Global Patterns of Cloud Optical Thickness Variation with Temperature

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ABSTRACT

The International Satellite Cloud Climatology Project (ISCCP) dataset is used to correlate variations of cloud optical thickness and cloud temperature in today's atmosphere. The analysis focuses on low clouds in order to limit the importance of changes in cloud vertical extent, particle size, and water phase. Coherent patterns of change are observed on several time and space scales. On the planetary scale, clouds in colder, higher latitudes are found to be optically thicker than clouds in warmer, lower latitudes. On the seasonal scale, winter clouds are, for the most part, optically thicker than summer clouds. The logarithmic derivative of cloud optical thickness with temperature is used to describe the sign and magnitude of the optical thickness–temperature correlation. The seasonal, latitudinal, and day-to-day variations of this relation are examined for Northern Hemisphere clouds in 1984. The analysis is done separately for clouds over land and ocean. In cold continental clouds, optical thickness increases with temperature, consistent with the temperature variation of the adiabatic cloud water content. In warm continental and in almost all maritime clouds, however, optical thickness decreases with temperature. The behavior of the optical thickness-temperature relation is usually, though not always, the same whether the temperature variations are driven by seasonal, latitudinal, or day-to-day changes. Important exceptions are noted. Some explanations for the observed behavior are proposed.

1. Introduction

Cloud feedbacks are a major source of uncertainty in general circulation model (GCM) climate simulations. One reason for the uncertainty is the lack of quantitative knowledge of the average cloud properties and their variations, as reflected in the simplistic representations of clouds that GCMs use. Changes in cloud cover and cloud height and their effects on climate warming have been investigated in several modeling studies (e.g., Hansen et al. 1984). Changes in cloud optical properties, however, have received less attention, even though they were shown to be as important as those in cloud cover and height (e.g., Wang et al. 1981). It is only recently that the incorporation in some GCMs of prognostic liquid water schemes (e.g., Smith 1990) allowed for a closer examination of those changes (Roeckner et al. 1987; Roeckner 1988; Mitchell et al. 1989; Le Treut and Li 1991). The key parameter that describes the effect of a cloud on both shortwave and longwave radiation is cloud optical thickness, which can change because of variations of cloud water content, vertical extent, and particle size distribution and shape. Until the advent of the International Satellite Cloud Climatology Project (ISCCP), only limited global observations of this cloud property have been available (Rossow and Lacis 1990).

Several recent studies have highlighted the possible climatic effects of cloud water content variations (e.g., Somerville and Remer 1984; Betts and Harshvardhan 1987; Platt and Harshvardhan 1988). A summary of observations from aircraft flights into clouds over the former Soviet Union (Feigelson 1978) suggested that cloud liquid water content generally increases with temperature. Somerville and Remer (1984), assuming that in a warmer atmosphere cloud liquid water contents will be systematically larger, extrapolated this relationship to a positive, global correlation between cloud optical thickness and temperature, and used a radiative convective model (RCM) to study cloud optical-thickness feedbacks on climate. Their approach is based on two assumptions that can be tested using global cloud datasets.

The first assumption is that the observed variations of cloud liquid water content with temperature can be directly related to cloud optical thickness variations. This will be true only if cloud vertical extent and particle size distribution do not vary greatly and systematically with temperature. Platt and Harshvardhan (1988) and Platt (1989), using observations of cirrus clouds, showed that changes in these two other parameters can significantly modify the relationship between

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cloud optical thickness and cloud liquid water content. Theoretical calculations for water clouds by Twomey (1977) and Charlson et al. (1987) showed that, for constant liquid water content, a doubling of droplet effective radius decreases cloud albedo by as much as 15%. Curry et al. (1990), in an analysis of satellite microwave observations, found no systematic increase in cloud liquid water path with temperature in high-latitude oceanic clouds, and attributed the finding to variations in cloud vertical extent that offset liquid water content variations.

The second assumption is that the increase in cloud water content with temperature, found in higher-latitude continental clouds, can be extended to clouds at all latitudes and locations on the globe. This assumption appears more plausible because of the theoretical explanation of the relationship proposed by Betts and Harshvardhan (1987). They showed that the adiabatic liquid water content of a cloud (the theoretical upper limit of condensed water amounts) increases with temperature and that the rate of increase decreases with mean temperature. At similar temperatures, the rate of increase derived from the Soviet observations agrees fairly well with their theoretically calculated adiabatic rate of increase. This agreement suggests that in midlatitude continental clouds, the nonadiabatic processes that can affect liquid water, like precipitation and entrainment, may not be predominant, or may not change with temperature. The fact, however, that the action and intensity of these nonadiabatic processes depends strongly on dynamic and microphysical considerations that vary significantly with latitude and location makes it unlikely that the dominance of adiabatic processes found in midlatitude continental clouds can be safely extended to clouds throughout the globe.

The preceding discussion identifies two very important points: 1) cloud optical property feedbacks on climate change can be properly estimated only if both global and regional cloud optical thickness variations with temperature are known, and 2) those same feedbacks can be understood and resolved only if variations in the key cloud parameters that determine optical thickness and the atmospheric processes that cause their variations are determined. In this study we address the first point using a global dataset to correlate latitudinal-seasonal-, and shorter-term variations of cloud optical thickness and temperature. We focus on low-level clouds in order to minimize the range of vertical extent variations and hence, the importance of those variations to optical thickness changes. Our objective is to document the optical thickness–temperature relation and to search for evidence of the effects of varying dynamic, thermodynamic, and microphysical conditions on this relation. Some proposals are discussed regarding the second point, and suggestions are given regarding the additional data needed to understand the processes that produce the observed cloud optical-thickness changes.

2. Dataset and analysis procedure

a. Dataset

The dataset we used is produced by the International Satellite Cloud Climatology Project (ISCCP) (Schiffer and Rossow 1983; Rossow and Schiffer 1991). This data will cover the period from July 1983 through June 1995; more than seven years are already completed. The dataset contains detailed information on the distribution of cloud radiative properties and their diurnal and seasonal variations, as well as information on the vertical distribution of temperature and humidity in the troposphere (Rossow et al. 1991). The raw observational data consist of satellite radiance measurements, taken from five geostationary satellites and at least one polar orbiter (Schiffer and Rossow 1985; Rossow et al. 1987).

