Comparison of the Climatologies of High-Level Clouds from HIRS and ISCCP

YAO JIN
Department of Geosciences, Columbia University, New York, New York

WILLIAM B. ROSSOW
NASA/Goddard Institute for Space Studies, New York, New York

DON P. WYLIE
Space Science and Engineering Center, University of Wisconsin—Madison, Madison, Wisconsin

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ABSTRACT

Comparison of individually matched analyses of high-level cloudiness from the High-Resolution Infrared Sounder (HIRS) CO_2-slicing analysis and the International Satellite Cloud Climatology Project (ISCCP) analysis of satellite data for 4 months shows that the former reports about 0.12 more high-level clouds than the latter. Almost all of the difference in high-level cloud amounts occurs as differences of thin cirrus, defined by infrared emissivity $\epsilon < 0.5$ or $\tau_{vis} < 1.3$, consistent with a previous comparison of Stratospheric Aerosol and Gas Experiment II and ISCCP. Some of this difference may be caused by the large field of view of the HIRS instrument. Over oceans the differences in cirrus cloud amounts are caused by the higher sensitivity of the HIRS analysis to optically thin clouds, aided by a small high bias of the sea surface temperatures used in the HIRS cloud detection step. Over land the higher detection sensitivity of the HIRS analysis was partially offset by the effect of large low biases in the surface temperatures used in the HIRS cloud detection step, most especially over high mountainous terrains. From these two datasets the authors conclude that about one-third of the earth is covered by high-level clouds (tops above the 440-mb level) and more than two-thirds of these clouds are cirrus, defined as those clouds that have a net radiative heating effect (i.e., infrared $\epsilon < 0.84$ or $\tau_{vis} < 3.6$). About half of all cirrus clouds are optically very thin ($\epsilon < 0.5$ or $\tau_{vis} < 1.3$). Optically thicker ($\tau_{vis} > 3.6$) high-level clouds appear to be more frequently associated with each other than with cirrus. Notable concentrations of cirrus in the Tropics mark regions of frequent deep convective activity. However, there are also prominent features associated with the subtropical jet streams. In midlatitudes, cirrus concentrations occur in the oceanic cyclone tracks, but they are even larger over major mountain complexes. Although the quantitative uncertainties of both datasets are large in the polar regions, the agreements and disagreements between them can be explained by the presence of large amounts of cirrus over both polar regions.

1. Introduction

Clouds produce two competing effects on the global radiative balance: they reflect solar radiation, which tends to decrease the surface temperature, and they absorb thermal radiation from the earth's surface (and lower atmosphere) and reradiate it at a lower temperature, which tends to increase the surface temperature. Overall, the former effect is stronger than the latter effect. On average, clouds reduce the net radiative heating of the earth, an effect that appears mostly at the surface (e.g., Rossow and Zhang 1995). Cirrus clouds are high-level (upper troposphere), optically thin clouds with both low solar reflectivities and low emissivities (Liou 1986). Unlike most other clouds, cirrus can increase the net radiative heating of the earth if they are optically thin enough, whereas thicker high-level clouds still decrease the net radiative heating. Thus, the overall effect of high-level clouds on the radiative balance depends on the distribution of their macrophysical and microphysical properties (Stephens et al. 1990).

High-level clouds, including cirrus, may play a more significant role in determining the general circulation of the atmosphere because they alter its vertical profile of radiative cooling. Ramanathan et al. (1983) showed with the National Center for Atmospheric Research Community Climate Model that cirrus clouds can accelerate the subtropical jets with a magnitude that depends on the cirrus emissivity. Slingo and Slingo (1988) also found an acceleration of the subtropical jets by high-level cloud radiative effects, along with increased precipitation and a strengthened Hadley cir-

Corresponding author address: Ms. Yao Jin, NASA/Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025.
E-mail: ciyxj@nasagiss.giss.nasa.gov

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TABLE 1. ISCCP cloud detection thresholds used for different surface types (Rossow and Garder 1993a). Infrared thresholds are given in kelvins and visible thresholds are given as scaled radiances (0–1.0).

