Comparison of ISCCP and Other Cloud Amounts

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ABSTRACT

A new 8-year global cloud climatology has been produced by the International Satellite Cloud Climatology Project (ISCCP) that provides information every 3 h at 280-km spatial resolution covering the period from July 1983 through June 1991. If cloud detection errors and differences in area sampling are neglected, individual ISCCP cloud amounts agree with individual surface observations to within 15% rms with biases of only a few percent. When measurements of small-scale, broken clouds are isolated in the comparison, the rms differences between satellite and surface cloud amounts are about 25%, similar to the rms difference between ISCCP and Landsat determinations of cloud amount. For broken clouds, the average ISCCP cloud amounts are about 5% smaller than estimated by surface observers (difference between earth cover and sky cover), but about 5% larger than estimated from very high spatial resolution satellite observations (overestimate due to low spatial resolution offset by underestimate due to finite radiance thresholds). Detection errors, caused by errors in the ISCCP clear-sky radiances or incorrect radiance threshold magnitudes, are the dominant source of error in monthly average cloud amounts. The ISCCP cloud amounts appear to be too low over land by about 10%, somewhat less in summer and somewhat more in winter, and about right (maybe slightly low) over oceans. In polar regions, ISCCP cloud amounts are probably too low by about 15%–25% in summer and 5%–10% in winter. Comparison of the ISCCP climatology to three other cloud climatologies shows excellent agreement in the geographic distribution and seasonal variation of cloud amounts; there is little agreement about day/night contrasts in cloud amount. Notable results from ISCCP are that the global annual mean cloud amount is about 63%, being about 23% higher over oceans than over land, that it varies by <1% rms from month to month, and that it has varied by about 4% on a time scale ≈2–4 years. The magnitude of interannual variations of local (280-km scale) monthly mean cloud amounts is about 7%–9%. Longitudinal contrasts in cloud amount are just as large as latitudinal contrasts. The largest seasonal variation of cloud amount occurs in the tropics, being larger in summer than in winter; the seasonal variation in middle latitudes has the opposite phase. Polar regions may have little seasonal variability in cloud amount. The ISCCP results show slightly more nighttime than daytime cloud amount over oceans and more daytime than nighttime cloud amount over land.

1. Introduction

The International Satellite Cloud Climatology Project (ISCCP) was established in 1982 as the first project of the World Climate Research Programme (WCRP) to collect and analyze a globally uniform satellite radiance dataset to produce a new cloud climatology (Schiffer and Rossow 1983). The basic dataset that is analyzed is a sampled and calibrated version of visible (VIS ≈ 0.65 ± 0.15-μm wavelength) and "window" infrared (IR ≈ 11 ± 1 μm) imagery from an international suite of weather satellites, both geostationary and polar orbiting, called the stage B3 dataset (Schiffer and Rossow 1985). The first step in the analysis, called cloud detection (Rossow 1989), separates the satellite observations (image pixels) into clear and cloudy categories. Key objectives are to understand the meaning of "clear" and "cloudy" and the significance of variations of the number of locations that are cloudy, commonly referred to as variations of cloud amount.

In two companion papers (Rossow and Garder 1993a,b), the design of the cloud detection method is fully described, supporting analyses of radiance statistics are presented, and the methodology is validated by verification of the inferred clear radiances. This paper assesses the accuracy of the ISCCP cloud amounts by quantitative comparisons to other, higher spatial

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TABLE 1. Summary of error estimates for surface temperatures, surface reflectances, and cloud amounts determined from comparisons of ISCCP and other measurements of these quantities (Rossow and Garder 1993b). Detection thresholds for IR and VIS radiances are also shown.

	Estimated error	IR radiance threshold	VIS radiance threshold (reflectance)
Surface temperature			
open water	<2 K	2.5 K (4.0 K near coasts)	
land	4 K	6.0 K (8.0 K in high, rough topography)	
sea ice	4 K	4.0 K	
Surface reflectance			
open water	3% (except in glint)		3.0% (≥3%)
snow-free land	3%–5%		6.0% (≥6%)
snow cover	10%		12.0% (>12%)
sea ice	10%		12.0% (>20%)
Cloud amount	<10%		

resolution measurements and to three other cloud climatologies.

The ISCCP cloud detection procedure is applied to each month of satellite data at eight times of day and consists of five steps (Rossow and Garder 1993a):

1) space contrast test (applied to individual IR images),
2) time contrast test (three consecutive IR images at constant diurnal phase),
3) cumulation of space/time statistics (both IR and VIS images),
4) construction of clear-sky composites for both IR and VIS (once every 5 days at each diurnal phase and location),
5) radiance threshold (both IR and VIS images).

The first test classifies as cloudy all pixels that are much colder (low IR radiance) than the warmest value in small spatial domains. It is a spatial contrast test because the warmest pixel is not classified as either clear or cloudy. The second test classifies as cloudy all pixels that have sharply lower IR radiances at the same location as compared with values one day earlier or later and classifies as clear all pixels that show little variation of IR radiance over one-day intervals. To avoid confusion with diurnal variations of surface temperatures, this test is done separately for each time of day. The results of these two tests are combined to label image pixels as clear only when they exhibit low variability in both space and time. The third step collects statistics on the variations of the IR and VIS radiances over larger spatial and temporal domains. These statistics are used in the fourth step, along with the results of the first two tests (number of clear pixels and average clear radiance), to estimate values of clear IR and VIS radiances for each location and diurnal phase, once every 5 days. In the final step, the original IR and VIS radiances in each pixel at each time are compared with the inferred clear values. If the observed radiances differ from the clear-sky values (lower IR or higher VIS) by more than the estimated uncertainty of the clear-sky values, they are classified as cloudy. A subset of these pixels, with radiance values close to the values dividing clear from cloudy, are referred to as marginally cloudy. All other pixels are classified as clear.

The statistics of IR and VIS radiance variations have been surveyed to support the assumptions used in the cloud detection method (Rossow and Garder 1993a). A series of sensitivity studies were conducted to test the effects of changing the parameters of the contrast tests, the assumed widths of the radiance distributions, and the magnitudes of the radiance thresholds applied to detect clouds. These results show that the regional variability of the test parameters improves the performance of the cloud detection method in a wide variety of circumstances. The sensitivity test results suggest an uncertainty in detected cloud amounts that is about 10% random, with regional biases of no more than 5% (except for the polar regions).

ISCCP cloud *detection* can be verified by confirming that the clear radiance values are not significantly biased and that random errors are about the same magnitude as assumed in the detection thresholds. Table 1 summarizes the radiance thresholds used and estimates of errors in the surface properties obtained from ISCCP based on comparisons with other measurements (Rossow and Garder 1993b).

We use a direct comparison of sea surface temperature (SST) to establish an upper limit on the uncertainty of the clear IR radiances over water. The resulting estimated error in clear IR radiances is 2 K, smaller than the assumed threshold value of 2.5 K. The only significant systematic errors (cloud contamination) appear in small portions of the marine stratus regimes and in the midlatitude storm tracks, where the ISCCP SSTs may be too low by 2–4 K and cloud amounts too low by 5%–15% at night. The only available dataset for comparison with satellite-measured land surface temperatures is near-surface air temperatures, rather than the actual temperature of the solid surface. Consequently, much of the difference between the ISCCP and air temperature measurements is found to be a function of time of day, season, and latitude, consistent with the effects of sunlight on the difference between air and solid surface temperatures. After removing the monthly mean diurnal cycle from both datasets to isolate the synoptic (day to day) variations, the rms differences are about 4 K, somewhat larger in winter than in summer. Since the estimated error in clear IR radiances is significantly smaller than the assumed IR radiance threshold value of 6 K, ISCCP cloud amounts are underestimated by 3%–6% over land. There is evidence for more cloud contamination of the clear IR radiances over higher-latitude land areas, especially in winter, with a consequent negative bias of cloud amount of 6%–10%.

The surface reflectance of open water is generally very low, but it varies strongly with illumination and viewing geometry. The estimated uncertainty in the inferred clear VIS radiances appears to be consistent with the assumed threshold value of 3%; but since the VIS threshold is a radiance difference, rather than a reflectance difference, the ISCCP algorithm is actually too conservative at larger solar zenith angles. The VIS radiance test is not used for near-glint geometries because errors are >20% rms. There are no available global surveys of land VIS reflectances to compare with the ISCCP values; however, direct comparisons of ISCCP values from different years and seasons show differences that are 3%–5%, rms, slightly smaller than the assumed VIS radiance threshold value of 6%.

The temperatures and reflectances for surfaces covered by snow and sea ice are examined separately because proper separation of clear and cloudy situations is expected to be much more difficult. Climatologies of sea ice surface temperatures indicate good agreement with ISCCP values except possibly in winter, where the ISCCP values might be biased high by ~2 K; ISCCP surface temperatures on the high ice sheets (Greenland and Antarctica) are generally consistent with published climatologies. Uncertainties in temperatures for ice- and snow-covered surfaces appear consistent with the assumed IR radiance threshold value of 4 K. ISCCP sea ice reflectances also agree within 10% of published estimates for the Arctic. However, since the ISCCP VIS threshold was set at 12% radiance difference, which is equivalent to a reflectance difference >20% for typical solar zenith angle values, the VIS threshold test was effectively eliminated over snow and ice surfaces. As a consequence about 3%–5% of low-level cloud, especially over sea ice, was missed.

The purpose of this paper is to compare ISCCP cloud amounts with other measurements of similar quantities to assess sources of error that arise when converting a detection result (spatial frequency of occurrence) to a fractional coverage of area. Comparison to several different types of measurements also provides an overall estimate of the uncertainties of the ISCCP cloud amounts. We focus most of our attention on surface weather observer estimates of sky cover because they differ most from the satellite measurements. Surface observers view clouds from below rather than from above, which affects their relative sensitivity to the presence of clouds: ground-based observers are probably better able to detect very low-level, highly broken clouds than satellites, but they are probably less able to detect high, thin cirrus than satellites. Since ground observers use a "visible radiometer" (their eyes), their ability to detect cloudiness at night is less reliable (Hahn et al. 1993). Surface observations have higher spatial resolution than most satellites, varying between about 1 m overhead to 10 m at 30-km range (Allen 1973), and cover an effective area of about 3000 km^2 [radius about 30 km, Barrett and Grant (1979), Henderson-Sellers et al. (1987)]. However, since sky cover is reported in octas (12.5%), the effective spatial resolution is much lower.

Section 2 describes the ISCCP cloud datasets and the other datasets used in this study. Section 3 presents comparisons between ISCCP and individual surface observations and discusses errors in interpreting ISCCP cloud amounts as fractional areal coverage. Section 4 compares the ISCCP cloud amount climatology with the surface observation climatology and two other satellite climatologies. Section 5 summarizes estimates of uncertainties in ISCCP cloud amounts and notable features of earth's cloud cover described by the ISCCP climatology.

2. Data

a. ISCCP cloud amount

The IR and VIS radiances [stage B3 data, Schiffer and Rossow (1985)] analyzed by ISCCP are samples of the original weather satellite images at 3-h and 30-km intervals (polar orbiter data are not sampled in time). The individual samples (pixels) represent the original IR fields of view (FOV) with sizes ranging from 4 to 7 km (areas of about 10 to 150 km^2). The presence or absence of cloud is decided for every individual sample: cloud amount for a single pixel is either 0% or 100%. During daytime[1] two cloud detection results are reported, one based on threshold tests of both VIS and IR radiances (called the VIS/IR cloud amount) and one based solely on the IR threshold test (called IR cloud amount) that is equivalent to the result reported during nighttime.

Statistics from the analysis of individual pixels are reported in two datasets, stage C1 and C2, in an equal-area map grid equivalent to 2.5° at the equator (Rossow and Schiffer 1991; Rossow et al. 1991). Each grid cell (area of 77 000 km^2) contains from 20 to 120 pixels at one time; thus, the ISCCP spatial sampling is equivalent to sampling 5% to 15% of the area at each time. Cloud amounts in grid cells are determined for the

[1] Daytime is defined by solar zenith angles <78.5°.

TABLE 2. Summary of differences in cloud amount between instantaneous ISCCP determinations of cloud amount over 280 × 280 km² areas and matched, individual surface observations. All values are in percent, except the number of cases, and negative values indicate smaller ISCCP cloud amounts. Differences between matched monthly mean cloud amounts are given in parentheses. See text for explanation of detection and area sampling errors.

Quantity	January 1984	July 1985	October 1986	Aggregated
Number of cases	243 251	187 546	246 075	676 872
Daytime				
Bias	−13.0 (−14.5)	−1.7 (−2.4)	−2.9 (−5.7)	−7.7 (−10.0)
Std dev	38.1 (20.6)	27.5 (15.7)	31.7 (19.1)	35.2 (18.5)
Nighttime				
Bias	−15.6 (−15.9)	−8.2 (−10.6)	−8.9 (−12.3)	−12.3 (−14.9)
Std dev	42.0 (20.8)	33.4 (17.9)	37.3 (19.1)	39.9 (19.9)
All day				
Bias	−14.9 (−15.1)	−6.3 (−7.9)	−7.2 (−10.4)	−11.0 (−14.0)
Std dev	41.0 (20.6)	31.9 (17.8)	35.9 (18.8)	38.7 (20.2)
Broken cloud				
Bias	−4.6 (−5.2)	−2.8 (−3.3)	−3.5 (−3.6)	−3.5 (−4.2)
Std dev	23.0 (10.8)	22.5 (9.3)	22.8 (9.5)	22.8 (8.5)
Detection and area sampling errors removed				
Bias	−1.1 (−1.7)	−0.3 (−0.9)	−0.3 (−1.1)	−0.7 (−1.3)
Std dev	14.3 (5.4)	14.8 (5.3)	14.4 (5.1)	14.2 (5.1)

stage C1/C2 datasets by the ratio of the number of cloudy pixels to the total number of pixels. The stage C1 data give global results at 3-h intervals, while stage C2 data give monthly averages at eight times of day (called 3-h monthly mean) and over all times of day (called monthly mean).