The ISCCP cloud analysis performs two functions: 1) decides which radiance values correspond to cloudy scenes and 2) infers cloud properties from the radiance values by comparison to radiative-transfer calculations. Cloud optical thicknesses are determined from visible ($\approx$0.6 μm) radiances measured in each satellite pixel determined to be cloudy. Clouds are assumed to cover each pixel (about 4–7 km across) completely and uniformly. The radiative model calculations include the variable effects of viewing and illumination geometry, ozone absorption, Rayleigh scattering, surface reflectance, and cloud Mie scattering. Ozone column abundances are specified as a function of date and location from the TIROS Operational Vertical Sounder (TOVS) data produced by NOAA. Rayleigh scattering is calculated to occur in gas layers above and below the cloud, partitioned according to the cloud-top pressure obtained from the IR radiative analysis for that image pixel. The surface reflectance is retrieved for each location and time period from the same satellite data using image pixels determined to be clear (cf. Rossow et al. 1985; 1989). Land-reflectance values vary from month to month with solar zenith angle, but are assumed isotropic for retrievals. Anisotropic ocean reflectances are specified by an adaptation of a model by Minnis and Harrison (1984). Sea ice and snow reflectances can vary between 5-day intervals. Since the retrieval radiative model includes no aerosol scattering, the surface-reflectance values include the effect of the background aerosol; large variations in aerosol would be detected as clouds. Cloud visible reflectances are calculated as conservative, multiple, Mie scattering from spherical liquid water particles with sizes specified by a "gamma" distribution (Hansen and Travis 1974) with an effective particle radius of 10 μm and an effective size variance of 0.15.

Results are reported every 3 hours as averages over 280-km-wide areas (equivalent to 2.5° resolution at the equator) and in seven pressure intervals in the vertical. For each grid box and pressure interval, one number is given for the number of cloudy pixels that belong to each of five optical thickness categories. Figure 1 shows the optical thickness categories and the cloud-top pressure intervals, together with radiometric cloud-type definitions. In this study, we focus on clouds with tops occurring in the pressure interval from 680–800 mb. A weighted mean of the optical thicknesses of all the cloudy pixels in a grid box is calculated. The mean temperature of the selected pressure interval is taken from the atmospheric vertical profile that is provided in the dataset; hence, "*cloud temperatures" discussed here are atmospheric temperatures that are independent of cloud-top temperature variations within this pressure interval.*

Tests of the sensitivity of retrieved values of cloud optical thickness to uncertainties in specified or measured input parameters are discussed in Rossow et al. (1989). The largest of these uncertainties is associated with assuming a constant cloud particle size: variations of particle size over a range from 5 to 20 μm would produce an uncertainty of about 15% in cloud optical thickness. Another source of uncertainty comes from the absolute calibration of the visible radiances, but this does not affect our measurements of optical-thickness variations as long as relative calibration stability is maintained over the whole dataset. For the ISCCP

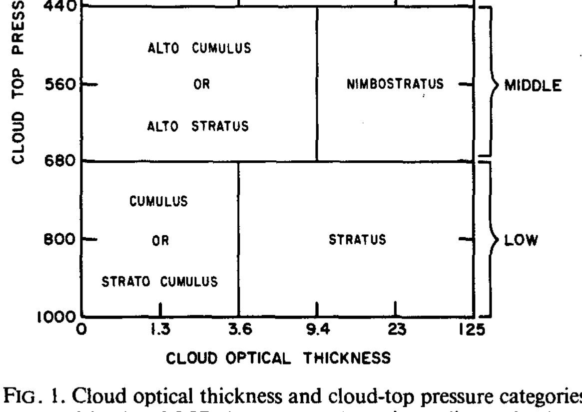

FIG. 1. Cloud optical thickness and cloud-top pressure categories as reported in the ISCCP dataset, together with radiometric cloud type definitions.

radiances, the bias is expected to be less than 5% relative and the possible variations over one year of data < 2% (Brest and Rossow 1992; Desormeaux et al. 1993).

Another important source of uncertainty, which is difficult to estimate, is the effect of small-scale (subpixel) variations in atmospheric optical properties, usually thought of as variations in cloud cover, though it is also valid to consider them as variations in cloud optical thickness (cf. Rossow 1989). A direct estimate of the effect is made by Wielecki and Parker (1992) using Landsat high-resolution images of several cloud types, most of which were selected as "some of the most difficult cases." For the pixel size in the ISCCP dataset (4–7 km), the estimated average error in cloud cover is <5%. The error occurring in individual pixels is both larger and smaller than this, but is rapidly reduced by averaging over many scenes and cloud fields. The average error over all cloud types is expected to be somewhat smaller. This magnitude is consistent with previous studies using a variety of higher-resolution datasets (see discussion in Rossow et al. 1989). Also in Rossow et al. (1989), a similar magnitude of this uncertainty is obtained if all "low" optical thickness values are ascribed to partial coverage of the satellite pixels. In section 4, we also assess the importance of this effect on the results of this study by excluding all regions (280 km in size) with lower cloud amounts.

There are few datasets that provide independent validation of cloud optical-thickness retrievals from satellite radiances. The best such datasets are from the First ISCCP Regional Experiment (FIRE), but there are few published results concerning this particular issue. We mention two results that, at least, do not indicate large problems with such retrievals for liquid water clouds. Nakajima et al. (1991) compare optical-thickness values inferred from cloud properties measured by an in situ aircraft with those inferred from radiance measurements made from a high-altitude aircraft, similar to a satellite. Although both values are derived using approximate relations, the agreement is reported to be good. In other words, radiative-transfer theory appears sufficiently accurate to perform this retrieval (cf. Nakajima and King 1990) as argued by Rossow et al. (1989). Blaskovic et al. (1991) summarize the diurnal variation of cloud water path in marine stratus clouds observed over San Nicolas Island during 19 days in July 1987 (FIRE experiment). Their results, averaged over the daylight period observed by the ISCCP, give a mean optical thickness of about 11. The monthly mean cloud optical thickness reported in the ISCCP data for this area is about 13. (There were no high-level clouds detected during this month, and variations of mean optical thicknesses among adjacent regions are only about ±1.) An indirect source of validation comes from a comparison of planetary albedos calculated from retrieved cloud optical thickness values and inferred from direct radiation budget measurements by satellites. Such a comparison indicates no large (>15%) errors in cloud optical thickness values (Rossow and Lacis 1990).