	IR thresholds	Visible threshold
Open ocean	2.5	0.03
Near-coastal ocean, lakes	3.5	0.03
Ice-covered water	3.5	0.12
Land	6.0	0.06
Snow-covered land	6.0	0.12
High or rough topography	8.0	0.06

culation. Ackerman et al. (1988) and Machado and Rossow (1993) showed that the anvil clouds in convective complexes induce large vertical heating rate gradients that reinforce convective instability and may alter upward energy and water transports in the Tropics. Again, these effects depend on the distribution of the high-level clouds and their properties.

One major uncertainty in the characteristics of high-level clouds is the amount and distribution of the thinner cirrus clouds that are present in the upper atmosphere. Satellite observations are the only way to determine cloud properties at synoptic to global scales, but the ability of current analysis methods to identify thin cirrus and measure their properties is uncertain (Rossow 1989). One effective way to verify cloud property retrieval techniques is to intercompare independent datasets that use different observations and retrieval methods.

This paper reports on a comparison of two global climatologies of high-level (cloud-top pressure ≤ 440 mb) clouds: one based on the analysis of infrared radiances from the High-Resolution Infrared Sounder (HIRS) by the CO_2-slicing method (Wylie and Menzel 1991; Wylie et al. 1994) and one based on the analysis of infrared and visible radiances from imaging radiometers by the International Satellite Cloud Climatology Project (ISCCP) (Rossow et al. 1991). This particular comparison is needed because the ISCCP analysis can confuse some lower-level broken clouds with higher-level transmissive clouds, whereas the HIRS CO_2-slicing analysis does not. Four months of results were compared, covering an annual cycle: July 1989, October 1989, January 1990, and April 1990. Section 2 gives a brief description of the HIRS and ISCCP datasets and analysis methods. Section 3 compares the two descriptions of the geographic and seasonal variations of high-level clouds as a function of optical thickness range. Notable differences are highlighted and the reasons for these differences are discussed in section 4. The comparison of these two climatologies, supplemented by a comparison of ISCCP with a climatology from the Stratospheric Aerosol and Gas Experiment II (SAGE II) reported in Liao et al. (1995a,b), gives more confidence that the patterns of geographic and seasonal variation of cirrus clouds are well represented. The major features of cirrus clouds obtained by ISCCP and confirmed by the HIRS data are summarized in section 5.

2. Datasets and analysis methods

a. The High-Resolution Infrared Sounder and the CO_2 slicing method

HIRS is a 19-channel infrared radiometer (with one visible channel at 0.7-μm wavelength) that is flown on the National Oceanic and Atmospheric Administration polar orbiting weather satellites. In this paper, we focus on the HIRS analysis by Wylie and colleagues because they have published a global, 4-yr cloud climatology (Wylie and Menzel 1991; Wylie et al. 1994). Monthly mean maps may be obtained on Internet at http://wylie.ssec.wisc.edu. Two other HIRS analyses (Wahiche et al. 1986; Susskind et al. 1987) have been proposed.

TABLE 2. Monthly mean cloud amounts for July and October 1989, and January and April 1990 from HIRS and ISCCP (in parentheses). Amounts are for high ($P_c \leq 440$ mb), middle ($440 < P_c \leq 680$ mb), low ($P_c > 680$ mb), and total cloudiness. The datasets have been matched for individual map grid cells on each day. The upper panel gives results over water, and the lower panel gives results over land (regions poleward of 60° latitude have been excluded).