For comparisons to individual surface observations, we use stage C1 data from January 1984, July 1985, and October 1986. Daytime comparisons use VIS/IR cloud amounts while nighttime comparisons use IR cloud amounts, which are expected to miss more low-level clouds. For comparisons to other cloud climatologies, we use stage C2 data for 1984 to 1988 that have been remapped to an equal-area map grid equivalent to 5° lat by 10° long at the equator.[2] The nighttime cloud amounts in C2 data have been corrected by adding the difference between the VIS/IR and IR cloud amounts interpolated from daytime measurements (original values shown in Table 3 in parentheses).

b. *Surface observations of cloud sky cover*

Routine surface weather station reports collected by the NOAA National Meteorological Center (NMC) for weather forecasts include an estimate of the fraction of the sky covered by clouds, as well as information about cloud types and amounts. Reporting intervals vary from hourly to twice-daily (four to eight times daily being most common) for some 3000 to 4000 stations. We use the complete collection of individual reports from three months (January 1984, July 1985, and October 1986) for comparison (we will refer to this dataset of individual surface observations as indSOBS). Individual surface observations are matched to ISCCP stage C1 data by location, date, and time. Whenever more than one surface station report occurs within an ISCCP map grid cell, we select one value for comparison. We obtain over 670 000 matches over these three months (see Table 2). The geographic distribution of these stations covers predominantly Northern Hemisphere land areas, though some islands are included. The reported total cloud cover is coded in octas (1 octa = 12.5%) from 0 to 8. A special "sky obscured" code is converted to complete cloud cover if the present weather code indicates fog, rain, snow, or thunderstorm, and discarded otherwise.

Sky cover is not the same quantity as the "earth cover" seen from a satellite viewing the nadir point (Warren et al. 1986, 1988; Sèze et al. 1986; Henderson-Sellers et al. 1987; Minnis 1989); however, since satellite cloud cover is estimated from a variety of viewing zenith angles, the average difference between these two quantities does not seem to be significant in practice when compared to other sources of uncertainty (Henderson-Sellers and McGuffie 1990). The effective area sampled by a ground observer can vary with location of the site, cloud altitude, and cloud amount and is estimated to be about 3000–8000 km², equivalent to a radius of about 30–50 km (Barrett and Grant 1979; Henderson-Sellers et al. 1987). This area is covered by 100–2000 satellite image pixels with sizes between 4 and 7 km; however, this area is sampled by about four pixels in the sampled dataset used by ISCCP.

A cloud climatology has been produced from these surface observations covering the period 1971–1981 over land (Warren et al. 1986) and 1952–1981 over oceans (Warren et al. 1988). We refer to this dataset

[2] For comparison, all gridded datasets are remapped to the same equal-area grid, which has a resolution determined by the lowest-resolution dataset (METEOR).

as SOBS. We use monthly mean total cloud cover maps that are compiled separately for land and ocean. For the day/night contrast comparisons we use seasonal means compiled separately at 8 synoptic hours for land and ocean. We use only data from 1971 to 1981 where both land and ocean are available. All data are remapped to an equal-area map grid equivalent to 5° lat by 10° long at the equator for comparison with the other cloud climatologies.

c. Nimbus-7 cloud climatology

Radiance measurements made twice daily (near noon and midnight) at an infrared (11.5 μm) wavelength and near noon at an UV (0.37 μm) wavelength from the *Nimbus-7* satellite have been analyzed to obtain a global cloud-cover climatology covering the period April 1979 to March 1985 (Stowe et al. 1988, 1989). We use the complete years 1980–1984 and refer to this dataset as *Nimbus-7.* Monthly mean total cloud cover fractions are compiled in an equal-area map grid with a resolution of about 500 km (equivalent to about 4.5° at the equator). Cloud amounts are determined in three steps: 1) counting the fraction of observations where the infrared radiance is lower by some threshold amount than a clear-sky value at each location, date, and time of day, where the clear IR value is determined from the U.S. Air Force analysis of surface air temperature measurements from weather stations, 2) calculating the ratio of observed UV reflectance to a model of reflectance as a linear function of cloud amount, and 3) combining the IR and UV cloud amounts (Stowe et al. 1988). We refer to the first set as the IR results and the third set as the IR/UV results. All data are remapped to an equal-area map grid equivalent to 5° lat by 10° long at the equator for comparison with the other cloud climatologies.

d. METEOR cloud climatology

A global, long-term climatology of monthly mean total cloud amount covering the years 1966 to 1988 has been produced from the manual analysis of imaging data from several satellites by different methods and can be obtained from the Hydrometeorological Center, Moscow, the National Meteorological Center (NMC) Climate Analysis Center, Washington D.C., or from the NASA Climate Data Center, Greenbelt, Maryland [see Mokhov and Schlesinger (1993) for details]. In order to avoid the effects of changed analysis methods and sparse sampling, we use only the results for the period from 1976 to 1988. These are obtained by the same interpretation of infrared (8–12 μm) images (and some visible images) from the METEOR series of weather satellites and are mapped at 5° × 10° resolution. For comparison to the other cloud climatologies all data are remapped to an equal-area grid equivalent to 5° lat by 10° long at the equator and gaps in the data are filled using linear interpolation over time.

3. Comparisons to higher-resolution datasets

a. Comparison to individual surface observations

All available ind-SOBS data for three months (January 1984, July 1985, October 1986) were matched to individual ISCCP results for the same locations, dates, and times of day (over 670 000 cases). Figure 1 shows the distribution of differences between the ISCCP and ind-SOBS cloud amounts aggregated over all three months; Table 2 summarizes the results for each month as well. On average, the ISCCP results are lower than the ind-SOBS results by about 11% with a standard deviation of almost 40%. The negative bias of ISCCP relative to ind-SOBS is seasonally dependent, being more negative in winter by about 8% than in summer. Nighttime ISCCP results are biased by about 3%–6% more than daytime results, especially in summer/autumn, and exhibit larger standard deviations by about 6%. Both ind-SOBS and ISCCP are expected to underestimate cloud amount at night (see discussion in section 4c).

The shape of the difference distribution in Fig. 1 presents several puzzles. 1) There is an unusually large population near zero difference in cloud amount. 2) The very large standard deviation is caused by a small number of cases with very large differences (±50%–100%) in cloud amount. 3) The bias is caused solely by the asymmetry in the number of negative and pos-

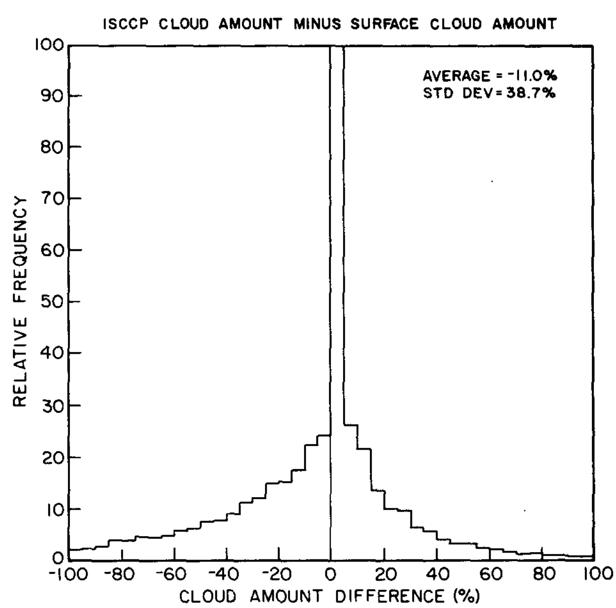


FIG. 1. Frequency distribution of differences between individual land surface weather station cloud amounts (three-hourly in octas converted to percent) and retrieved ISCCP cloud amounts (three-hourly, averaged over an equal area grid equivalent to 2.5° resolution at the equator). If more than one surface station is present in the ISCCP grid, one value is selected randomly. Results are for all available surface station reports for January 1984, July 1985, and October 1986 (over 670 000 cases).

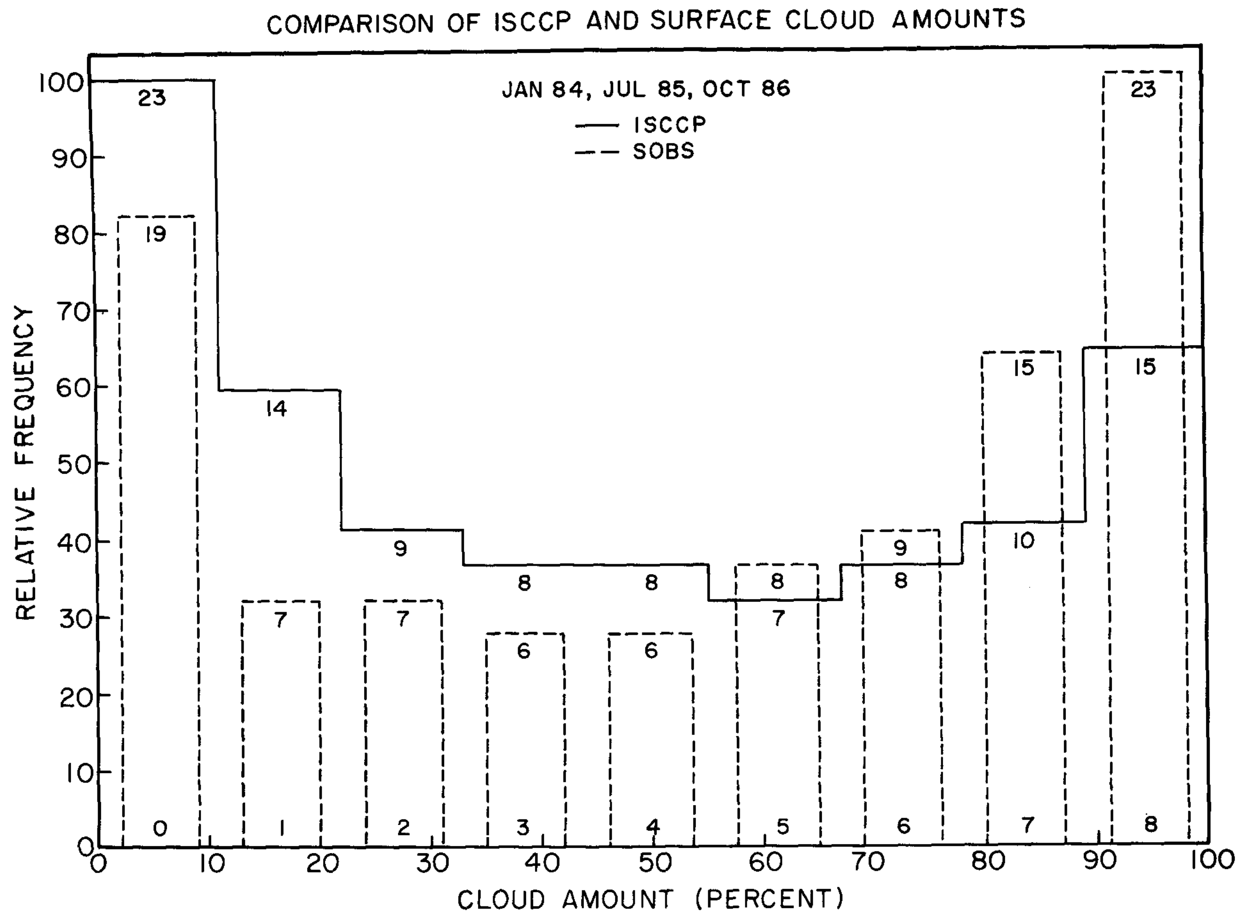


FIG. 2. Frequency of occurrence of cloud amount values in each octa (12.5%) interval from individual surface observations (ind-SOBS, dashed) and the ISCCP analysis (solid) for January 1984, July 1985, and October 1986. Fraction of total population (in percent) in each cloud amount interval is indicated by numbers near the top of the histogram bars.

itive differences. The non-Gaussian shape of the difference distribution suggests a more complicated explanation of the differences between the two datasets and indicates that the value of the standard deviation may not represent the actual uncertainties of either dataset. These puzzling features of Fig. 1 arise from a combination of five different situations that can be explained with two other displays of the cloud amounts and their differences.

Figure 2 shows the frequency of occurrence of each cloud amount value (in octas) for ISCCP and ind-SOBS. About 60% of the cases are reported as either clear or overcast[3] by both datasets, with ISCCP reporting about 10% more completely clear cases and about 15% fewer completely overcast cases than ind-SOBS. Since the two observations usually agree whenever the cloud amount is 0 or 100%, which occurs more than half the time, a large spike at zero difference is produced in the difference distribution in Fig. 1. This situation is displayed more clearly when the cloud amount differences are plotted against the ISCCP cloud amount (or the ind-SOBS cloud amount), as in Fig. 3a. Figure 3b gives the relative population of cases in several subareas in Fig. 3a to which we will refer in the subsequent discussion.[4] The zero-difference population along the zero axis (in Fig. 3b: 21.4% + 15.4% + 18.1%) splits into two peaks, one each at 0% (21.4%) and 100% (18.1%) cloud amount, with some values (15.4%) at intermediate cloud amounts. The shape of the distribution along the zero difference axis in Fig. 3a, if projected onto the cloud amount axis, is the same as shown

[3] Surface observers tend to overreport cloud amounts of 1 and 7 octas because these values are reported whenever any cloudy or cloud-free sky is present, no matter how little (Warren et al. 1986). Therefore, we combine ind-SOBS cloud amounts of 0,1 octas to represent clear and 7,8 octas to represent overcast, respectively.

[4] We use precise values from Fig. 3b in this discussion so that the reader can determine which portions of the figure contribute to each case; however, there is no claim that the accuracy of these relative proportions is any better than ± a few percent.