There are other limitations of the ISCCP dataset. Radiance measurements in the visible channel, for instance, are made only during the daytime. This limitation is less significant for low-level clouds that primarily reflect solar radiation. The presence of multiple cloud layers in the vertical is a small source of uncertainty for the visible radiance analysis, since the radiances measured by the satellite in this case include the integrated effect of all the cloud layers on the radiation. This effect is also minimized in our work by the fact that only low-level clouds are examined. Finally, in the analysis of the radiance fields, it is difficult to discriminate between ice/snow covered surfaces and clouds, so we avoid higher latitudes in this study.

b. Analysis procedure

The optical thicknesses of clouds with tops in the 680–800-mb range are examined for 1984 in relation to the mean atmospheric temperature in the 680–800-mb range, hereafter referred to as cloud temperature. A separate selective analysis of clouds with tops in the 800–1000-mb range revealed only small quantitative differences with the results presented here, indicating that our results are valid for all low clouds in the dataset.

The analysis procedure includes four basic parts. In the first part, the data are averaged over time and space to obtain the seasonal and latitudinal distributions of cloud optical thickness and temperature. Only cloudy pixels are included in the averaging. In the second part, the variation of the optical thickness–temperature relation with season is investigated. (In this and the two parts that follow, there is no averaging of the 3-hour observations, except for illustrative purposes in part three.) Low clouds for the whole year are divided into tropical (0°–15°N), subtropical (15°–35°N), and midlatitude (35°–55°N) groups, and then sorted into 15 K temperature intervals according to their respective cloud temperatures. The temperature intervals overlap and are separated by 5 K. For each interval, a parameter is calculated, defined as the logarithmic derivative of cloud optical thickness with temperature ($d\ln\tau/dT$). The correlation coefficient between optical thickness and temperature is also calculated, and its statistical significance is evaluated through the use of an analysis-of-variance F test. Then $d\ln\tau/dT$ is plotted against the mean cloud temperature in each interval. Each curve on the plot illustrates how the optical thickness–temperature relation varies with cloud temperature changes (driven primarily by seasons) in the same climate regime (latitude zone), while a comparison of the three curves provides information on how the relation varies with climate regime.

In the third analysis part, the latitudinal variation of the optical thickness–temperature relation is examined separately for each month of 1984. Day-to-day temperature variations at a certain latitude during a period of one month form the temperature interval for which $d\ln\tau/dT$ is calculated. This analysis is done only for latitudes of 25°–55°N because at lower latitudes the temperature variation during a period of one month is too small to obtain meaningful statistics. Scattergrams of optical thickness and temperature for specific latitudes are drawn, and $d\ln\tau/dT$ is plotted against the mean cloud temperature for each latitude and month. Each curve on the plot shows the latitudinal variation of the optical thickness–temperature relation in a certain month, while a comparison of the curves provides additional information on the seasonal variation of the relation.

In the second and third parts of the analysis, temperature variations driven by seasonal and latitudinal changes are used as the domain for which the optical thickness–temperature relation is investigated. In both cases, these temperature variations are known to be accompanied by changes in dynamic regime. To isolate the effects of temperature changes on the relation, a fourth analysis part was performed. In this part, data from the same latitude and month are sorted into temperature intervals, and $d\ln\tau/dT$ calculated for the clouds in each interval.

3. Results

The latitudinal distribution of the annual mean optical thickness of all clouds in 1984 is shown in Fig. 2, together with the latitudinal distribution of the annual mean cloud-top temperature (there are no large differences between these curves and those for averages over 1984–86). High-latitude clouds in both hemispheres have colder tops and are optically thicker than low-latitude clouds. In the tropical region, however,

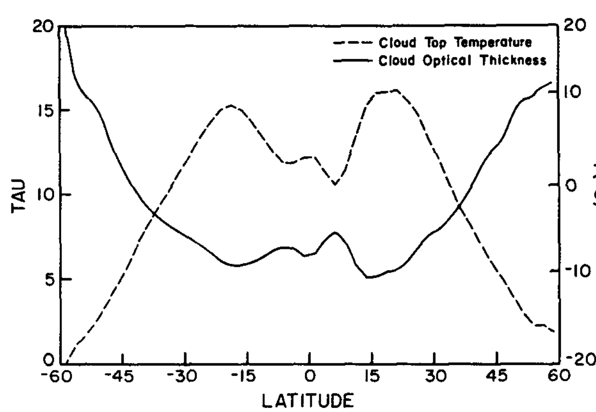

FIG. 2. Annual zonal-mean distributions of optical thickness and top temperature for all clouds in 1984.

cloud-top temperature drops, due apparently to an increase in cloud-top heights associated with the tropical convective zone. The local minimum in cloud-top temperature near 5°N also coincides with a local maximum in cloud optical thickness. This indicates that changes in cloud vertical extent could significantly affect total cloud optical-thickness variations at least in the tropics. The pattern of the optical thickness variations of total cloudiness is hard to interpret, since it merges together the effects of different cloud types that vary significantly in their vertical extents, water phases and contents, and particle size distributions. In order to simplify the problem, we focus on low-level clouds, which consist primarily of liquid water droplets of comparable radii and are restricted in their vertical extent variations.

Figure 3a shows the latitudinal distribution of the annual mean optical thickness of low clouds, together with the latitudinal distribution of their annual mean temperature. The contrasting shapes of the curves indicate that low clouds in the colder higher latitudes of both hemispheres are, on the average, optically thicker than low clouds in the warmer lower latitudes. The minimum in low-cloud optical thickness occurs near 15°N, with a local maximum near 5°N. The quantitative resemblance of the optical thickness curves in Figs. 2 and 3a shows that low clouds are the dominant component of the total cloud optical thickness field.

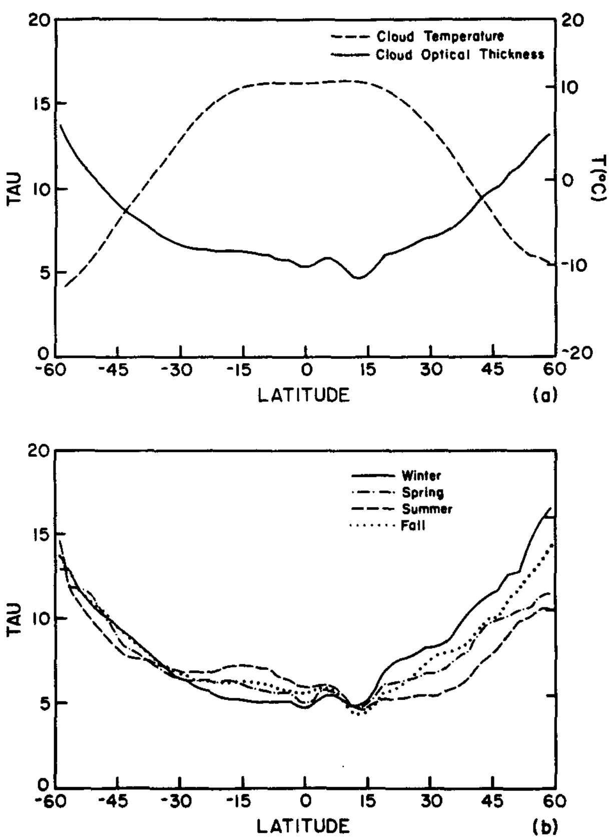

FIG. 3. (a) Annual zonal-mean distributions of optical thickness and temperature for low clouds in 1984; (b) Seasonal zonal-mean distributions of optical thickness for low clouds in 1984. Seasons are for the Northern Hemisphere.