	July 89	October 89	January 90	April 90	Mean
			Over ocean		
High cloud	0.36 (0.22)	0.36 (0.20)	0.37 (0.21)	0.38 (0.23)	0.36 (0.22)
Middle cloud	0.18 (0.15)	0.20 (0.18)	0.20 (0.18)	0.19 (0.17)	0.19 (0.17)
Low cloud	0.26 (0.30)	0.24 (0.31)	0.23 (0.30)	0.24 (0.26)	0.24 (0.29)
Total cloud	0.79 (0.67)	0.81 (0.69)	0.80 (0.69)	0.81 (0.67)	0.80 (0.68)
			Over land		
High cloud	0.32 (0.20)	0.32 (0.19)	0.36 (0.23)	0.35 (0.23)	0.34 (0.21)
Middle cloud	0.16 (0.15)	0.18 (0.17)	0.17 (0.17)	0.17 (0.17)	0.17 (0.17)
Low cloud	0.16 (0.13)	0.15 (0.14)	0.12 (0.11)	0.14 (0.14)	0.14 (0.13)
Total cloud	0.64 (0.48)	0.65 (0.50)	0.65 (0.51)	0.66 (0.55)	0.65 (0.51)

TABLE 3. HIRS and ISCCP high-level cloud amounts and their differences as a function of cloud visible optical thickness (τ_{VIS}) over water and over land (polar regions excluded).

	July 89	October 89	January 90	April 90	Mean
			Over ocean		
$\tau_{VIS} < 1.3$					
HIRS	0.19	0.18	0.18	0.20	0.19
ISCCP	0.07	0.06	0.06	0.08	0.07
HIRS–ISCCP	0.12	0.12	0.12	0.12	0.12
$\tau_{VIS} \geqslant 1.3$					
HIRS	0.16	0.18	0.18	0.18	0.18
ISCCP	0.15	0.15	0.15	0.15	0.15
HIRS–ISCCP	0.02	0.03	0.03	0.03	0.03
			Over land		
$\tau_{VIS} < 1.3$					
HIRS	0.12	0.12	0.13	0.13	0.13
ISCCP	0.06	0.07	0.07	0.07	0.07
HIRS–ISCCP	0.06	0.06	0.06	0.06	0.06
$\tau_{VIS} \geqslant 1.3$					
HIRS	0.20	0.19	0.23	0.22	0.21
ISCCP	0.14	0.12	0.16	0.16	0.15
HIRS–ISCCP	0.06	0.07	0.07	0.06	0.06

However, both of these methods retrieve an effective cloud amount (emissivity times cloud cover) from radiances *averaged* over very large areas (>8000 km^2). Although a similar ''slicing'' method is used to determine cloud-top pressures, high-level clouds were not reported separately in these papers. It will be useful to compare the cloud climatology produced by these methods once they become available. Henceforth, we refer to the results of the analysis by Wylie and colleagues as the HIRS data.

The climatology produced by Wylie et al. (1994) started in June 1989, using HIRS data from *NOAA-10* and *NOAA-11* to complement the ISCCP climatology with independent observations. Individual HIRS fields of view (FOVs) are about 17 km in size at the nadir (<300 km^2). The data are sampled at every third pixel on every third scan line, providing results at intervals of about 100 km, to make processing more manageable. The analysis is restricted to observations made at scan angles < 25° from the nadir to eliminate problems with slant views through the atmosphere [the results reported in Wylie et al. (1994) are restricted to scan angles < 10°]. The analysis of Wylie et al. (1994) uses the partially absorbing CO_2 channels from 13- to 15-μm wavelength (channels 4–7), along with the ''window'' channel at 11.1 μm (channel 8) and a water vapor channel (channel 10 is at 8.3 μm on *NOAA-10* and 12 μm on *NOAA-11*) to identify clouds that are partially transmissive to terrestrial radiation.

