors in the ISCCP cloud top pressure determination. Nevertheless, there are likely to be specific climate regimes where this source of error in the ISCCP results is larger.

The SAGE II results for type C clouds provide an estimate of the average physical depth of such clouds (Figure 9). The global mean value is 2–2.5 km with relatively little variation with latitude. This estimate is limited by the vertical resolution of the SAGE II instrument.

3.3.4. Type D: Thin high cloud layer overlying thick high cloud. If an optically thin cloud overlies a thicker high-level cloud (Figure 4d), SAGE II will report the location of the top of the upper thin cloud top correctly. However, ISCCP will observe a total optical thickness that is much larger than that of the upper layer and will interpret an infrared radiance emitted mostly from the lower layer, but attenuated by the upper layer, as a warmer cloud top temperature and higher P_c. This case is similar to type B except that the upper layer is separated from the lower layer. The amount of the bias in P_c depends on the optical thickness of the upper layer: Significant biases are produced only if the (visible) optical thickness of the thin cloud layer is small.

The SAGE II shows that this type of cloud occurs <5% of the time in the global mean but almost 10% of the time in the tropics. In these cases, the ISCCP cloud top pressures can be as much as 250 mbar larger than the SAGE II values in the tropics, a difference which is reduced to about 150 mbar at midlatitudes. The globally averaged difference in P_c is -158 mbar, larger than for the type B clouds (Table 2); but the distribution of individual cloud top pressure differences for type D is roughly similar in shape to that of the type B clouds (Figure 6).

Note that our result is only for cases where the cloud top pressure of the lower cloud layer is also <440 mbar and does not provide an estimate of the frequency of multiple cloud layers. However, if we assumed that at least half of the type C clouds also overlie some lower-level cloud, then about 17% of optically thin, high-level clouds are multilayered. This fraction is equivalent to a global cloud cover of only 0.036. Hence we conclude that the predominant reason for the high bias of ISCCP cloud top pressures is the generally diffuse nature of the uppermost portion of most high-level clouds, rather than overlap of optically thin high-level and lower-level clouds.

3.4. Seasonal Changes of Cloud Top Profiles

Figure 5 shows significant shifts with season of the relative proportion of type A and type C clouds in midlatitudes: in winter there is more type C and less type A than in summer, whereas the proportion of type B is nearly constant. These changes account for the seasonal changes of the average cloud top pressure differences shown in Figures 1 and 2. Figure 8 shows the detailed changes of type B and type C clouds in the three pressure ranges in three latitude zones for January and July. Associated with the seasonal changes in total high-level cloud amounts (paper 1), there are changes in the proportions of these different cloud types. The warmer and more convective summer hemisphere has more type B clouds at higher levels (Figures 8c and 8d) as in the tropics (Figures 8b and 8e). Type C clouds are also shifted into upper levels. In colder middle latitudes (Figures 8a and 8f), a more stable atmosphere tends to have both type B and C clouds at lower levels, along with a higher proportion of sharp-topped clouds (type A, Figure 5).

4. Summary

Returning to Figures 1, 2, 5, and 6 and Tables 1 and 2, we can summarize the reasons for the disagreement between SAGE II and ISCCP cloud top pressures as follows.

1. The SAGE II results show that the ISCCP overestimates the cloud top pressures of high-level clouds by about 60 mbar, but the bias ranges from almost 150 mbar in the tropics to <20 mbar in winter midlatitudes. The primary reason for this bias in the ISCCP values is that about 56% of all high-level clouds have diffuse tops (including a small number of cases with an optically thin overlying layer). The proportion of these cloud types is even larger in the tropics (>70% of all high-level clouds) and much smaller in winter midlatitudes (<35%). Summer midlatitudes have intermediate proportions of these cloud types. This implies that seeking a precise cloud top location may not be entirely meaningful. The ISCCP cloud tops, which are equivalent to the effective radiating level, may be appropriate for cloud radiation studies, even if it disagrees with the physical location of cloud top height. However, for cloud process studies the distinction between sharp and diffuse tops and their locations is probably significant.

2. At middle latitudes, where the SAGE II and ISCCP cloud top pressures agree best, clouds with sharp tops reach a maximum relative proportion of the total high-level cloud amount (about 30-40%), and diffuse-topped clouds are reduced to their minimum (about 30-40%).

3. The next most abundant high-level cloud type (26% of all high-level clouds) appears as a single, optically thin layer (we have only determined that no other high-level cloud lies below, not whether middle-level or low-level clouds are present). The average ISCCP cloud top pressure for this cloud type is actually 27 mbar smaller than the SAGE II values; however, this average result combines several different cases. In the majority of the cases, the optical thickness of the clouds is high enough that ISCCP values of P_c are relatively accurate. In some cases, the treatment of radiation in these ice crystal clouds using a water droplet model overestimates cloud τ and P_c. In some cases, the ISCCP procedure to handle cases where the optical thickness retrieval fails assigns P_c values that are too low, mostly at midlatitudes.

4. Estimates of significant frequencies of overlap between high-level and lower-level clouds suggest that there should be large errors in the ISCCP values of P_c if the cloud optical thickness is low enough. Our results show, however, that more than half (57%) of all high-level clouds detected by SAGE II (Table 1) are optically thick enough to reduce the importance of this source of error. Of

the remaining 43%, 12% are missed completely by ISCCP because $\tau < 0.1$, 11% are mislabeled by ISCCP as lower-level clouds, and 20% are detected, correctly labeled as high-level and P_c accurately determined for most cases. Thus of the optically thin portion of high-level clouds, about one third are mislabeled as lower level, which is roughly consistent with the expectation based on cloud overlap statistics.

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