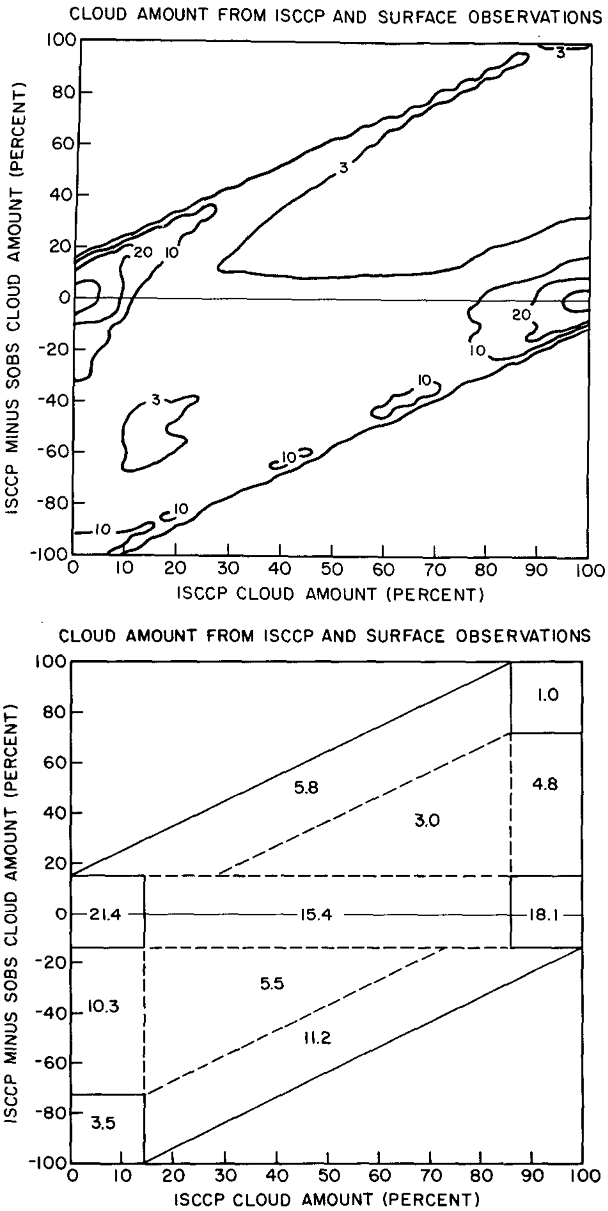


FIG. 3. (a) Differences shown in Fig. 1 plotted against the ISCCP cloud amount. Contours indicate frequencies in percent relative to the maximum value; the innermost (unlabeled) contours near (zero, zero) and (zero, 100%) indicate a relative frequency of 50%. (b) Percentage of the total population within each indicated subregion of the diagram in part (a).

in Fig. 2. Thus, the large population of zero differences in cloud amount in Fig. 1 is a consequence of the large frequency of either completely clear or completely overcast cases.

Figure 3 also shows that the extreme "wings" in the distribution in Fig. 1 are highly correlated with the total cloud amount, forming two slanting branches, one that goes from zero difference and zero cloud amount toward +100% difference and 100% cloud amount (in Fig. 3b: 5.8%) and one that goes from zero difference and 100% cloud amount toward −100% difference and zero cloud amount (Fig. 3b: 11.2%). These two branches also arise from the frequent occurrence of completely clear or completely overcast conditions but are produced by the comparison of two "perfect" cloud datasets, which observe very different sized areas (ind-SOBS represent areas that are about 5%–10% of the area covered by ISCCP). If the surface observations represented "perfect point measurements" of cloud amount, reporting only 0% and 100%, and they are compared to "perfect area measurements," then the pattern shown in Fig. 3a would necessarily result. Whenever the area is covered uniformly (cloud amount = 0% or 100%), the point measurement would always have the same value as the area measurement; this would cause the two peaks at zero difference and 0% and 100% cloud amount as already explained. Whenever the area is partially covered by a solid cloud layer, then the point measurements would always differ by the maximum possible amount, since the point values can only be 0% or 100%. For a large number of comparisons of areas to points located randomly within them (as done here), the number of cases with positive and negative differences would vary with the fraction of the area covered by cloud. For example, if 20% of the area is covered by cloud, the chances of a randomly located point measurement being either 0% or 100% would be 80% and 20%, respectively. If we remove from the lower branch in Fig. 3b a small population (about 4%–5%) that is similar in distribution to the differences between the two cloud amount distributions at low values shown in Fig. 2, representing a tendency for the ISCCP analysis to miss some clouds completely, then the ratio of the number of cases occurring in the two branches in Fig. 3a varies as a function of cloud amount just as predicted by this argument. Thus, the general shape of Fig. 1 (spike at zero difference and extreme "wings") is produced by comparing two "perfect" cloud measurements representing very different area sizes, where one measurement represents an area much smaller than the typical area covered by a cloud.

This supposition is confirmed by two additional results. First, we compared matched pairs of ind-SOBS observations located within individual ISCCP map grid cells. The resulting cloud amount difference distribution (Fig. 4) has the same shape and standard deviation as Fig. 1, but without the bias. Thus, cloud amounts reported at nearby surface sites can disagree by the maximum possible amount as expected from the discussion above. Second, we repeated the comparison of ind-SOBS to ISCCP for grid cells containing at least five surface reports; but instead of selecting one ind-SOBS value for comparison, we averaged three or five values. The resulting standard deviations of the differences decrease by about 7% and 10%, respectively. Thus, the large differences in individual cloud amounts in the wings of the distribution do not represent actual

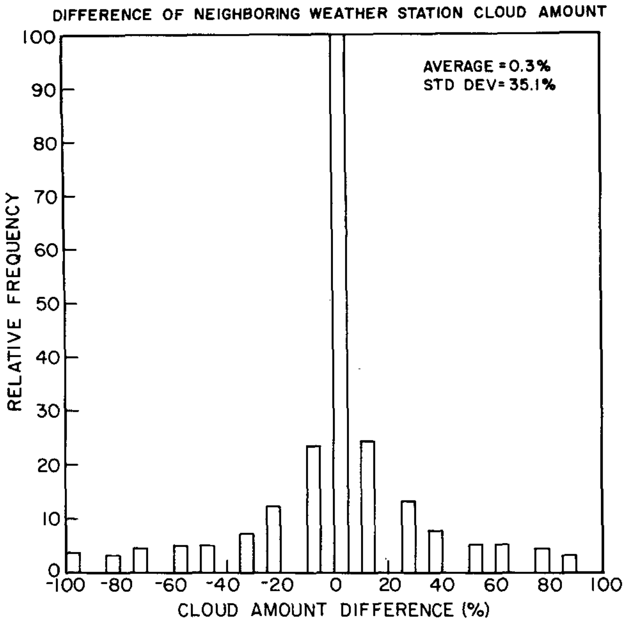


FIG. 4. Same as Fig. 1 but for differences of cloud amounts reported by pairs of surface observers within ISCCP map grid cells. Results are for January 1984, July 1985, and October 1986.

errors in measurement; rather they represent uncertainties in estimating areas associated with collecting too small a sample of the area.

Surface observers report fractional cloud amounts about 40% of the time (Fig. 2), some of which is associated with smaller-scale, broken cloud fields rather than partial coverage by solid cloud layers. In Fig. 3b, the area marked by dashed borders (3.0% + 15.4% + 5.5%) represents the cases where both ind-SOBS and ISCCP report partial cloud cover; the relative frequency of this situation is similar to the frequencies of occurrence of cumulus cloud types (cumulus, altocumulus, cirrocumulus) reported in the SOBS cloud climatology (Warren et al. 1986). If in the comparison of ind-SOBS and ISCCP we isolate the part of the distribution with partial cloud cover, then we obtain a more proper estimate of the uncertainty in measuring cloud cover fraction. Table 2 shows that if we remove the cases related to large-scale clear or cloud layers (in Fig. 3b: 21.4% + 5.5% + 18.1% + 11.2%) and the cases associated with missed clouds or cloud holes (10.3% + 3.5% + 1.0% + 4.8%), the standard deviation of the cloud amount differences is reduced to about two octas with a negative bias of a few percent. The small bias is consistent with estimates of the difference between "sky cover" and "earth cover," which should be largest for small-scale broken clouds (cf. Warren et al. 1986). Thus, the upper limit on the uncertainty in ISCCP determinations of cloud cover fraction in cases where the clouds are broken on smaller scales is about 25%. Since the estimated uncertainty of the surface observations is at least one octa (Sèze et al. 1986; Henderson-Sellers et al. 1987), the ISCCP uncertainty may be <20%.

In Fig. 3 there is a group of cases at 0% cloud amount and a range of differences from 0% to −100% (in Fig. 3b: 10.3% + 3.5%) that represent cases where the ISCCP analysis apparently missed the clouds completely and a group at 100% cloud amount and a range of differences from 0% to +100% (in Fig. 3b: 1.0% + 4.8%) where the ISCCP analysis may have falsely detected clouds. However, there are two additional effects that contribute to these cases. 1) Surface observers report 1 octa of cloud cover whenever any cloud is present, no matter how little, and they report 7 octas of cloud cover if any clear sky is present, no matter how little (Warren et al. 1986). 2) The typical number of satellite image pixels used to determine cloud amount in the ISCCP dataset is about 50 and samples only about 10% of the map grid cell area. This means that when the actual cloud amount falls below about 10% or is above about 90%, the probability that such a limited spatial sample misses the small amount of cloudy or clear area sharply increases. Both of these effects can cause the distribution of cases where ISCCP reports 0% cloud amount, but the ind-SOBS reports a small amount of cloud cover (typically 1–2 octas), and the cases where ISCCP reports 100% cloud amount, but ind-SOBS reports slightly less cloud cover (typically about 1 octa less).

The remaining points in the lower-left and upper-right corners in Fig. 3a (in Fig. 3b: 3.5% and 1.0%, respectively) can be interpreted as missed and falsely detected clouds in the ISCCP results, if the ind-SOBS results are taken to be perfect. In addition, about 10% of the cases distributed near the 3.5% area in Fig. 3b also seem to represent missed clouds [cf. discussion in Rossow and Garder (1993b)]. These cases, together with the larger number of negative than positive differences in Figs. 1 and 2, point to an underestimate of cloud amount over land by ISCCP. This conclusion is consistent with the effects of a small cold bias of surface temperatures retrieved from the clear IR radiances, of an IR threshold that is too large, and of a VIS radiance threshold that is too large (Rossow and Garder 1993b). Table 2 shows the effects of removing[5] both the detection errors and the cases that arise from the difference in area sampling: the bias is almost eliminated and the standard deviation is reduced to about 15%. Thus, we conclude that almost two-thirds of the bias in the ISCCP results is caused by detection errors and one-third is associated with an underestimate of broken cloudiness. Moreover, about one-third of the total standard deviation of the differences is caused by detection errors and about one-third by the sampling of

[5] Individual cases are removed by testing where they fall in the subareas defined in Fig. 3b: the ISCCP cloud amount and the difference with the ind-SOBS cloud amount define coordinates for each case.

different areas. The remaining standard deviation amount is associated with the error in estimating fractional area cover.

The overall summary of the results presented in Figs. 1, 2, and 3, based on the interpretation given above, is that individual ISCCP and ind-SOBS measurements of cloud amount agree to within about 15% in over 60% of the cases, with differences of about 25% for the cases with small-scale broken cloudiness (about 20% of the cases). In about 15% of the cases, there are larger disagreements because of the very large difference in the areas observed by the two systems; but, since these cases are caused by partial cover by large-scale clouds, this does not indicate any large errors in the ISCCP results. In about 5% of the cases, the ISCCP results report clouds not reported by the surface observer, whereas in about 15% of the cases, the ISCCP does not report clouds reported by the surface observer. At least half of these cases may be caused by the overreporting of 1 and 7 octas by the surface observers. Adding the detection errors to the last entry in Table 2, we estimate the instantaneous ISCCP cloud amounts at 280-km scale to be biased by about −10% with an rms uncertainty of about 25% over land. Thus, the two largest sources of error in the ISCCP results are detection errors (causing most of the bias and about half of the remaining standard deviation in the differences) and errors in estimating fractional area coverage by counting pixels (causing the other half of the remaining standard deviation).

b. *Effect of subpixel cloud variations*

Determination of cloud areal coverage by counting the number of satellite image pixels that contain cloud produces errors when broken cloudiness is composed of many individual cloud elements that are smaller than the satellite field of view (cf. Coakley and Bretherton 1982). There have been many assessments of the effect of image pixel size on cloud cover determinations [see references in Rossow et al. (1985), Rossow et al. (1989), Wielicki and Parker (1992)], but almost all of these studies examine the worst cases, namely, fair weather, boundary-layer cloudiness. The most thorough study of these worst cases (Wielicki and Parker 1992) shows that, at the pixel sizes used by ISCCP, the average bias in cloud cover is $\leqslant +5\%$ for low-level cloudiness; however, there are three other conclusions from this work that are equally important.

First, there are significant variations of optical thicknesses within the smaller-scale clouds, such that the transition from cloudy to clear conditions is represented by very small differences in measured radiances ($\sim$1%–2% in VIS and 1–2 K in IR) and occurs over a finite distance. This is especially true for marine boundary-layer clouds (Wielicki and Parker 1992); transitions are somewhat sharper over land (Parker et al. 1986). Kuo et al. (1988) illustrate the same continuum of cloud reflectances for cirrus. The main implication is that the threshold selected to divide cloudy and clear portions of an image is ambiguous and somewhat arbitrary, regardless of the spatial resolution of the data. In other words, the definition of "cloudy" is not entirely clear (cf. Rossow 1989) and the magnitude of changes in cloud amount produced by changing spatial resolution depends on the threshold used to make the cloudy–clear distinction and on the type of clouds considered (Wielicki and Parker 1992). Neglect of this optical thickness effect in earlier studies of the resolution dependence of cloud amounts caused a significant overestimate of the magnitude of the effect (Wielicki and Parker 1992).

Second, the rather small average overestimate of broken cloud amounts found by Wielicki and Parker is actually caused by two offsetting effects. The actual sensitivity of the cloud amounts determined with the ISCCP thresholds to changes in spatial resolution from
$1/18 + 1$
km to 8 km is an increase of cloud amount by 10%–15% as resolution decreases (for boundary-layer cumulus), with most of the change occurring at pixel sizes >1 km. At the highest resolutions, however, the thresholds used by ISCCP underestimate total cloud amount because some very optically thin clouds are missed altogether. This effect also causes a systematic underestimate of the very thin cirrus clouds (optical thickness of the missed clouds is only a few tenths) examined by Wielicki and Parker, which exhibit little dependence on spatial resolution.