An extensive description of the CO_2-slicing algorithm is given in Wylie et al. (1994; see also Wylie and Menzel 1989, 1991; Menzel et al. 1992). The analysis involves two passes through the HIRS data. First, clear HIRS fields of view (FOV) are detected by comparing the 11.1-μm radiances (expressed as brightness temperatures) with global surface temperature analyses from the National Oceanic and Atmospheric Administration (NOAA), the National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center), and the National Environmental Satellite, Data and Information System (NESDIS) operational analyses. Over land, the NCEP analysis from the medium-range forecast model is used. Over the ocean, the NESDIS operational SSTs are used. The 11.1-μm brightness temperature is converted to a surface temperature by correcting for water vapor attenuation and emission, using radiances measured by the ''water vapor'' channel (channel 10). All HIRS FOVs with moisture-corrected 11.1-μm brightness temperatures greater than the NOAA surface temperatures minus 2.5 K are labeled as clear. The clear HIRS radiances are interpolated into cloudy areas for use in the CO_2-slicing analysis.

Cloud-top pressures (P_c) and infrared emissivities (ϵ) are obtained in the second pass, which processes only cloudy FOVs. The CO_2-slicing equation (Wylie et al. 1994) compares radiances at two nearby wavelengths with their clear values estimated from nearby clear FOVs. (In practice, a solution is found that minimizes the radiance differences for several pairs of wavelengths). The retrieval of P_c assumes that only one cloud layer is present and calculates radiances for comparison to the measurements using the NCEP analyses of temperature and humidity profiles. The slicing equation retrieves P_c independently of the cloud emissivity so that lower-level broken clouds cannot be con-