The seasonal variation of the optical thicknesses is illustrated in Fig. 3b by the latitudinal distributions for Northern Hemisphere winter, spring, summer, and fall. In northern middle and high latitudes, a pronounced seasonal progression in low-cloud optical thickness is observed, with the winter clouds at each latitude having the highest optical thicknesses, the summer clouds having the lowest, and the clouds of spring and fall having values in between. In the Southern Hemisphere, greater seasonality is observed in the tropical and subtropical latitudes, where winter (NH summer) clouds are optically thicker than the summer (NH winter) ones. In the southern middle and high latitudes, the seasonal differences are smaller, but the summer (NH winter) clouds are generally optically thicker than the winter (NH summer) ones. The distinct differences in the seasonal behavior of low clouds in the two hemispheres suggest that clouds over land and ocean behave differently with respect to the variation of their optical properties. Moreover, low-latitude behavior may also be different from that at high latitudes. In the analysis that follows, Northern Hemisphere clouds are examined separately over land and over ocean.

The latitudinal and seasonal distributions of the low-cloud optical thickness presented above do not support the notion that cloud liquid water contents are larger at warmer temperatures. In the next two parts of the analysis, we examine how low-cloud optical thickness changes with temperature in specific latitude zones and in specific seasons. In the second part, the seasonal variation of the optical thickness–temperature relation is examined separately for clouds in three climate regimes (latitude zones).

Figure 4 shows $d \ln\tau / dT$ for clouds in each 15 K cloud temperature interval plotted against their mean temperature, separately for tropical, subtropical, and midlatitude clouds in 1984, located over land (Fig. 4a) and over ocean (Fig. 4b). Open symbols on the graphs indicate correlation coefficients above the 99% significance level. For low clouds over land (Fig. 4a), optical thickness increases with temperature, and $d \ln\tau / dT$ has a value of about 0.04 for midlatitude clouds with mean temperatures below −8°C. This is consistent with the value that Somerville and Remer (1984) derive from the Soviet aircraft observations for the change of cloud liquid water content with temperature. It is also within the range of the thermodynamic calculations of the adiabatic cloud liquid water content change with temperature (Betts and Harshvardhan 1987). The results in Fig. 4a, however, also show that, in all clouds warmer than about −6°C, optical thickness consis-

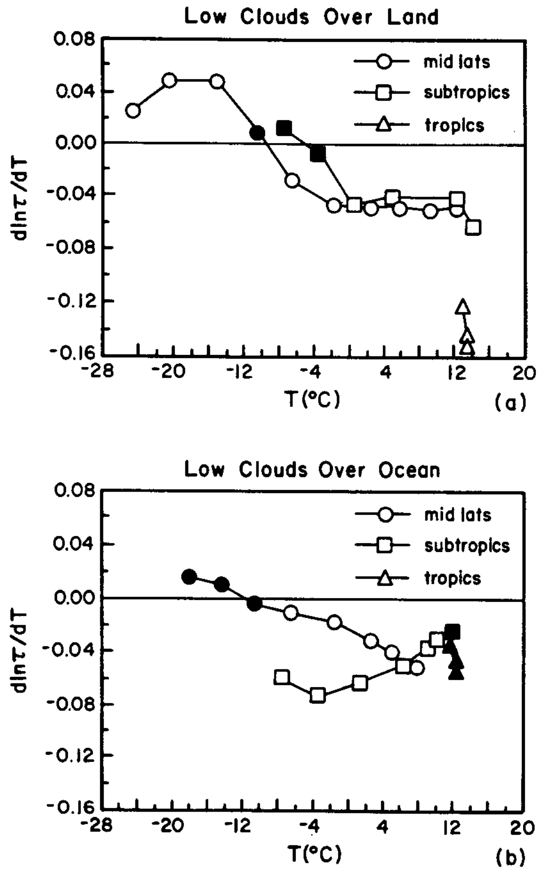

FIG. 4. $d\ln\tau/dT$ (see text for definition) as a function of mean cloud temperature for NH tropical (0°–15°N), subtropical (15°–35°N), and midlatitude (35°–55°N) low clouds in 1984 that are sorted in 15 K temperature intervals and are located (a) over land, and (b) over ocean. Open symbols denote correlation coefficients above the 99% significance level.

tently decreases with temperature. Warm clouds in the subtropical and middle latitudes show remarkable agreement in the character and magnitude of their optical thickness–temperature relation as they both have values of $d\ln\tau/dT$ around -0.04. Tropical low clouds, however, show a steeper decrease of optical thickness with temperature with an average value of $d\ln\tau/dT$ around -0.14.

For low clouds over ocean (Fig. 4b), optical thickness decreases with temperature in most climatic regimes and temperature ranges. The mean value of $d\ln\tau/dT$ at the warmer temperatures is again around -0.04. Middle-latitude clouds below -10°C show some uncertain positive correlations. When compared to midlatitude clouds over land (Fig. 4a), midlatitude clouds over ocean show a similar decrease in the value of $d\ln\tau/dT$ with temperature, but with a less steep drop from positive to negative values. As a result, cold midlatitude clouds over ocean do not show the large, statistically significant, positive correlations that clouds over land show at similar temperatures. This behavior implies a seasonal variation of land–ocean contrasts in cloud radiative effects. In subtropical clouds the optical thickness–temperature correlations are negative in all temperature ranges, but the magnitude of $d\ln\tau/dT$ increases with temperature and the statistical significance of the correlations drops at the higher temperatures. This increase in the value of $d\ln\tau/dT$ with increasing temperature makes subtropical clouds over ocean distinctly different from subtropical clouds over land, as well as from midlatitude clouds over ocean. Finally, tropical low clouds over ocean show negative correlations between optical thickness and temperature, but those correlations are of low statistical significance.