Third, the average bias error arises from much larger (20%–30%), but partly random, errors for specific cases (we discuss the reasons for this below). The result is only a small bias that depends on both the threshold magnitudes and image pixel size. Wielicki and Parker (1992) recommend thresholds over ocean of 5% for VIS and 3 K for IR for 8-km resolution. Since the resolution of ISCCP data varies from 4 to 7 km and the threshold values are 3% for VIS and 2.5 K for IR, the estimated overestimate for marine boundary-layer clouds is <5%.

For the cases where both the ISCCP and ground observers report partial cloud cover (in Fig. 3b: 3.0% + 15.4% + 5.5%), the two observations agree to within about 25% (Table 2). This magnitude of rms error is consistent with that found by Wielicki and Parker (1992), for individual 8-km pixels. One analysis of all-sky camera photographs shows a very high correlation (>0.8) of overhead cloud amount with cloud amount over the whole dome (Willand and Steeves 1991), which suggests that there is a preponderance of clouds with scales larger than about 2–3 km over the eastern United States. If broken cloudiness is generally at a scale (say 2–6 km) similar to the satellite pixel sizes, it would explain the good agreement between the satellite and ground observer measurements. Nevertheless, fair weather boundary-layer clouds do exhibit size distri-

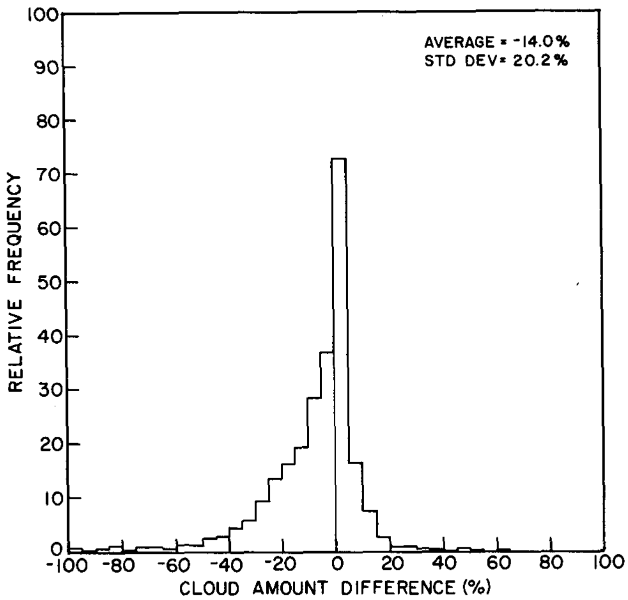


FIG. 5. Same as Fig. 1 but the ISCCP and individual surface observations are averaged over each month before differencing.

butions where the majority of the area is covered by cloud elements about 0.5–2 km across (e.g., Wielicki and Welch 1986; Parker et al. 1986; Welch et al. 1988; Cahalan and Joseph 1989; Joseph and Cahalan 1990; Sengupta et al. 1990). However, Sengupta et al. (1990) also show that these small individual clouds are clumped at scales ≥ 15 km and that in the clumps, the average spacing of the smaller clouds is of order 1 to 2 times their diameter. Thus, even if the cloud cover error in individual pixels is $\sim 50\%$, the error varies substantially from pixel to pixel because the clouds occupy varying portions of different pixels; clumping causes the fractional area actually covered in different pixels to vary; and the very broad size distributions produce a variety of cloud cover amounts with location. Moreover, since the small-scale statistics remain homogeneous over much larger scales (Sèze and Rossow 1991), the errors begin to cancel in a large enough sample of pixels. All of these properties of small-scale broken cloudiness, when combined with variations of optical thickness, explain why the *average* overestimate of cloud cover using satellite data with 4–7-km pixels is so small (Wielicki and Parker 1992), even for the worst cases.

One effect not considered by Wielicki and Parker is how sampling of the satellite image, as done by ISCCP, may alter the estimate of cloud amount. Since the total cloud cover produced by clouds with very small-scale elements is usually low (in the cases examined by Wielicki and Parker, cloud cover is <50%), the fact that the ISCCP dataset samples only about 10% of the total area implies that the likelihood of missing the cloud altogether increases as the total cloud cover decreases. This additional sampling effect could further reduce the ISCCP estimate of cloud amount for highly broken clouds.

c. Effects of averaging

The explanation of the differences between the satellite and surface observations of cloud amount, given in sections 3a and 3b above, implies contributions to the uncertainty (difference) that are systematic, such as detection errors, and some that are more random, such as estimating the fractional area coverage for broken cloudiness. Figure 5 and Table 2 illustrate the results of repeating the whole comparison of matched ISCCP and ind-SOBS observations after averaging each dataset over individual months. For the aggregated results, the bias increases slightly and the standard deviation of the differences decreases by about a factor of 2 to about 20%. The bias is strongly influenced by a few locations with very large persistent negative differences in cloud amount (Fig. 5); these are predominantly coastal stations where large spatial gradients in cloud amount exist. Therefore, the results in Table 2 exaggerate the bias error in the monthly mean ISCCP cloud amounts; comparison of the ISCCP and SOBS climatologies does not indicate as large a bias (see next section). With the detection and area-sampling errors removed, the standard deviation of the monthly mean differences is only about 5%, about a factor of 3 smaller than for differences of individual observations. Since cloud variation time scales are governed by atmospheric motions, the number of independent samples obtained in one month is estimated to be about 10–15 because the autocorrelation time scale is 2–3 days. If all the errors were completely random, we would expect the standard deviation of differences in monthly mean cloud amounts to decrease by at least a factor of 3. Thus, the errors in estimating the fractional area coverage behave as if they are random, decreasing from about 15% to 5% for monthly averages (from about 25% to about 8% for broken clouds). However, the detection errors are more systematic than random and increase the standard deviation of the differences in monthly cloud amounts by about 10%, similar to their effect on differences between individual observations. Combining both sources of error, the differences of monthly mean ISCCP and ind-SOBS cloud amounts are about -10% on average, due almost entirely to detection errors (we assume that the $\approx 4\%$ bias associated with the difference in "sky cover" and "earth cover" is not error in the ISCCP results), and have a standard deviation of about 15%, most (10%) of which is caused by the detection bias (cf. Fig. 5). Both the bias and standard deviation are slightly smaller when near-coastal surface sites are eliminated from the comparison.

4. Comparison to other cloud climatologies

a. Global, regional, and seasonal comparisons

Table 3 summarizes average cloud amounts for a variety of time and space domains from four cloud climatologies. The differences between the values are summarized in the last column by the rms differences of the values shown, calculated with and without the *Nimbus-7* results. In general, the ISCCP, SOBS, and METEOR total cloud amounts are very similar with global annual mean values >60%; the *Nimbus-7* cloud amount is about 9% less (cf. Stowe et al. 1989; Mokhov and Schlesinger 1993). Regional and seasonal cloud amounts differ among the four climatologies by <10%, except for the polar regions and the ocean. If the *Nimbus-7* results are excluded, then the differences are generally <6%, except for the polar regions, southern land areas, and oceans at night. The results for polar regions will be discussed in section 4d. The large difference between *Nimbus-7* and the other cloud amounts over oceans is directly attributable to the larger detection threshold used in the *Nimbus-7* analysis (about three times the ISCCP threshold), which lowers its sensitivity to low-level clouds. This interpretation is supported by the fact that the largest cloud amount differences occur in regions dominated by marine stratus and by the improvement in the agreement between the ISCCP and *Nimbus-7* results when the ISCCP thresholds are increased by a factor of 2 [Stowe et al. (1989) illustrate this effect on monthly zonal mean cloud amounts]. The effective detection threshold for the METEOR results has not been documented; however, the METEOR ocean cloud amounts generally lie between the ISCCP and *Nimbus-7* amounts.

Table 3 shows that the ISCCP cloud amounts are generally about 5% higher than the SOBS amounts over oceans, but are almost 10% larger than SOBS amounts over midlatitude oceans and over oceans at night (nighttime differences will be discussed in section 4c and large differences near sea ice margins and over the summer Arctic Ocean will be discussed in section 4d). This result occurs despite evidence that some clouds may be missed because of cloud contamination of the ISCCP clear radiances (Rossow and Garder 1993b). Warren et al. (1986, 1988) discuss several sources of bias error in the SOBS data over oceans. The systematic difference between the sky cover observed from the surface and the earth cover observed from satellite is expected to be very small over oceans because of the more horizontally homogeneous conditions (Warren et al. 1988). The weather bias is caused by ships trying to avoid foul weather, emphasizing fair weather conditions in the observations, but this is offset by ships spending more time in foul weather because of larger winds and waves. There is also an observer bias because the ship observers are not generally as well trained as land weather station observers. The weather bias is estimated to be about −0.4%, but may be as large as −2%, and the observer bias is estimated to be about −1.4% (comprised of an overestimate of cumulus cloud amounts and underestimates of stratus and cirrus cloud amounts). The underestimate of cirrus may be much larger at night and may be enhanced in daytime by the presence of more extensive low cloudiness, by hazier boundary layers over oceans, and by a tendency for observers to report cirrus only when an associated convective system is in view (Warren 1990, personal communication).

Figure 6 shows the zonal mean differences between the ISCCP and SOBS cloud amounts over land (upper panel) and ocean (lower panel), averaged over June–July–August (boreal summer) and December–January–February (boreal winter). The structure (two peaks) of the small differences near the equator over oceans suggests that the ITCZ as observed from satellites extends to higher latitudes than observed from the surface, consistent with an underreporting of cirrus cloud over oceans when it is far from the convective systems.

The large systematic differences in midlatitude cloudiness over oceans have a different geographic distribution (Fig. 7) and seasonal dependence in the two hemispheres. The Southern Hemisphere difference is about the same magnitude in all seasons and at most longitudes. The variation of differences in the Indian Ocean is caused by a weak zenith angle dependence of the ISCCP cloud amounts (Rossow and Garder 1993b). The zenith angle effect cannot account for all of the difference between ISCCP and SOBS cloud amounts, but it can account for the smaller differences between ISCCP and METEOR results. The METEOR results confirm higher cloud amounts in southern midlatitude oceans (Mokhov and Schlesinger 1993). Histograms of SOBS monthly cloud amount anomalies over the southern midlatitude oceans (difference of monthly mean and long-term mean values) show a standard deviation of about 15%, which is about half the estimated sampling error for a single observation (Warren et al. 1988), about twice the value obtained for SOBS data in northern midlatitude oceans, and twice the values obtained from all three satellite datasets for both hemispheres. Such a large standard deviation suggests that the SOBS results over southern oceans are less reliable because of a small sample size. The systematic difference in cloud amount may also be associated with a larger than usual weather bias in this area.

The Northern Hemisphere difference in ocean cloud amounts is comprised of a summer difference only in the Atlantic and a winter difference located along the equatorward edge of the storm-track zone, similar to the Southern Hemisphere difference (Fig. 7). The North Atlantic difference in summer cloud amount is located along the east coast of North America. This cloud difference pattern is consistent with the storm-track and low surface pressure anomaly patterns as-

TABLE 3. Comparison of cloud climatologies from the ISCCP C2 dataset (1984–1988), gridded surface weather station reports (SOBS: 1971–1981), a manual nephanalysis of METEOR images (1976–1988), and *Nimbus-7* (1980–1984). All cloud amounts are in percent and all differences are with respect to ISCCP amounts. RMS diff values are based on the values in the first four columns; those values shown in parentheses are calculated without *Nimbus-7* values. Parenthetical values under ISCCP are explained in section 2a. All results are in an equal-area grid equivalent to 5° latitude and 10° longitude at the equator.

Domain		ISCCP	SOBS	METEOR	*Nimbus-7*	RMS diff
Global	annual	62.6	61.5	60.9	52.9	5.7 (1.4)
	day	62.3	60.6	—	51.2	7.9 (1.7)
	night	62.2 (57.7)	56.4	—	54.1	7.0 (5.8)
	winter	62.4	61.9	60.7	52.8	5.6 (1.3)
	spring	62.6	61.3	60.3	53.5	5.5 (1.9)
	summer	62.7	61.2	61.4	51.8	6.4 (1.4)
	autumn	62.6	61.7	61.0	53.5	5.4 (1.3)
Northern Hemisphere		59.7	59.0	55.7	51.7	5.2 (2.9)
Southern Hemisphere		65.4	64.0	66.0	54.1	6.6 (1.1)
Eastern hemisphere		60.4	59.6	57.2	52.6	4.9 (2.3)
Western hemisphere		64.9	63.4	64.7	53.2	6.8 (1.1)
Polar		52.3	68.6	50.4	58.0	10.0 (11.6)
Midlatitude		72.2	67.3	68.5	56.9	9.5 (4.3)
Tropical		58.4	55.4	58.2	48.5	6.0 (2.1)
Land		47.1	53.3	46.5	45.5	3.7 (4.4)
Ocean		70.2	65.5	67.9	56.5	8.5 (3.7)
Land	annual	47.1	53.3	46.5	45.5	3.7 (4.4)
	day	48.8	52.5	—	43.9	4.3 (3.7)
	night	44.3 (40.0)	46.0	—	46.7	2.1 (1.7)
	winter	45.4	53.7	45.5	44.2	4.8 (5.9)
	spring	48.0	53.9	46.8	47.7	3.5 (4.3)
	summer	47.6	52.9	47.3	44.6	3.5 (3.8)
	autumn	46.3	53.5	46.5	45.7	4.2 (5.1)
Northern Hemisphere		49.0	53.0	47.6	44.6	3.5 (3.0)
Southern Hemisphere		43.3	54.0	44.3	47.3	6.6 (7.6)
Eastern hemisphere		45.0	50.9	43.5	42.7	3.8 (4.3)
Western hemisphere		50.8	57.4	51.8	50.4	3.9 (4.7)
Polar		40.5	62.4	37.7	49.6	13.8 (15.6)
Midlatitude		51.4	53.3	49.7	44.4	4.3 (1.8)
Tropical		47.1	49.2	48.4	44.3	2.2 (1.7)
Ocean	annual	70.2	65.5	67.9	56.5	8.5 (3.7)
	day	69.0	64.7	—	54.8	10.5 (4.3)
	night	71.1 (66.4)	61.5	—	57.7	11.7 (9.6)
	winter	70.8	65.8	68.2	57.0	8.6 (4.0)
	spring	69.9	64.8	67.0	56.4	8.5 (4.1)
	summer	70.1	65.1	68.3	55.3	9.1 (3.8)
	autumn	70.6	65.6	68.2	57.3	8.3 (3.9)
Northern Hemisphere		68.1	63.7	62.1	57.2	7.6 (5.3)
Southern Hemisphere		71.7	66.7	72.1	56.1	9.5 (3.5)
Eastern hemisphere		71.2	65.5	66.8	59.6	7.9 (5.1)
Western hemisphere		69.4	65.4	68.8	54.0	9.2 (2.9)
Polar		65.8	74.9	64.6	67.8	5.4 (6.5)
Midlatitude		81.6	73.7	77.0	62.5	12.2 (6.5)
Tropical		63.0	57.9	62.1	50.3	7.9 (3.7)

sociated with the Sahelian drought (Landsea and Gray 1992; Ward 1992), which was more intense in the 1980s, which are covered by ISCCP results, than in the 1970s, which are covered by SOBS results (Nicholson 1989). The seasonal dependence of the Pacific cloud amount difference, which corresponds with a significant seasonal variation of SOBS sample sizes, suggests that small sample size and a weather bias might also explain this difference.