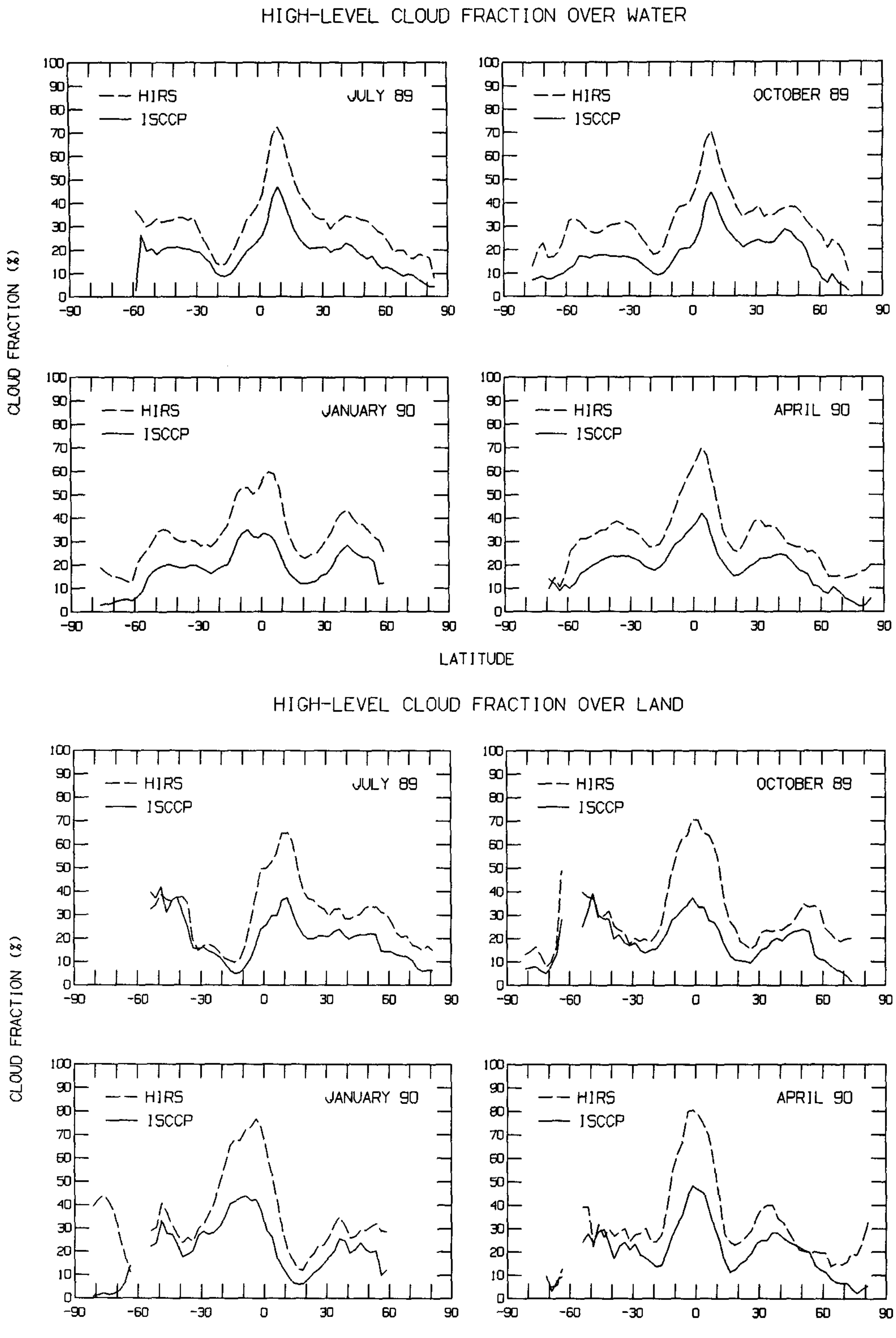

FIG. 1. Zonal monthly mean high-level ($P_c \leq 440$ mb) cloud amounts over ocean and land from HIRS CO_2-slicing analysis (dashed lines) and from ISCCP analysis (solid lines) for July and October 1989, and January and April 1990. Results are from daily datasets that have individually matched observations at 280-km resolution. Comparison is restricted to illuminated parts of the globe by the ISCCP analysis of visible radiances.