The results of the second part of the analysis revealed a significant seasonal variation in the behavior of the optical thickness–temperature relation (Figs. 4a,b). In the third part, the latitudinal variation of the relation is examined separately for each month of 1984. The results for January are presented first to illustrate the analysis procedure.

The optical thicknesses of low clouds over land in January are positively correlated with temperatures at the higher, colder latitudes of the range examined. An example is shown in Fig. 5a, where monthly mean cloud optical thicknesses and temperatures, for each longitude box over land at 41.25°N, are plotted. (The monthly mean fields are used for illustration purposes only; $d\ln\tau/dT$ values for each latitude are derived from the 3-h observations.) Optical thickness generally increases with temperature. The slope of the regression line decreases and eventually becomes negative as one moves toward lower, warmer latitudes. Figure 5b shows the optical thickness–temperature relation for low clouds over land at 31.25°N. Low clouds over water show weaker positive optical thickness–temperature correlations at the higher, colder latitudes. Figure 6a shows results for clouds over water at 53.75°N. The correlations turn strongly negative at the lower, warmer latitudes, as shown in Fig. 6b, where results for clouds over water at 36.25°N are plotted.

The (latitudinal) variation of $d\ln\tau/dT$ is summarized for the 25°–55°N latitude band in Fig. 7. Open circles on the plot denote correlation coefficients above the 99% significance level. The strong positive correlations for cold land clouds and strong negative ones for warm land and water clouds are evident. The value of $d\ln\tau/dT$ for the cold high-latitude clouds over land is again around 0.04. For warm low-latitude clouds over land and almost all clouds over water, however, $d\ln\tau/dT$ assumes negative values that can reach as low as -0.1. The near-zero values of $d\ln\tau/dT$ observed in high-latitude maritime clouds are consistent with the zero correlations between cloud liquid water path and cloud temperature that were found, for the same type of cloud, in the microwave observations of Curry et al. (1990).

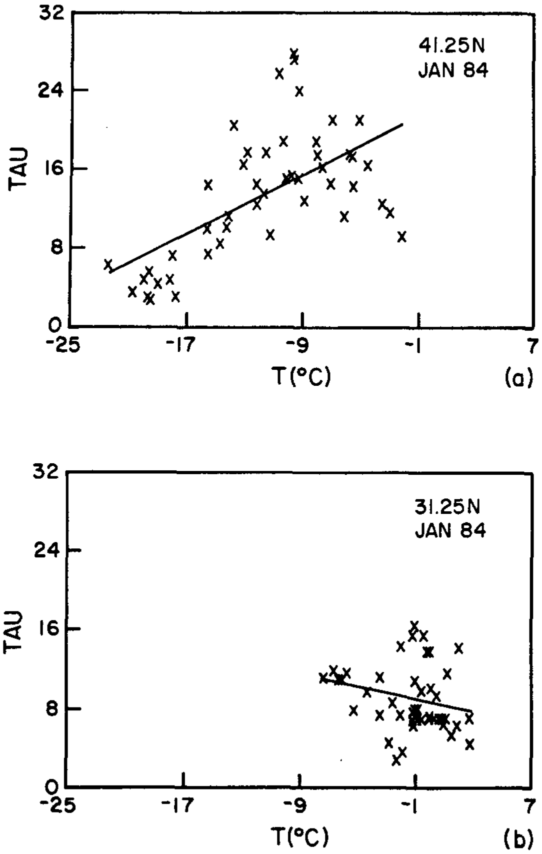

FIG. 5. Monthly mean (Jan 1984) optical thickness vs temperature of low clouds over land for each longitude box at (a) 41.25°N latitude, and (b) 31.25°N latitude. The solid line represents a linear least-squares fit through the data.

A similar analysis is done for all 12 months of 1984. Figure 8a shows $d\ln\tau/dT$ versus the zonal-mean cloud temperature for low clouds over land for four months representative of their respective seasons. The x marks on the plot denote correlation coefficients above the 95% significance level, and the open circles correlation coefficients above the 99% significance level. Here, $d\ln\tau/dT$ is positive at the colder latitudes in the winter and late fall months and negative at all the other latitudes and seasons. The plot shows little change in the overall character or the value of $d\ln\tau/dT$ with season. At similar temperatures, clouds of different seasons have approximately the same value of $d\ln\tau/dT$, with the possible exception of lower-latitude clouds during the late fall.

The same plot for low clouds over ocean is shown in Fig. 8b. Some coherent positive optical thickness–temperature correlations are observed in the colder winter latitudes, while in the warmer latitudes during the rest of the year the correlations are found to be mostly negative. One notable exception is clouds in the southernmost latitudes during the late summer–early fall season where the values of $d\ln\tau/dT$ turn positive again, and the correlations are significant. This exception produces differences between summer clouds and the clouds of the other three seasons, since $d\ln\tau/dT$ is, for similar temperature ranges, consistently higher in summer clouds than in clouds of any other period of the year.

The last two parts of the analysis revealed a tendency in the optical thickness–temperature correlations to become negative at the warmer latitudes and seasons. In the fourth part, clouds of the same latitude and month are sorted into temperature intervals and $d\ln\tau/dT$ was calculated for the clouds in each interval. The purpose is to investigate the extent to which the seasonal and latitudinal variations of $d\ln\tau/dT$ are driven by changes in temperature or changes in dynamic regime. The resulting variations of $d\ln\tau/dT$ with temperature are found to be very similar to those shown in Figs. 4 and 8. When, for example, midlatitude winter clouds over land are examined by temperature interval, negative $d\ln\tau/dT$ values are present at warmer temperatures, while in subtropical winter clouds over land positive values are present at the colder temperatures. One feature that appears to be dependent on both lat-