All three satellite cloud amounts are in close agreement over land (Table 3), except in the polar regions (see section 4d), with the ISCCP results slightly higher and the *Nimbus-7* results slightly lower than the METEOR results. These results are consistent with estimated differences in sensitivity, where the *Nimbus-7* IR thresholds are larger than ISCCP thresholds over land by about 2–3 K. However, the SOBS cloud amounts are about 7% higher than all the satellite results (cf. Table 2); this difference is much larger in the Southern Hemisphere (Table 3). The maximum difference between "sky cover" and "earth cover," which has been estimated from observations only over land areas, is 20% at 50% sky cover, with sky cover being larger (Warren et al. 1986). Since sky cover in the range 25%–75% occurs about 40% of the time and the average difference over this range is about 12.5%, the

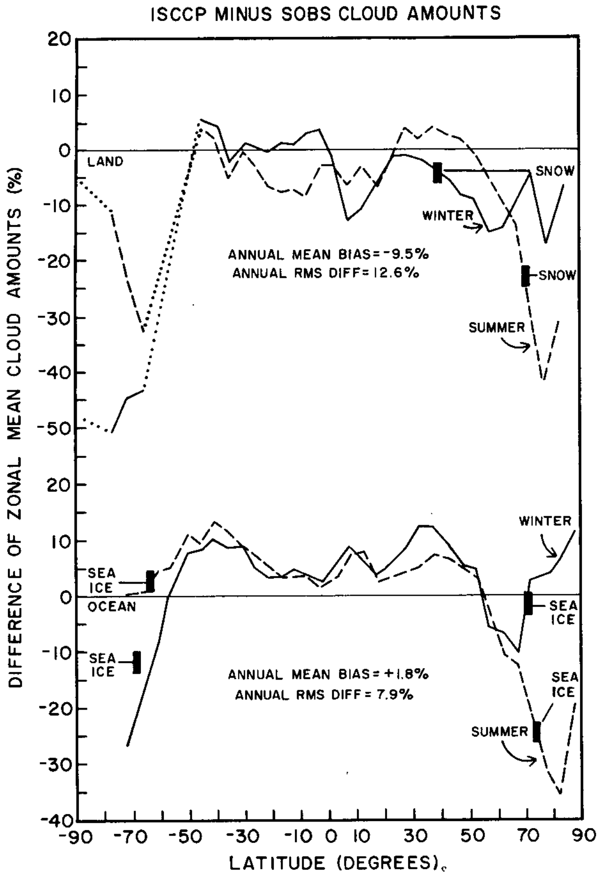


FIG. 6. Zonal mean differences in monthly mean cloud amounts between ISCCP results and the surface observations climatology (SOBS) of Warren et al. (1986, 1988) over land (upper panel) and ocean (lower panel), averaged over summer (June, July, August—dashed lines) and winter (December, January, February—solid lines). Equatorward extents of snow cover and sea ice cover in these two seasons are indicated by small black bars. Monthly results for ISCCP cover the period 1984–1988; results for SOBS cover the period 1971–1981.

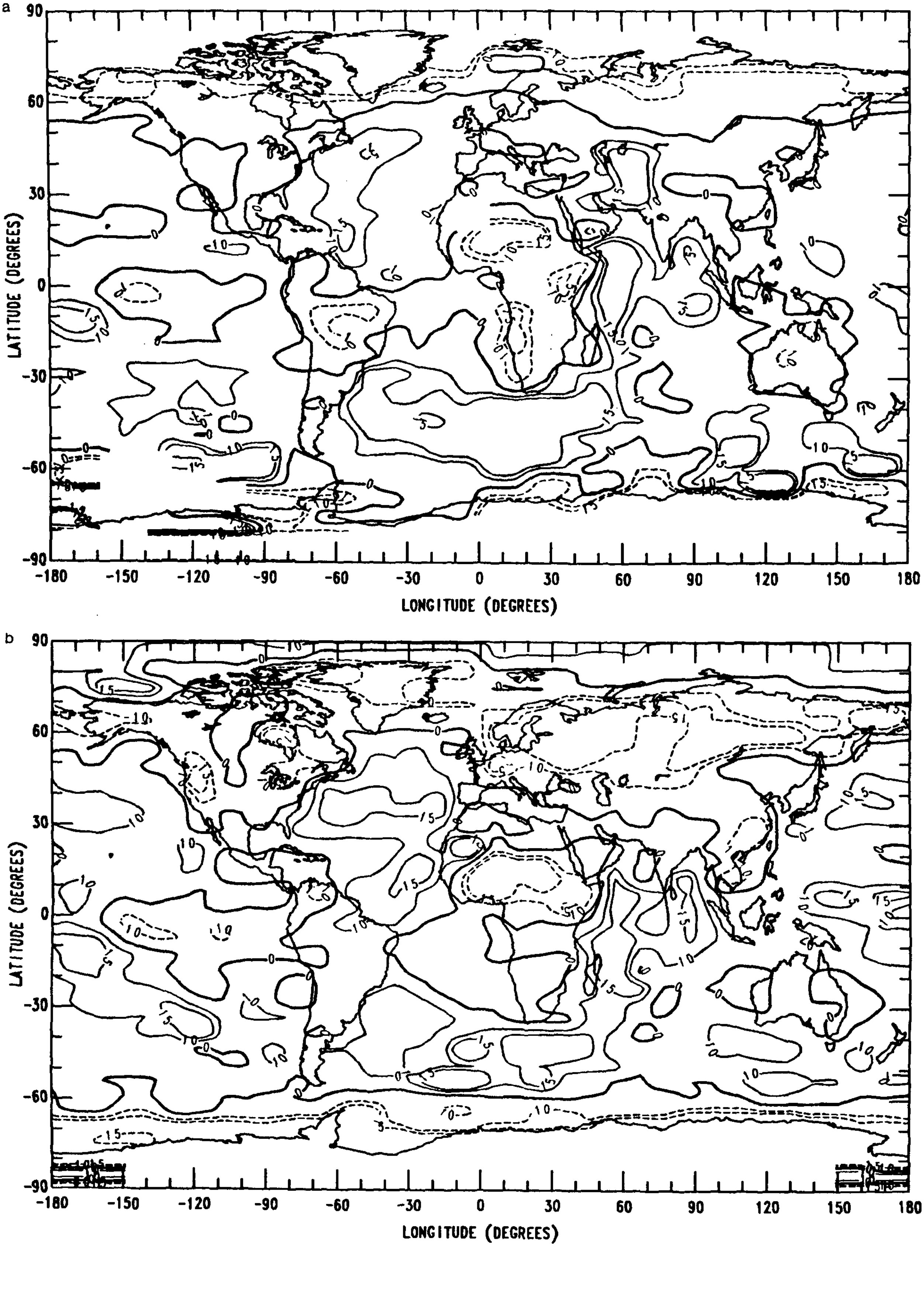
average bias expected between satellite and SOBS cloud amounts is no more than 5%. This is consistent with the small negative bias in ISCCP cloud cover relative to surface observations when broken clouds are isolated (cf. section 3, Table 2). A more recent study by Henderson-Sellers and McGuffie (1990) suggests that this source of bias is smaller in practice, which is also consistent with our results when all cloud types are included in the comparison (Table 2). The larger negative bias of ISCCP cloud amounts over land in winter (Fig. 6) is consistent with the interpretation that the detection errors in ISCCP cloud amounts can explain general differences with SOBS of 5%–10%.

The geographic distribution of the differences in ISCCP and SOBS cloud amounts (Figs. 6 and 7) highlight three particular regions of larger differences: high-latitude land areas in Asia in winter, subtropical and tropical Africa, and the Caspian–Aral seas area. Although the ISCCP results underestimate winter cloud amounts somewhat more (cf. Table 2), because of more variable surface temperatures and reflectances and reduced infrared and visible radiance contrasts, the larger differences shown in Fig. 7 over Asia may be due partly to real changes in cloudiness between the 1970s and 1980s. Such large differences do not appear in the comparison between ISCCP and METEOR cloud amounts (Mokhov and Schlesinger 1993). Several other climate indicators also exhibit changes between these two decades: snow cover (Robinson and Dewey 1990), lower-tropospheric humidity (Gaffen et al. 1991), surface pressure patterns (Trenberth 1990), and surface temperatures (Hansen and Lebedeff 1988). The surface temperature and cloud amount changes, in particular, appear to have similar geographic features. The cloud amount differences over Africa (and the differences in dry season cloudiness over central South America) may be associated with the more severe drought conditions in the 1980s than during the 1970s (Nicholson 1989; Ward 1992). The larger ISCCP summer cloudiness near the Caspian and Aral seas may indicate increased dustiness caused by poor land management practices in this area (almost all of the ISCCP cloudiness present there is very warm and optically thin).

b. Cloud type comparison

To test whether the regional cloud amount differences between ISCCP and SOBS in Fig. 7 are associated with difficulties in observing particular cloud types, we sort the differences into categories defined by the mean cloud optical thickness and cloud-top pressure determined by ISCCP (Table 4). When predominantly low-level clouds are present over oceans, their detection with satellite IR radiances is difficult (e.g., Wielicki and Coakley 1981). During daytime conditions, VIS radiance tests overcome this limitation, accounting for the persistent difference of about 10% between the IR and VIS/IR cloud amounts over oceans. This effect also explains the even smaller ocean cloud amounts obtained from *Nimbus-7* results, which were obtained using a larger IR threshold than used by ISCCP. In general over oceans (Table 4), the ISCCP results indicate smaller cloud amounts than SOBS for low-level clouds and larger cloud amounts than SOBS for high-level clouds. These results are consistent with the ten-

FIG. 7. Geographic distribution of differences in (a) summer and (b) winter mean cloud amounts between ISCCP and SOBS (covering the same periods as indicated in Fig. 6). Heavy solid contour indicates zero difference, thin solid contours indicate larger ISCCP cloud amounts, and dashed contours indicate larger SOBS cloud amounts.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dency noted by Warren et al. (1988) for untrained ship observers to overestimate cumulus cloud amounts, to underestimate stratus cloud amounts, and to underestimate the amount of altocumulus cloudiness. These results also support the suggestion that ship observers underestimate cirrus cloud amounts.

Over land, the ISCCP cloud amounts are generally smaller than the SOBS amounts, with the largest differences for optically thin, middle- and upper-level clouds. The underestimate of the thinner clouds, which are detected primarily by the IR threshold test, is caused partly by the overly large IR threshold used.

c. Day/night comparison

Table 5 summarizes differences in day and night cloud amounts from three climatologies (the METEOR dataset has no information on day/night variations), where the *Nimbus-7* results are from local noon and midnight (without UV radiance tests), while the SOBS and ISCCP results are averages over three-hourly observations. The ISCCP results in Table 5 (and Table 3) have been corrected for the difference in sensitivity to low-level clouds between the VIS/IR detection algorithm and the IR-only algorithm by adding to the nighttime (IR only) cloud amounts the difference of the VIS/IR and IR-only cloud amounts interpolated in local time from the daytime results. Over oceans where the diurnal variation of surface temperature is very small, this correction procedure should work well; over land, where surface temperature decreases at night, this correction may be underestimated. The magnitude of this correction to ISCCP cloud amounts is indicated in Table 5 by the values in parentheses, which show the uncorrected nighttime cloud amounts (see also the parenthetical values in Table 3). This correction does not alter the phase of diurnal cloud variations in the ISCCP dataset. The *Nimbus-7* results shown in Table 5 are based on an IR-only analysis; the values in parentheses show the day–night cloud amount differences using the IR/UV algorithm during daytime and the IR-only algorithm at night.

There is no agreement even on the sign of the day–night cloud amount contrast. Surface observers have more difficulty identifying cloudiness at night, particularly higher-level clouds, and are expected to underestimate nighttime cloud amounts (Warren et al. 1986). This detection bias is also expected to be larger over oceans than land because low-level stratus are more frequent (Warren et al. 1988). Comparing observations on moonlit nights to those with less illumination suggests underestimates of 3%–5% over land and 5%–10% over oceans (Hahn et al. 1993). Globally and annually (Table 3), there is almost no difference in day/night cloud amount in the ISCCP results, however, this lack of difference results from canceling land–water and seasonal variations. Over land, daytime cloud amounts are larger by 3% in winter and 6% in summer; over ocean, nighttime cloud amounts are larger by about 2% in all seasons. SOBS results, if corrected for variations of nighttime illumination, may confirm a larger daytime than nighttime cloud amount over land, but with a difference that is smaller in magnitude than ISCCP, and may show a slightly larger nighttime than daytime cloud amount over oceans.

d. Polar cloudiness

Table 3 and Fig. 6 show very large differences in polar cloud amounts, which have also been found in other datasets (Hughes 1984; Key and Barry 1989; Rossow and Lacis 1990; Curry and Ebert 1992; Schweiger and Key 1992; Mokhov and Schlesinger 1993). Comparison of the three satellite climatologies shows a different relationship among them for polar regions than for the rest of the globe (Table 3): the *Nimbus-7* cloud amounts are usually lower than the METEOR and ISCCP values, but they are higher than both in the polar regions (Mokhov and Schlesinger 1993). All the satellite values are lower than SOBS cloud amounts in the polar regions.