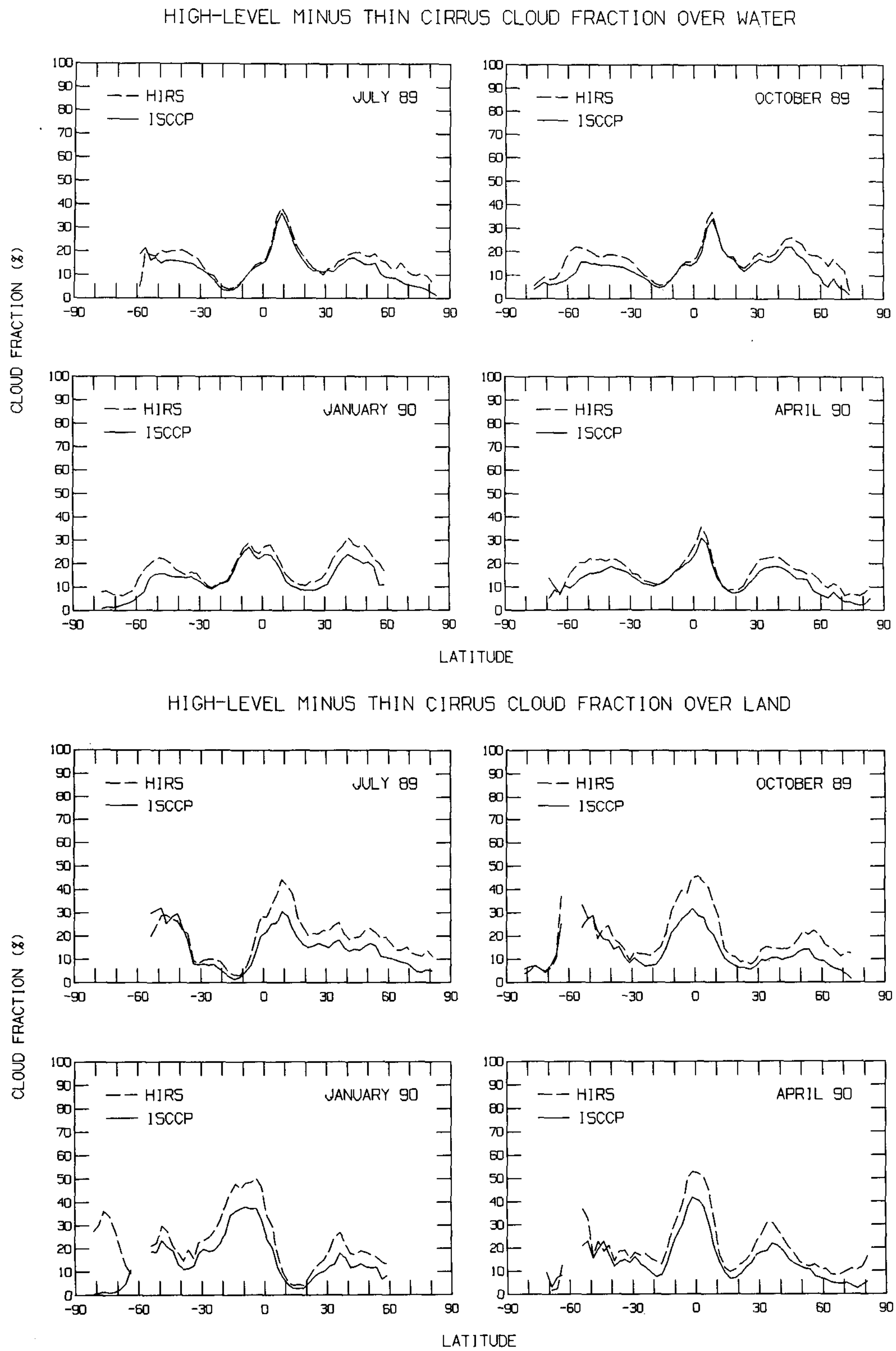

FIG. 2. Same as in Fig. 1 except that the thin cirrus ($\tau_{VIS} < 1.3$) have been excluded from both datasets.