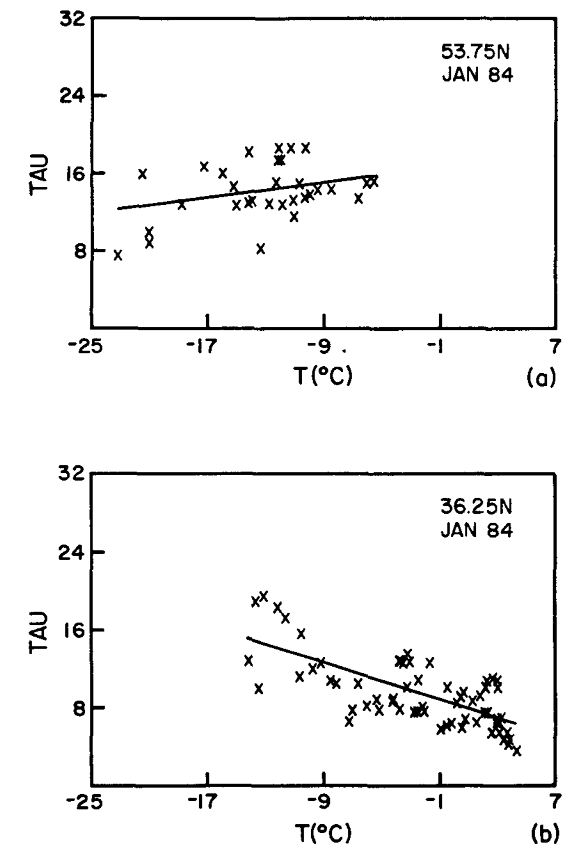

FIG. 6. As in Fig. 5 but for low clouds over water at (a) 53.75°N, and (b) 36.25°N.

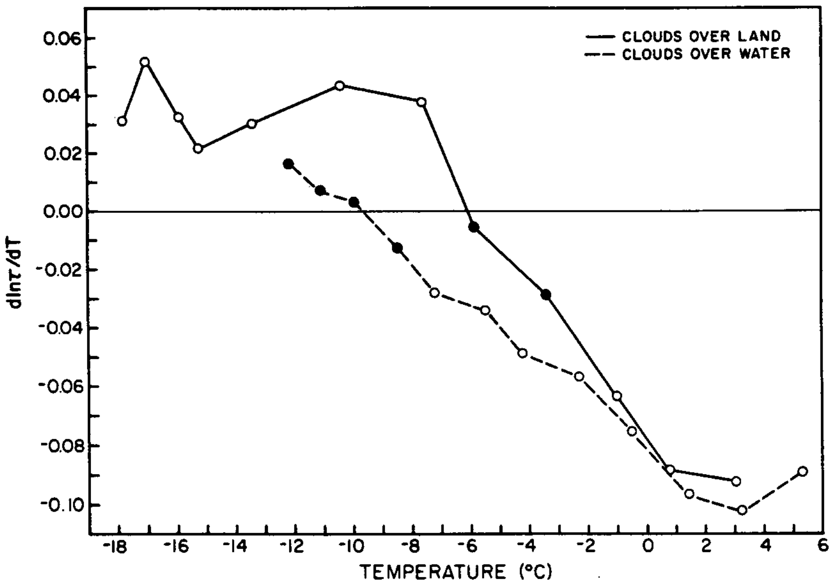

FIG. 7. $d\ \ln\tau/dT$ as a function of monthly mean temperature of low clouds over land (solid line) and low clouds over ocean (dashed line) for all latitudes in the 25°–55°N latitude range for January 1984. Open circles denote correlation coefficients above the 99% significance level.

itude and season is the positive $d\ \ln\tau/dT$ peak found in the subtropical late-summer maritime clouds (Fig. 8b). This peak is not present when the warm clouds of any other latitude band and season are examined. Thus, we conclude that the basic shape of the curves shown represents the effect of changes in cloud process(es) with cloud temperature, although the variation in magnitude of the $d\ \ln\tau/dT$ values at warmer temperatures suggests that other factors play a secondary role.

4. Discussion and summary

One year of data has been analyzed in order to document the optical thickness–temperature relation for low clouds around the globe and to examine the behavior of this relation in varying dynamic regimes, represented by different latitude zones and seasons. We find that, in all colder continental clouds, cloud optical thickness increases with increasing temperature and that the rate of increase decreases with increasing temperature. This result agrees quantitatively with aircraft observations of the variation of cloud water content with temperature over the former USSR and with the calculated increase of adiabatic cloud water content. The agreement suggests that, for these colder continental clouds, cloud water content variations proportional to the variation of the adiabatic water content explain the dominant portion of the cloud optical thickness changes. In contrast, in warmer continental clouds and almost all maritime clouds, optical thickness decreases with increasing temperature. In these clouds, then, either cloud water content does not follow the adiabatic variations, or larger and opposite effects on optical thickness are caused by changes in cloud particle size or vertical extent, or both.

The ISCCP retrieval of cloud optical thickness assumes constant cloud particle size (Rossow et al. 1991). Thus, a factor of 2 decrease in particle size with fixed water content would appear as a small increase in cloud optical thickness. The magnitude of this effect is only about ±10%–15% for a factor of 2 change in particle size either way relative to 10 μm (Rossow et al. 1989; Nakajima and King 1990). Other estimates of the effect are consistent, a change of cloud particle size from 5 to 20 μm, while holding the liquid water content fixed, would decrease the cloud albedo by about 30% (e.g., Twomey 1977; Charlson et al. 1987). Such a large change of cloud particle size with increasing temperature would produce an apparent value of $d\ \ln\tau/dT$ of about −0.02. At warmer temperatures, such an increase of cloud particle size with temperature could partially offset the effect of the increase of water content (proportional to the adiabatic value) and bring $d\ \ln\tau/dT$ values close to zero. It could not, however, explain the large negative values that we find. In any case, large increases in cloud particle size without changes in cloud water content might occur systematically with latitude or season, but are not plausible for day-to-day variations in clouds. Field studies suggest, in fact, that cloud water content increases primarily by an increase of cloud particle size (e.g., Stephens 1987), but the magnitude of the particle size changes is less than half of the range from 5 to 20 μm. In the cases examined by