Figure 8 compares the annual cycle of cloud amount from ISCCP and SOBS, averaged over different latitude ranges for the North and South poles, and illustrates recently proposed revisions of the surface climatology. Curry and Ebert (1992) argue that "diamond dust," a form of ice precipitation that occurs mostly in polar winter, is not counted as cloud by surface observers even though optical thicknesses >5 have been observed from aircraft (Curry et al. 1990). They estimate that winter cloud amounts in the central Arctic are similar to summer cloud amounts [based on Huschke (1969) and Warren et al. (1986), (1988)].

Similar large disagreements occur over Antarctica in winter. The winter SOBS values at the South Pole are suspect because the frequency of monthly mean values that are precisely equal to the long-term climatological value is about five times larger than any other value, suggesting a large number of bogus reports. Schneider et al. (1989) find that reported cloud amounts at the South Pole in winter are highly correlated with lunar (actually sky) brightness (cf. Hahn et al. 1993). Using the observed linear relationship, they estimate the corrections to winter cloud amounts shown in Fig. 8, leaving little annual variation in cloud amount. Most of the cloud that is missed during winter is "nonopaque" (Schneider et al. 1989). Similar corrections are presumably needed for the Arctic as well.

ISCCP (and the other satellite) analyses underestimate cloud amounts at both poles by about 10% in winter [but see discussion in Schweiger and Key (1992) of *Nimbus-7* and ISCCP wintertime values] and at least 25% in summer. This assessment is supported by preliminary analyses using other spectral channels on

TABLE 4. Average differences in total mean seasonal cloud amount (percent), ISCCP (1984–1988) minus SOBS (1971–1981), as a function of the mean seasonal cloud optical thickness (TAU) and cloud-top pressure (PC in mb) from ISCCP. Seasons are for the Northern Hemisphere.

	PC = 115	245	375	500	620	740	900
Summer land							
TAU = 0.5	−31.2	−4.4	−22.5	−12.0	—	—	—
2.3	—	—	0.4	−6.8	−19.8	—	—
6.0	—	—	—	−3.4	−2.0	2.7	—
14.5	—	—	—	—	—	—	—
30.0	—	—	—	—	—	—	—
Winter land							
TAU = 0.5	—	—	0.3	−10.1	—	—	—
2.3	—	—	−1.7	−10.6	−18.2	—	—
6.0	—	—	—	−3.1	−2.2	−3.0	—
14.5	—	—	—	—	—	—	—
30.0	—	—	—	—	—	—	—
Summer ocean							
TAU = 0.5	—	—	—	—	—	—	—
2.3	—	—	7.7	7.9	4.3	7.4	—
6.0	—	—	—	7.8	6.5	3.2	−4.7
14.5	—	—	—	—	—	—	—
30.0	—	—	—	—	—	—	—
Winter ocean							
TAU = 0.5	—	—	—	—	—	—	—
2.3	—	—	8.9	12.1	−0.3	2.9	—
6.0	—	—	—	9.9	8.2	3.3	−7.0
14.5	—	—	—	—	—	—	—
30.0	—	—	—	—	—	—	—

AVHRR to detect clouds (Key and Barry 1989; Yamanouchi and Kawaguchi 1992; Rossow and Garder 1993b). The cause of this general underestimate is not only an overall decrease in contrast between clear and cloud IR and VIS radiances, but also an increase in the frequency of occurrence of optically thin, low-level, persistent cloud types that do not alter radiances at 0.65 or 11 μm.

e. Space and time variability

Table 3 summarizes general features of the average cloud distribution: 1) ocean cloud amounts exceed land values by 10%–20%, 2) higher latitudes are cloudier than lower latitudes, 3) there is little seasonal or diurnal variation in global mean cloud amounts. Table 6 gives more detail of the variability of cloud amount associated with diurnal, seasonal, and interannual time scales determined from each of the climatologies. The most obvious disagreements occur in the polar regions and the Southern Hemisphere. The Southern Hemisphere interannual variability is about twice as large in the SOBS dataset and the seasonal variability is almost three times larger than that obtained from satellite observations. In contrast, in the Northern Hemisphere, even over the oceans, there is much better agreement among the four climatologies in the magnitude of seasonal and interannual cloud amount variations. We conclude that the SOBS climatology is less reliable in the Southern Hemisphere.

We analyze variations in the ISCCP dataset using empirical orthogonal functions (Lorenz 1959), in which each month is normalized by its global mean cloud amount and the spatial standard deviation of the monthly mean. The first three principal components (PC) represent the mean annual spatial pattern and its seasonal cycle. Figure 9 shows the time variations (eigenvectors) of the first four components of variance and Fig. 10 shows the spatial structures of the first three components. About 70% of the total variance is associated with the mean annual geographic distribution

TABLE 5. Average differences between daytime and nighttime cloud amounts (percent). Values in parentheses under ISCCP and *Nimbus-7* show differences without adjustment for day–night algorithm differences (see text for explanation). Negative values indicate larger nighttime cloud amounts.

	ISCCP	SOBS	*Nimbus-7*
Summer, land, total	6.3 (11.3)	5.6	−3.8 (−1.4)
polar	5.9 (7.8)	3.2	−3.4 (2.5)
midlat	11.8 (16.8)	6.8	−3.0 (−0.1)
tropics	2.3 (8.7)	5.8	−4.6 (−4.3)
ocean, total	−1.9 (3.1)	3.4	−3.6 (−1.7)
polar	0.2 (1.4)	1.9	−2.8 (4.6)
midlat	−0.9 (5.0)	3.2	−2.3 (3.2)
tropics	−2.9 (2.1)	3.8	−4.7 (−6.2)
Winter, land, total	2.8 (5.9)	6.8	−6.2 (−3.5)
polar	0.0 (0.2)	3.2	−4.9 (−3.3)
midlat	3.8 (6.1)	7.7	−6.0 (0.4)
tropics	3.4 (8.6)	7.9	−7.0 (−6.6)
ocean, total	−2.1 (2.1)	2.9	−4.8 (−3.0)
polar	0.6 (2.2)	1.5	−4.2 (0.6)
midlat	−1.6 (3.1)	1.1	−4.7 (0.8)
tropics	−2.9 (1.5)	4.5	−5.1 (−6.5)

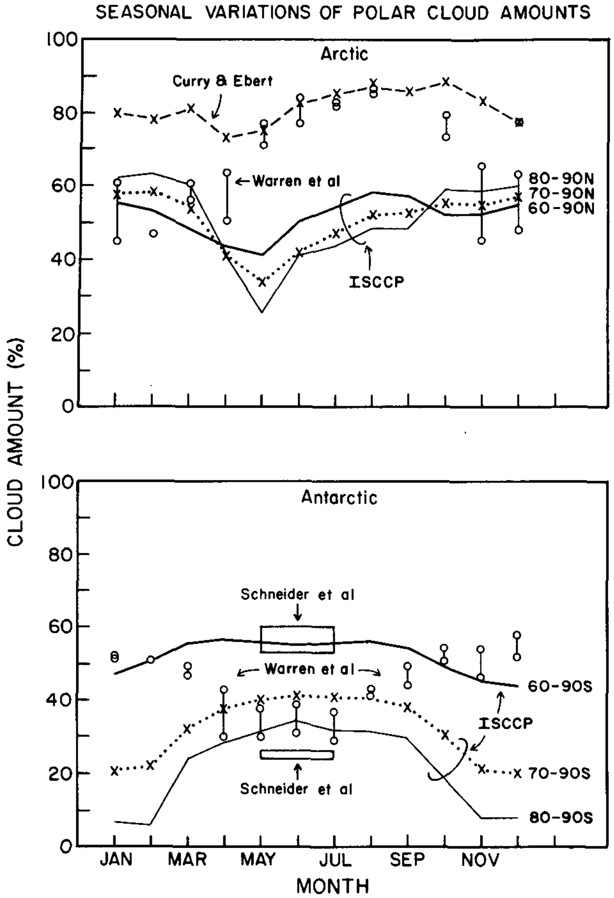


FIG. 8. Comparisons of the seasonal variations of average cloud amount in the (a) Arctic and (b) Antarctic determined by ISCCP and other cloud climatologies. The climatology of Warren et al. (1986, 1988) is represented by connected open circles, where the upper circle represents an average over 60°–90°N in the Arctic and 60°–90°S in the Antarctic and the lower circle represents near-polar values. The average cloud amounts in the central Arctic, adopted from Huschke (1969) by Curry and Ebert (1993), are shown by dashes in (a). Corrections to winter South Polar cloud amounts proposed by Schneider et al. (1989) are indicated by open bars in (b), where the lower bar represents opaque clouds and the upper bar represents total cloudiness.

of cloud amount. Well-known features are readily apparent: three zonal bands of high cloud amount, one within about 10° of the equator, and one in each hemisphere between 30° and 60° latitude (Fig. 10a). The cloud band in southern midlatitudes is the most nearly continuous, whereas the other two bands are interrupted over land areas. Land areas are generally less cloudy than ocean areas at all latitudes; the difference in average cloudiness in the two polar regions is also consistent with this distinction.

The seasonal cycle (approximately represented by the second and third PCs) accounts for about 14% of the total variance. The spatial pattern of the seasonal cycle shows that it is dominated by tropical variations and that the phases of the tropical and midlatitude seasonal changes oppose one another (cf. Rossow and Lacis 1990). The larger variation (second PC) is in phase with the solstice seasons while the third PC is in phase with the equinoctal seasons. The fact that it takes two PCs to represent the seasonal oscillation is indicative of significant asymmetries in the time variations (see, e.g., Mitchell and Wallace 1992).

Table 7 compares the results of an EOF analysis of the ISCCP, SOBS, METEOR, and *Nimbus-7* cloud climatologies by showing the amount of variance found in each of the first six PCs and aggregated for all higher-order PCs, as well as the correlations of the spatial maps for the first four PCs. The quantitative agreement of both the spatial maps and the amount of variance explained is excellent (cf. Mokhov and Schlesinger 1993), with the exception of the amount of variance accounted for by the first PC in SOBS data. The fact that there is so much variance in higher-order PCs for SOBS and that the amount of variance is constant over all higher PCs suggests that the SOBS results have much more variance that behaves like "white noise," which may be due to the very sparse coverage over oceans and the Southern Hemisphere. The much larger interannual variability determined from SOBS for southern midlatitudes (Table 6) supports this idea. If we rescale the relative variances by the total contained in the first six PCs (numbers in parentheses), we get much better agreement. SOBS also agrees less well on the spatial patterns because of poor coverage of the Southern Hemispheric oceans.

The results in Table 7 suggest good agreement among the datasets for the first three PCs, but not the fourth one; the first three PCs account for about 80% of the variations in the three satellite datasets and about 60% of the variations in SOBS (or 94% of the variance in the first six PCs). Thus, the features of the cloud distribution that we can confirm are the annual mean geographic distribution (with the polar regions somewhat more uncertain) and the amplitude and phase of the seasonal variations.

5. Discussion

a. Uncertainty in ISCCP cloud amounts

The uncertainty in a single determination of cloud amount comes from four sources: 1) estimation of fractional area coverage, 2) area sampling, 3) time sampling, and 4) detection errors.

1) When we isolate small-scale broken cloud cases in the comparison between ISCCP and ind-SOBS, we find a small ($\approx$4%) negative bias that is consistent with other estimates of the difference between "sky cover" and "earth cover" (Warren et al. 1986). We also find an rms difference of about 25% that is consistent with studies of the effects of finite satellite resolution on determination of fractional cover (Wielicki and Parker 1992). The magnitude of errors in single pixels is probably larger still; however, the variations of cloud

TABLE 6. Summary of cloud amount variation statistics reported in percent. Values in parentheses indicate secondary frequency maxima.

Climatology	Region	Diurnal range (mean/std dev)	Local time of maximum	Local time of minimum	Seasonal range (mean/std dev)	RMS interannual variations Total	Winter	Spring	Summer	Autumn
ISCCP	Global	12.8/8.7	0600	1500	23.2/13.7	7.1	7.9	7.6	6.9	6.9
	Land	18.7/9.4	1500	0600	30.7/15.3	7.4	8.0	7.4	7.0	7.3
	Ocean	10.1/6.9	0600	1500	19.8/11.4	7.2	7.9	7.7	6.8	6.8
	N. Polar	19.3/10.5	0600	0300	28.0/9.2	7.3	7.4	7.7	7.2	7.1
	N. Midlat	14.6/10.6	1200	1500 (0600)	22.2/9.1	6.6	7.0	6.1	6.6	7.0
	Tropics	12.3/7.5	0300 (1500)	1500 (0900)	27.8/15.1	8.4	9.3	9.0	7.6	7.7
	S. Midlat	9.1/6.4	0600	1500	10.6/5.1	4.9	5.1	4.9	4.8	4.8
	S. Polar	15.0/9.4	0600	1500	21.0/9.6	5.6	4.8	5.6	6.5	5.2
SOBS	Global	25.4/23.7	0600 (1800)	0000	26.2/16.3	10.4	11.0	10.3	10.3	10.4
	Land	22.8/20.0	1500	0000	29.6/15.3	8.6	9.3	8.4	7.9	8.7
	Ocean	26.7/25.2	0600 (1800)	0000	24.6/16.5	11.3	11.7	11.2	11.3	11.2
	N. Polar	24.0/26.8	1030	0000	29.5/14.8	12.0	13.5	12.3	11.0	11.0
	N. Midlat	17.0/16.2	1500 (0600)	0000	22.8/10.0	6.8	7.2	6.4	6.5	7.0
	Tropics	21.0/13.0	0600 (1800)	0000	23.6/13.5	9.7	10.2	9.5	9.4	9.8
	S. Midlat	41.9/32.4	0600	0000	29.0/18.5	15.1	14.9	14.8	15.9	14.9
	S. Polar	35.1/37.9	0000	0000	48.0/27.4	14.1	13.5	15.3	13.8	13.9
METEOR	Global	—	—	—	16.8/12.9	7.2	7.3	7.3	7.2	7.0
	Land	—	—	—	24.7/14.1	7.9	8.4	7.9	7.6	7.8
	Ocean	—	—	—	12.9/10.2	6.8	6.7	7.0	7.0	6.6
	N. Polar	—	—	—	30.5/14.5	8.3	9.5	7.7	7.1	8.6
	N. Midlat	—	—	—	20.0/10.2	7.3	7.2	7.2	7.5	7.5
	Tropics	—	—	—	19.2/12.8	7.9	8.0	8.4	8.0	7.5
	S. Midlat	—	—	—	4.8/2.8	4.4	4.5	4.3	4.4	4.5
	S. Polar	—	—	—	8.1/5.5	6.3	6.4	6.0	6.3	6.4
Nimbus-7	Global	—	—	—	28.0/16.1	8.1	8.8	8.9	7.2	7.6
	Land	—	—	—	35.4/17.6	7.3	7.6	7.4	6.6	7.7
	Ocean	—	—	—	24.7/14.1	8.5	9.2	9.5	7.4	7.5
	N. Polar	—	—	—	32.0/10.1	7.6	7.8	7.7	7.5	7.5
	N. Midlat	—	—	—	27.9/10.0	6.6	6.6	6.2	6.9	6.6
	Tropics	—	—	—	33.0/18.0	9.5	10.6	10.8	7.7	8.5
	S. Midlat	—	—	—	13.1/5.3	5.3	5.3	5.6	5.3	5.1
	S. Polar	—	—	—	27.8/10.6	7.4	5.6	7.0	8.2	8.6

sizes, shapes, clumping, and location within the image pixels combine with the effects of finite radiance threshold and variations of cloud optical thickness to make a large proportion of this error random in character. Consequently, a sufficiently large sample of pixels in a small area can provide an estimate of fractional area coverage with an uncertainty of about 25% (in other words, averaging quickly reduces random errors). Further averaging over a month reduces the rms uncertainty to <10%. However, the effect of finite image pixel size, offset by the effect of a finite threshold, contributes some bias error that depends on cloud detection sensitivity, size of pixels, and the nature of the clouds. These biases seem to be <10% in magnitude but may vary in sign.