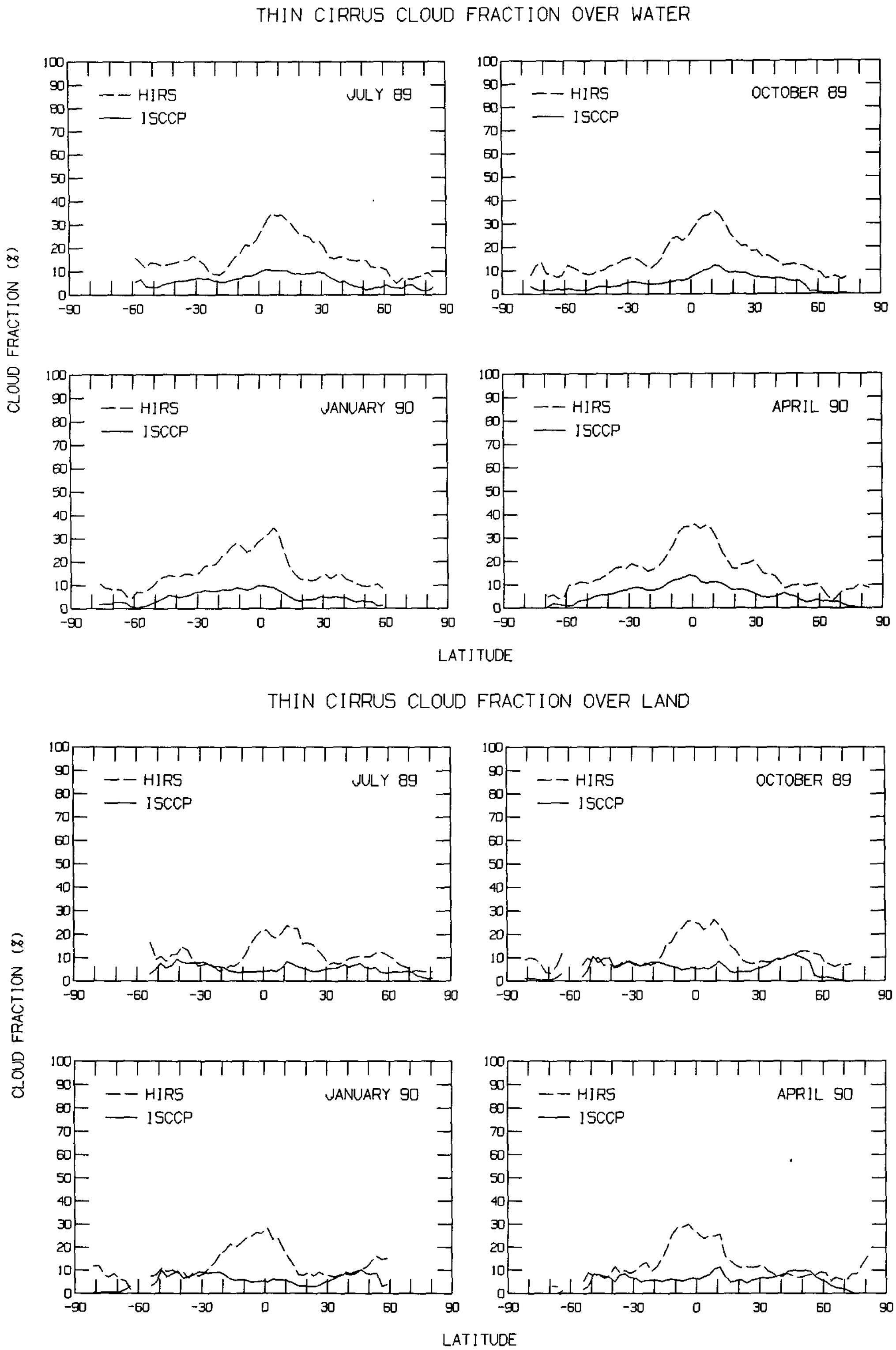

FIG. 3. Same as in Fig. 1 but for thin cirrus ($\tau_{VIS} < 1.3$) only.