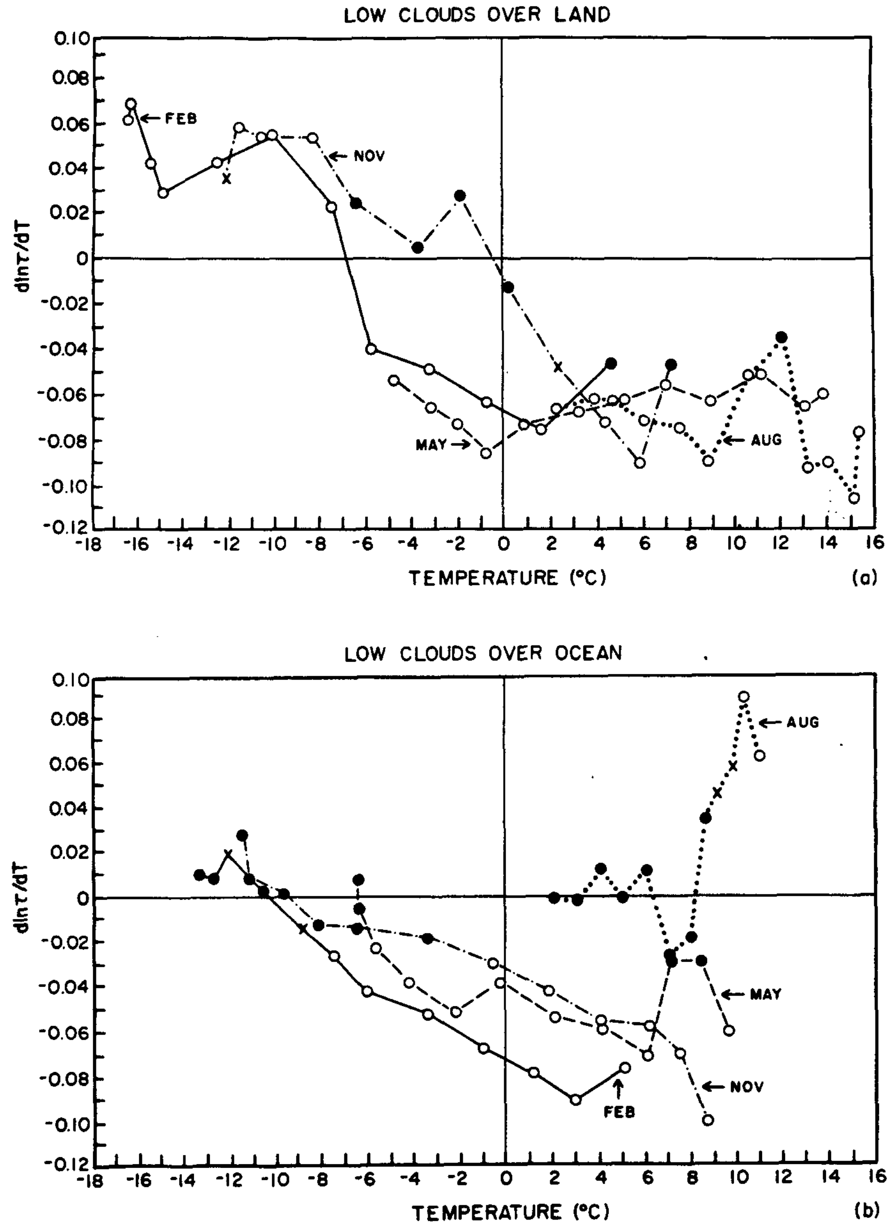

FIG. 8. As in Fig. 7 but for (a) clouds over land, and (b) clouds over ocean for February, May, August, and November of 1984. The x marks denote correlation coefficients above the 95% significance level, and the open circles correlation coefficients above the 99% significance level.

Nakajima et al. (1991), particle size increases from 5 to 12 at optical thicknesses < 10, but remains roughly constant for higher optical thicknesses. Values of $d\ln\tau/dT$ in the case of this more plausible correlated increase of water content and particle size would be underestimated in our results by about 0.01 due to the constant particle size assumption made in the ISCCP analysis.

The effects of changes in cloud vertical extent on the optical thicknesses are minimized by the restriction of this study to clouds with tops in the 680–800-mb range, since cloud bases are usually near the top of the planetary boundary layer that occurs in about the 850–950-mb range over oceans and in about the 800–900-mb range over land (e.g., Warren et al. 1986; 1988). This still means that the cloud layers we are examining are 50–200 mb in depth and may undergo significant changes [e.g., marine stratus do change vertical extent diurnally as reported by Betts (1990), Albrecht et al. (1990), and Blaskovic et al. (1991)]. If the variation of cloud water content continues to follow the adiabatic value at warmer temperatures, then clouds at higher temperatures would have to become systematically thinner (in the physical sense) by a factor of up to 4 to offset and apparently reverse the effect of growing water contents on optical thickness; observed changes appear to be no more than a factor of 2 (Albrecht et al. 1990). Decreasing vertical extent with increasing water content seems counterintuitive, but it cannot be ruled out. In the particular case of marine stratus clouds, in fact, variations of vertical extent may play a significant role.

The derivation of cloud optical thickness from the visible radiances assumes that clouds cover each image pixel (about 4–7 km across) completely and uniformly. The average overestimate from this assumption of cloud cover at the resolution used by ISCCP is about 5%–10%, somewhat larger for cumulus clouds and somewhat smaller for stratocumulus (Wielicki and Parker 1992), which implies an average underestimate of optical thickness for these clouds of a similar magnitude. If such subpixel cloud cover variations occurred systematically with temperature, they would introduce a small ($\approx$0.01–0.02) negative bias in our estimates of $d \ln\tau / dT$. To estimate the possible magnitude of this bias, we repeated the analysis of January 1984 ocean data using only optical thickness values from grid cells (about 280 km across) that were at least 80% cloud covered and that contained at least 40% cloud cover with tops in the 680–800-mb range. We argue that such subpixel effects are much less likely in regions that are mostly overcast at mesoscales. The main effect of this restriction is to increase the negative values of $d \ln\tau / dT$ by amounts that are variable with temperature and that range from 0.04 to 0.01. The larger increases, however, are concentrated at the lower latitudes that have negative $d \ln\tau / dT$ values of about -0.1 (Fig. 7). This effect then is as large as expected from the estimates of ISCCP's cloud cover overestimation, and, even though it increases the negative part of the $d \ln\tau / dT$ curve, it does not change the transition of this parameter to negative values.

These smaller-scale cloud variations can also be considered as variations of cloud optical thickness, including a value of zero. From a radiative standpoint, the distinction is not critical, and our general result, that the reflectivity of low-level clouds decreases with temperature, is directly demonstrated by the data. The importance of this behavior to potential cloud radiative feedbacks cannot be ignored. The difference, however, between cloud cover and optical thickness variations is more important to our interpretation of the changes than it is to the determination of the radiative consequences. It may be that, when cloud cover begins to break up on scales < 10 km, cloud optical thickness also decreases; either change amounts to less water in the area covered by the satellite pixels. Thus, we adopt, but cannot demonstrate, the interpretation that, for the most part, the transition of $d \ln\tau / dT$ from positive to negative values with increasing temperature reflects a change in the operation of additional, nonadiabatic cloud processes that influence cloud water content more at warmer temperatures than at colder temperatures. The fact that the transition occurs at about the same temperature, whether one goes from colder to warmer latitudes and seasons (Figs. 4 and 8) or from colder to warmer clouds in the same latitude and month, supports the contention that the change is associated with conditions *in* the clouds. We propose two plausible processes that can explain the changed behavior at higher temperatures; however, given the uncertainties discussed before, we cannot establish the explanation without analysis of datasets containing coordinated observations of more cloud and atmospheric properties.