Small-scale broken clouds constitute only about 20%–30% of the cloudy cases; most of the clouds appear to be larger scale such that surface observations, covering areas about 30–50 km in radius, behave almost like point measurements. In comparing the ISCCP and ind-SOBS observations, the larger-scale overcast cases reduce the differences by producing nearly perfect agreement in about 40% of the cases. Combining these overcast cases with the broken cloud cases produces an average difference in estimated fractional area cloud cover of about −1% and an rms difference of about 15% for individual measurements. These results are consistent with other studies (Sèze et al. 1986; Henderson-Sellers et al. 1987) that concluded that the "sky cover"–"earth cover" bias did not appear to be as large as estimated and that the rms differences between satellite and surface observations of cloud amounts are about one octa. Averaging over a month reduces the rms differences to about 5%.

2) The large difference in the area sampled by the ind-SOBS and ISCCP datasets leads to an increase in the standard deviation of the differences by about 10% when all cases (except detection errors) are included. Since the ind-SOBS data represent a very sparse (single) sample of the ISCCP map grid area in our comparison, very large differences between the ind-SOBS and ISCCP cloud amounts arise when the area is partially overcast. When many ind-SOBS measurements in the same area are averaged, the differences with the ISCCP cloud amounts are reduced (by about 10% for five samples) about as much as

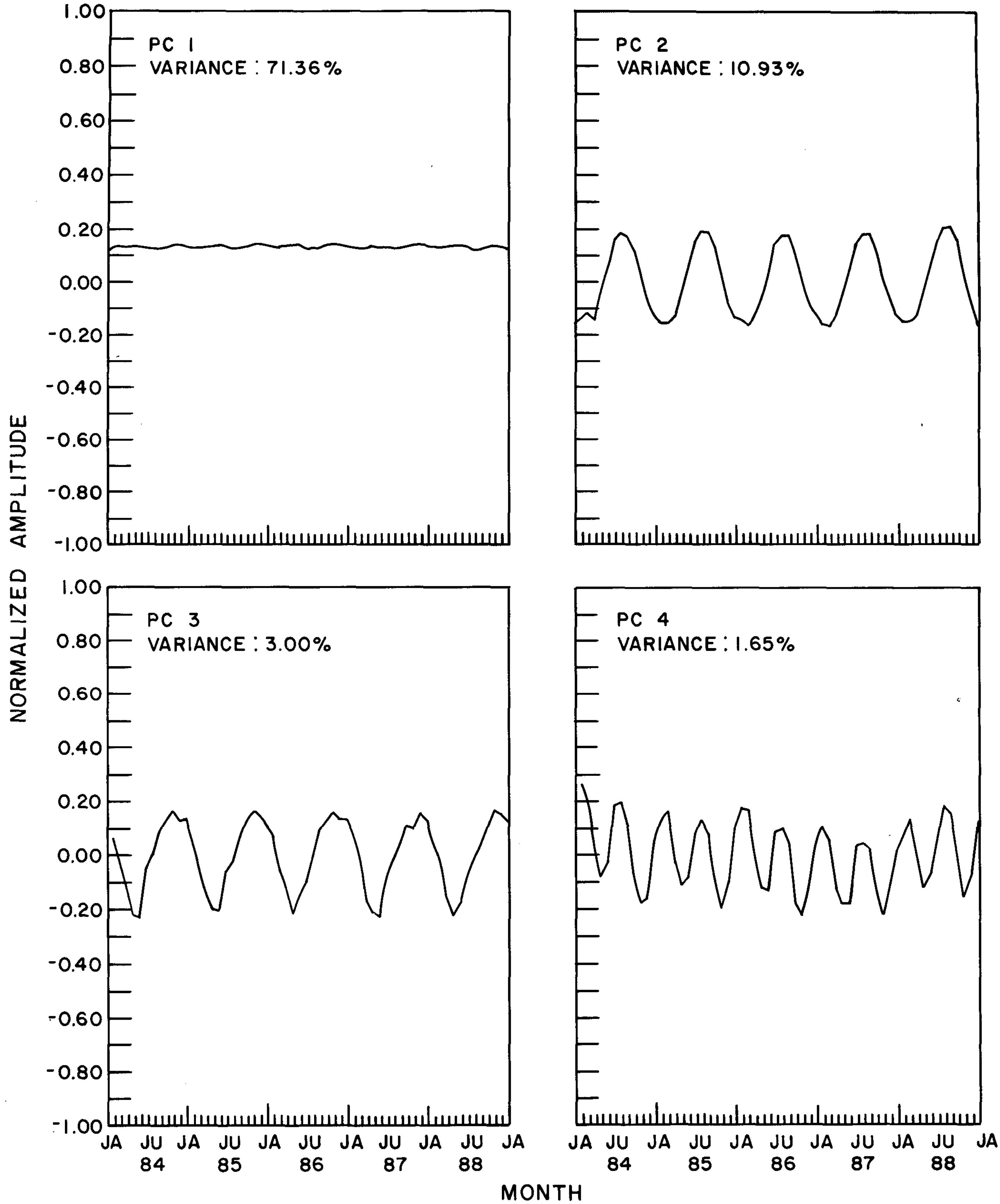


FIG. 9. First four eigenvectors (time variations) for monthly mean cloud amounts determined by EOF analysis from ISCCP results on an equal-area map grid equivalent to 5° × 10° resolution at the equator and covering the period 1984–1988. Fraction of the total variance explained by each principal component is indicated.

removing these cases completely from the comparison. This result implies geographic variations in the uncertainty of gridded surface observations because of changing sample population sizes (cf. Warren et al. 1986, 1988).

An equivalent, though smaller, problem occurs because the ISCCP results are based on a sparse spatial sampling of the original satellite image, representing only about 10% of the map grid area. Whenever the fractional area cloud cover is very small or very large, there is some finite probability that the sampled pixels will miss some cloud or holes. The study by Sèze and Rossow (1991) showed that the radiance variation statistics are relatively homogeneous over much larger scales than the size of the pixels so that 20–120 pixels per ISCCP map grid cell represent a reasonably large sample.

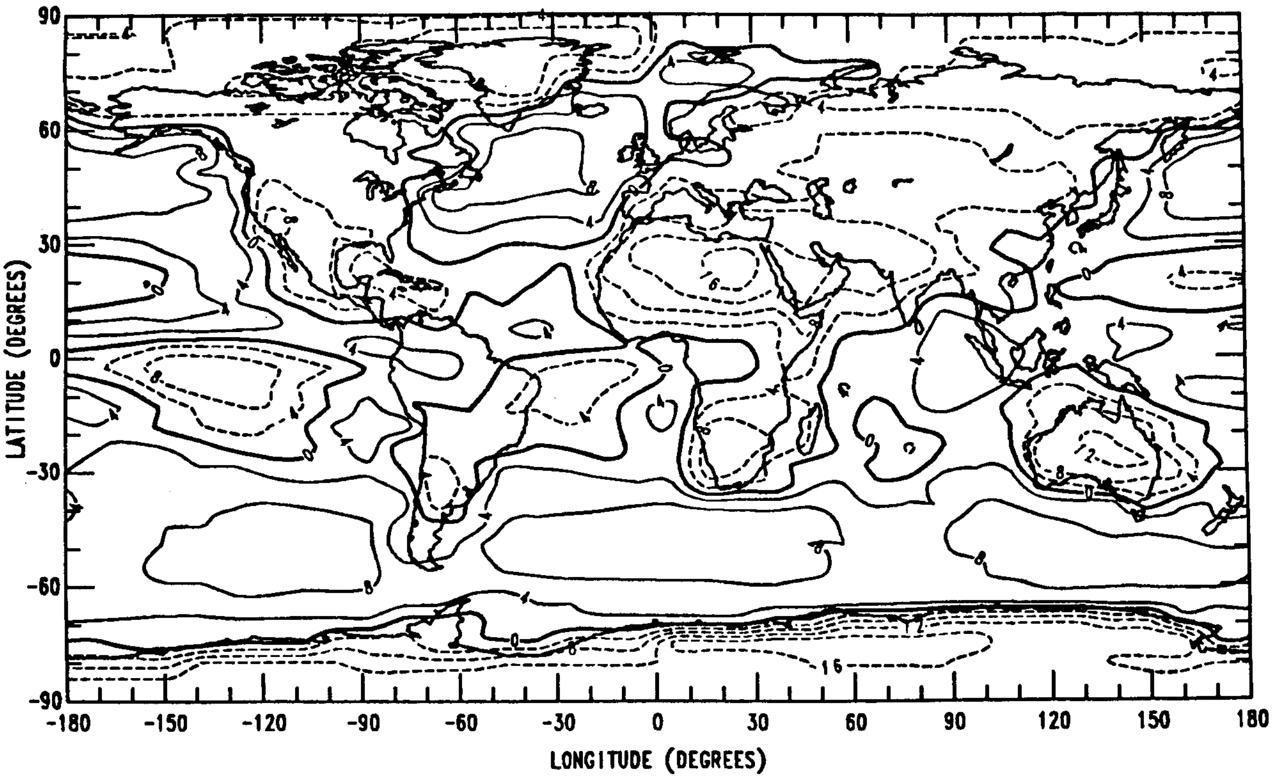
3) The bimodal shape of the cloud amount frequency distribution (Fig. 2), which is similar for observations at scales of about 30-50 km (ind-SOBS) and at about 280 km (ISCCP), has a large standard deviation of about 30%–40%. Consequently, there is an uncertainty in any average cloud amount determined from a time sampling of this probability distribution that depends on the size of the sample. Warren et al. (1986, 1988) examined this issue for surface observations to determine the minimum sample size required for reliable cloud amount statistics. As we have already discussed, cloud amounts vary on space and time scales related to the most energetic motions in the atmosphere and thus are correlated over scales of $\approx$500–2000 km and $\approx$1–3 days (smaller scales occur in the tropics and larger scales at higher latitudes). Thus, in one month there are only about 10–15 independent samples at one location. This number of samples of cloud amount from a probability distribution like Fig. 2 implies an uncertainty of the monthly mean cloud amount of about 10%, solely because of the sampling. As the results in Table 2 illustrate, a reduction of the rms differences between the ind-SOBS and ISCCP cloud amounts by a factor of 3 occurred when we considered cases without detection or area-sampling errors.

The rms differences among the regional, monthly mean cloud amounts from the cloud climatologies in Table 3 range from 10%–20%: the smallest differences are between ISCCP and SOBS and the largest differences are between ISCCP and *Nimbus-7* (cf. Mokhov and Schlesinger 1993). The sampling effect is illustrated by comparing ISCCP and SOBS results averaged over 1, 3, 5, and 8 yr[6] (on a $5° \times 10°$ map grid): the rms differences in regional, monthly mean cloud amounts decrease from about 18% to about 12% between 1- and 8-yr averages. However, these cloud amount differences are much larger in the Southern Hemisphere where SOBS sampling is sparse and in the polar regions, where both datasets have larger uncertainties. If the same comparison is limited to Northern Hemisphere land areas between 0° and 60° latitude, the rms differences decrease from 13% to about 9%. This difference is similar in magnitude to the standard deviation of the monthly cloud amount anomalies obtained from ISCCP (and from SOBS in the Northern Hemisphere).

4) Detection errors, because they can be partly systematic, are the dominant contribution to uncertainty in the monthly mean cloud amounts for all of the climatologies. In other words, the errors in estimating fractional area cloud cover are not important to determining accurate monthly mean cloud amounts unless the analysis procedure or dataset produces a large bias. Detection errors occur when the clear-sky radiances are biased or the radiance threshold is larger than the natural variability (uncertainty) of the clear radiances (or both). Thus, the most important feature of a satellite cloud algorithm is its sensitivity to the presence of clouds and the key to validation of the ISCCP cloud amounts is verification of the clear-sky radiances. We have shown that over oceans the clear radiances and thresholds are essentially unbiased, but that the use of a VIS radiance threshold, instead of a reflectance threshold, misses a small (<5%) amount of clouds at high latitudes. Over land the clear radiances are also unbiased, except for IR values at high latitudes in winter, but the IR threshold is too large (the same high-latitude effect in the VIS also occurs). Over snow and sea ice in polar regions, the clear radiances are accurate, though wintertime clear IR may be a little too large, and the IR threshold consistent with the uncertainties. However, the VIS radiance threshold is too large, almost eliminating the VIS test near the poles. Nevertheless, more frequent occurrences of optically thin and/or low-lying cloud types in polar regions cause the most significant underestimates. These clouds do not affect the IR and VIS radiances enough to be detected reliably. With the exception of the polar regions, the comparisons between ISCCP and ind-SOBS and SOBS suggest that detection errors are generally <15% for monthly averages (Table 2).