One cloud process that can reduce liquid water contents is an increase in the efficiency of the formation of precipitation. Cloud water content is determined by a balance between water condensation and droplet removal processes, particularly precipitation (cf. Rossow 1978). For example, Albrecht (1989) uses a cloud microphysical model to show that an increase in precipitation efficiency results in a decrease in cloud water content for marine stratus clouds. If condensation produces increasing amounts of cloud water at higher temperatures, proportional to the adiabatic water content, then precipitation may also change effectiveness with temperature. In fact, although the adiabatic water content continues to grow as temperature increases, the rate of growth slows considerably at the higher temperatures (Betts and Harshvardhan 1987), whereas the production of precipitation by droplet collisions increases rapidly as the number density and the size of the droplets (i.e., the water content) increases (Rossow 1978). The abruptness of the transition to negative $d \ln\tau / dT$ values for continental clouds near the freezing temperature is suggestive of a transition from a process that depletes cloud water less efficiently at colder temperatures in ice phase clouds, to one that depletes cloud water more effectively at higher temperatures in liquid phase clouds. Moreover, the transition temperature seems higher for continental than maritime conditions suggesting a difference in the effectiveness of this process between clouds over land and ocean.

Over land, a much larger number density of cloud condensation nuclei (CCN) inhibits precipitation by causing the formation of more numerous, but smaller, cloud droplets than in clouds over oceans. The smaller droplet size requires larger cloud water contents to reach the critical size for precipitation formation (Rossow 1978) and may explain the different transition temperature of $d \ln\tau / dT$ for continental clouds. (Since we consider only low-level clouds here, the Bergeron process may not be as important to precipitation; however, the transition from a "warm rain" to a mixed-phase rain regime may also change $d \ln\tau / dT$.) At much colder temperatures, where much less efficient snow formation occurs, the cloud water amount appears to follow the variation of the adiabatic water content. Over oceans, the much lower CCN number densities allow for the onset of precipitation at much lower water contents. Thus, if precipitation formation increases in efficiency relative to condensation at warmer temperatures, this would lead to negative values of $d \ln\tau / dT$. The transition temperature would be determined by a change from snow to rain.

Another process that can reduce the liquid water content (but also the vertical extent and horizontal coverage) of the clouds is cloud-top entrainment. In marine stratocumulus clouds, solar heating of the cloud base level during the daytime decouples the cloud from the subcloud layer (Nicholls 1984), separating it from its moisture source. The effect of this decoupling is enhanced by the presence of evaporating drizzle in the subcloud layer (Albrecht 1989). When this decoupling occurs, cloud-top entrainment tends to reduce the vertical extent of the cloud (Betts 1989), but it would also reduce the cloud water content (Paluch and Lenschow 1991). Subtropical, late summer, maritime clouds show positive $d \ln\tau / dT$ values that are higher than for the same clouds in other seasons and for all other maritime clouds (Fig. 8b). The late summer period is the time when sea surface temperatures reach their peak, and therefore, the time that the boundary-layer convection is forced most strongly. Where large-scale subsidence occurs, low-level convective instability would favor the formation of shallow cumulus rather than stratocumulus. Betts and Ridgeway (1989) propose that the vertical extent of such shallow cumulus layers will increase with increasing SST and atmospheric potential temperature. A transition, then, from a stratocumulus-dominated regime in which daytime solar heating decouples the cloud layer from the boundary layer to a shallow cumulus–dominated regime in which convection is more directly driven by surface temperature could explain the switch from negative $d \ln\tau / dT$ values in the former regime to positive $d \ln\tau / dT$ values in the latter (Fig. 8b).

The latitudinal and seasonal distributions of low cloud optical thickness (Fig. 3) show that the low clouds in the colder regimes are generally thicker than in warmer regimes. Moreover, examination of the optical thickness–temperature relation (Figs. 4 and 8) shows that cloud optical thickness decreases with temperature in most low clouds, with the exception of cold continental and late-summer subtropical maritime clouds. The presence of strong correlations between cloud optical thickness and temperature with opposite signs and varying magnitudes, including significant regions of little correlation in midlatitudes, makes it evident that the inference of "global" relations and their feedbacks on climate from limited regional datasets can lead to erroneous conclusions. Moreover, it is difficult to prescribe a single "global" relation for use in climate models. The results of our analysis suggest that, in the event of a global atmospheric warming or poleward migration of today's climate zones, there would be a decrease in global mean low-cloud optical thickness, suggesting a positive feedback on climate. The variations of regional changes, however, make it difficult to determine whether this average decrease in cloud optical thickness would actually cause a net increase in solar heating without more detailed calculations.

In summary, the results of this study reveal a relatively consistent pattern of cloud optical thickness variation with temperature for low-level clouds: optical thicknesses increase with increasing temperature for clouds colder than about $-10°C$, but they decrease with increasing temperature for clouds warmer than about $-2°C$. The average value of $d \ln\tau / dT$ at the colder temperatures is about 0.04, consistent with the temperature variation of the adiabatic water content. At warmer temperatures, $d \ln\tau / dT$ is about -0.05 ± 0.02. The values of $d \ln\tau / dT$ found in this study are subject to the limitations and uncertainties associated with the ISCCP dataset. The overall behavior of this parameter, however, and in particular the change of sign at the warmer temperatures was carefully tested and was found to be beyond the limits of these uncertainties. We propose that this change in cloud behavior is caused, for the most part, by an increase of precipitation efficiency relative to condensation at higher temperatures, which would explain the nearly "universal" similarity of the $d \ln\tau / dT$ values.

There are also, however, significant regional deviations from this behavior that suggest, in particular, that for some cloud types the effects of changes in boundary-layer dynamics on cloud vertical extent can be the predominant influence on cloud optical thickness variations. This analysis has not fully established these explanations because we could not eliminate other possible effects on cloud optical thickness. If we can establish the roles of boundary-layer dynamics and precipitation processes in the changes of cloud optical thickness measured by satellites, then the ISCCP dataset could be used to constrain the representation of these processes in atmospheric models. Further analysis of a dataset that combines global radiation, cloud property, surface, and atmospheric dynamical information is required to resolve the processes that influence cloud optical property variations and their feedbacks on climate change.

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