The cloud amount determined by our analysis can be considered accurate from a specific practical perspective. When clouds are examined at very high spatial resolution, they exhibit a continuum of radiances (e.g., Wielicki and Welch 1986; Kuo et al. 1988; Cahalan and Joseph 1989; Wielicki and Parker 1992), so that determination of cloud cover is really a process of relabeling the lowest optical thicknesses as "not cloud." Since the ISCCP dataset reports a distribution of optical thickness values, the "not cloud" category is just an additional category (zero optical thickness) in this dis-

[6] In the last comparison an 8-yr average of ISCCP results is compared with the 11-yr average of SOBS results.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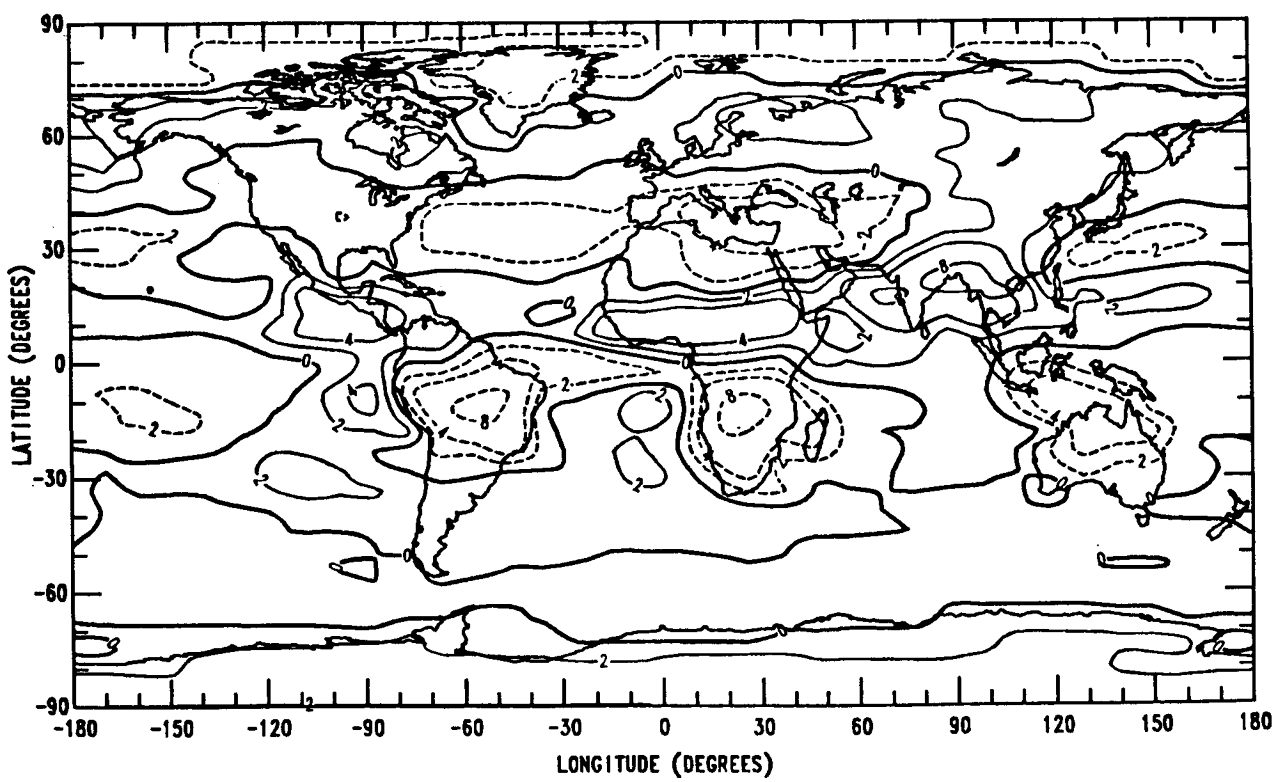
a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LONGITUDE (DEGREES)

b

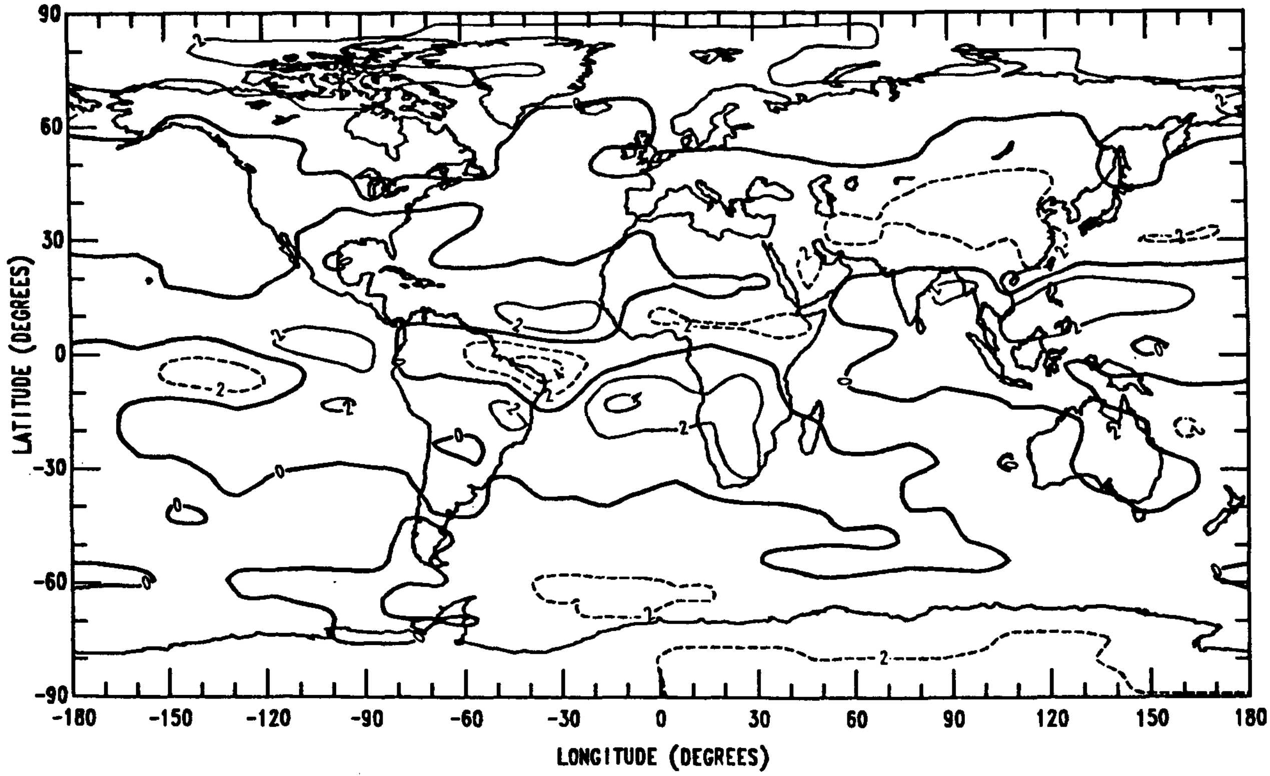

FIG. 10. Geographic structure of first three principal components, (a) PC1, (b) PC2, (c) PC3, of monthly mean cloud amounts determined by EOF analysis from ISCCP results covering the period 1984–1988. Solid contours indicate positive amplitudes and dashed contours indicate negative amplitudes.

tribution. It is the distribution and variation of optical thickness that cause variations in radiative fluxes. What we are able to detect are those clouds that alter the satellite radiances "significantly," so that the remaining errors in cloud amount do not translate into similar magnitude errors in radiative fluxes.

b. Description of cloud amount distribution and variations

The ISCCP stage C1/C2 datasets represent a detailed description of the global distribution of cloud amount with a resolution of about 280 km and of the variations

TABLE 7. Empirical orthogonal function analysis of cloud amount climatologies produced from ISCCP (1984–1988), SOBS (1971–1981), METEOR (1976–1988), *Nimbus-7* (1980–1984). Correlations are with respect to ISCCP. Numbers in parentheses are rescaled by excluding variance for principal components PC > 6 and renormalizing.

	ISCCP	SOBS	METEOR	Nimbus
Variance explained				
PC # 1	71.4 (80.2)	45.6 (70.7)	73.0 (83.0)	58.0 (67.6)
PC # 2	10.9 (12.2)	12.6 (19.5)	10.4 (4.8)	17.9 (20.9)
PC # 3	3.0 (3.4)	2.7 (4.2)	1.7 (1.9)	3.8 (4.4)
PC # 4	1.6 (1.8)	1.5 (2.3)	1.1 (1.2)	2.7 (3.1)
PC # 5	1.1 (1.2)	1.1 (1.7)	0.9 (1.0)	2.0 (2.3)
PC # 6	1.0 (1.1)	1.0 (1.6)	0.8 (0.9)	1.4 (1.6)
PC # >6	11.0 —	35.5 —	12.0 —	14.2 —
Correlation of spatial maps				
PC # 1	—	0.76	0.89	0.74
PC # 2	—	0.80	0.72	0.87
PC # 3	—	0.67	0.67	0.65
PC # 4	—	0.59	−0.36	−0.64

of cloud amount on time scales from 3 h to 8 yr (July 1983 through June 1991).[7] This dataset has more uniform coverage of the whole globe at all times of day with the densest sampling, thereby minimizing the uncertainties associated with spatial and temporal sampling. Much work by many researchers will be required to examine these data thoroughly and determine the meaningful behavior of clouds. We have presented only some simple summaries. Some notable features of the cloud distribution are listed below (cf. Table 3).

1) The global annual mean cloud amount is about 63% and exhibits little (<1% rms) variation from month to month. Over the whole 8-yr ISCCP record, the global annual mean cloud amount has undergone a slow cycle, apparently associated with El Niño occurrences, with an amplitude of ±4%.

2) The mean annual Southern Hemisphere cloud amount is almost 6% larger than the mean Northern Hemisphere cloud amount; the mean western hemisphere cloud amount is a little more than 4% larger than the eastern hemisphere cloud amount. Both of these facts arise from a systematic difference between the average cloud amount over ocean and land and from the differences in hemispheric land fractions. The mean annual ocean cloud amount is about 23% larger than the land cloud amount (the ISCCP results probably overestimate this difference by 5%–10%).

3) If each hemisphere is divided into latitude zones of 30° width, the middle zone (30°–60°) has the largest mean cloud amount in the ISCCP results, about 10% larger than the global mean value. However, the average cloud amount of the tropical–subtropical zone is a combination of smaller (than global mean) subtropical cloud amounts and larger cloud amounts in the tropics. Consequently, the largest latitudinal contrast in cloud amount occurs between the tropics and subtropics. Since both the ISCCP and SOBS results underestimate polar cloudiness, the polar regions may actually have slightly larger cloud amounts than middle latitudes.

4) The land/ocean differences in mean cloud amount imply longitudinal contrasts of cloudiness that are as large as the latitudinal contrasts. The largest contrasts occur in the subtropics between land deserts and marine stratocumulus regimes near the west coasts of continents.

5) The seasonal variation of global mean cloud amount is very small (<0.5%); however, this occurs because of cancellation of seasonal changes between lower and middle latitudes (all climatologies show large seasonal variations at polar latitudes, but these may be exaggerated by detection errors) and between the Northern and Southern hemispheres. Low-latitude cloud amounts are largest in summer, while middle-latitude cloud amounts are largest in winter. The amplitude of the seasonal cloud amount variations is larger in the Northern Hemisphere because seasonal variations are larger over land than oceans.

6) In the ISCCP results there is almost no difference in global and annual mean cloud amounts between daytime and nighttime; however, this occurs because of cancellation between land and ocean diurnal variations. Mean cloud amounts are larger during nighttime than during daytime over oceans and larger during daytime than during nighttime over land. Most of the diurnal variation of cloud amounts over oceans occurs at lower latitudes. Over middle-latitude land the amplitude of the diurnal variation of cloud amount is about twice as large in summer as in winter.

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APPENDIX

ISCCP Participants

ISCCP data processing has been accomplished by the combined efforts of several institutions, which are listed here along with their representatives (in chronological order). The capture of original satellite datasets, quality checking, and their reduction by sampling are performed by the sector processing centers (SPC). For NOAA polar orbiters, the SPC is the National Oceanic and Atmospheric Administration (represented by G. Hunolt, H. Jacobowitz, H. Drahos, J. Gibson, M. Mignono, and K. Kidwell). For Meteosat, the SPC is the European Space Agency (ESA) (R.

[7] ISCCP data collection, processing, and analysis is planned to continue through at least 2000.

Saunders, B. Mason). For GOES-East, the SPC was the University of Wisconsin (R. Fox, D. Wylie) and is now the Atmospheric Environment Service (AES) of Canada (S. Woronko, S. Lapczak, F. Bowkett, D. McKay, Y. Durocher). For GOES-West, the SPC is Colorado State University (CSU) (G. G. Campbell). The University of Wisconsin serves as a backup to AES and CSU and produces special datasets for related research. For GMS, the SPC is the Japan Meteorological Agency (JMA) (A. Kurosaki, I. Kubota, T. Nuomi, K. Shuto). Normalization of geostationary satellite radiances to those measured by the polar orbiters is performed by the Satellite Calibration Center (SCC) at the Centre de Meteorologie Spatiale in France (N. Beriot, G. Therry, Y. Desormeaux). The ISCCP datasets are produced and analyzed at the Global Processing Center at NASA Goddard Institute for Space Studies (processing group led by E. Kinsella and A. Walker). NOAA also serves as the International Central Archives (ICA) for ISCCP. In addition to the data center representatives, membership of the JSC Working Group on Data Management for ISCCP (now for all WCRP radiation projects) included T. Vonder Haar and E. Raschke; ex-officio members representing the WCRP are S. Benedict (who succeeded T. Kaneshige) and R. Schiffer (project manager).

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