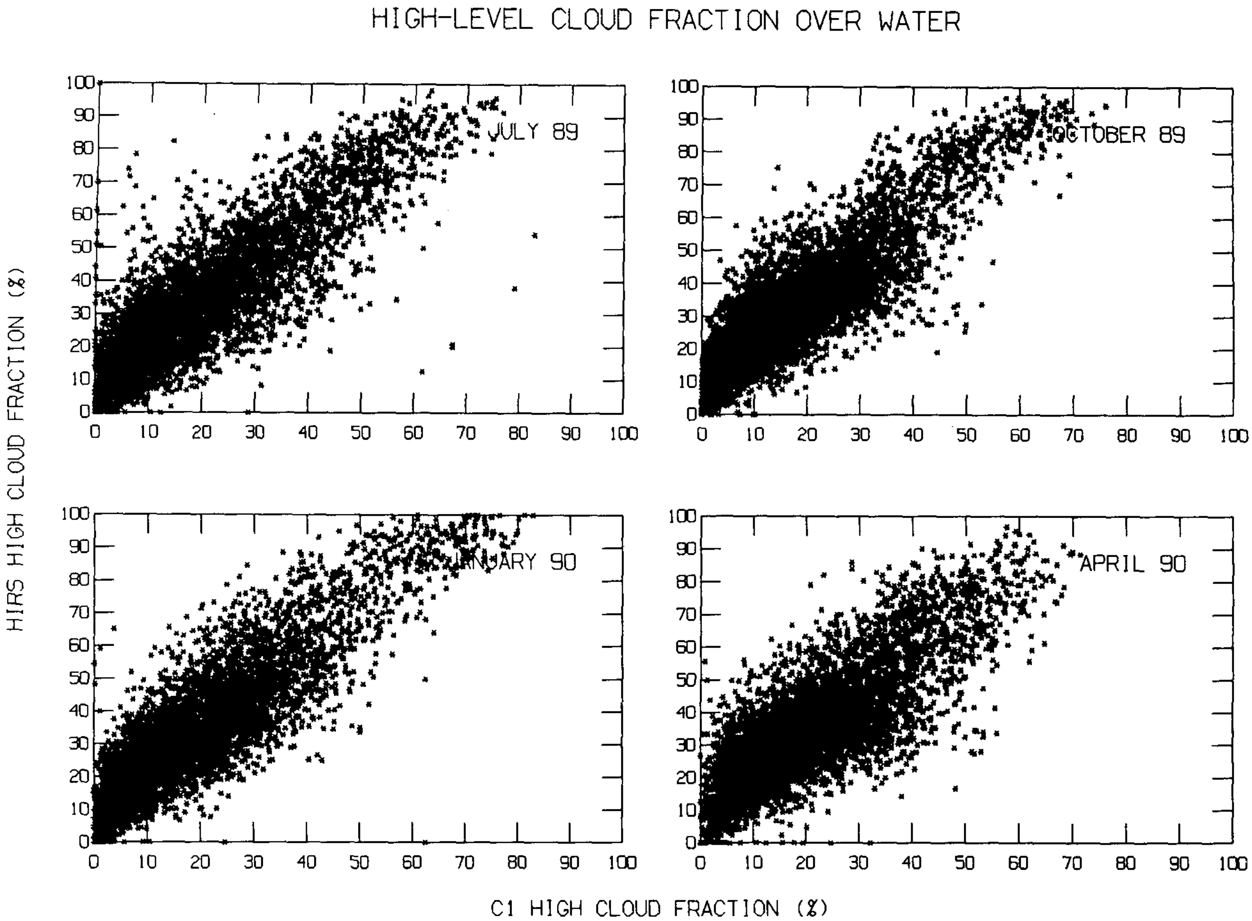

FIG. 4. Scatterplots of individually matched map grid cell values of monthly mean high-level cloud amounts over (a) oceans and (b) land from HIRS (ordinate) and ISCCP (abscissa) for July and October 1989, and January and April 1990. Regions poleward of 60° have been excluded.

fused with high-level transmissive clouds (Wylie et al. 1994). If the calculated cloud-top pressure is $\geqslant$1000 mb, then the pixel is reclassified as clear. If the radiance difference between cloudy and clear at either wavelength is smaller than five times the instrument noise level, then $\epsilon = 1$ and P_c is obtained directly from 11.1-μm brightness temperature. This situation occurs mostly for low-level clouds with $P_c > 700$ mb. For other clouds, a value of ϵ is obtained from the 11.1-μm brightness temperature and the retrieved value of P_c. We focus attention on high-level clouds with $P_c \leqslant 440$ mb. This analysis gives values of P_c that are near the center of a transmissive cloud layer and near the actual top of an opaque cloud layer (Wylie et al. 1994).

The two-step process has a feature that is important for an understanding of later results. Cloud detection is actually performed only in the first step by a single wavelength threshold test. Although the slicing analysis in the second step can change the label of some FOVs from cloudy to clear, the FOVs labeled as clear in the first step are not checked again for possible cloudiness. Consequently, to maximize the number of cloud detections and the quality of the clear radiances, the threshold used in the first step is made very small. Because diurnal changes of surface temperature are not represented in the NCEP land surface temperature analysis, about half of the data over land areas are discarded to avoid spurious cloud detections, especially over subtropical deserts. Over land only the afternoon orbits (1400–1600 LST) of *NOAA-11* and the early evening orbits (1930–2030 LST) of *NOAA-10* are used, while all orbits are used over oceans.

b. *International Satellite Cloud Climatology Project*

ISCCP uses a bispectral analysis to identify high-level clouds and to separate opaque from transmissive clouds. ISCCP also reports results from the analysis of a single infrared radiance measurement both day and night, but we focus on the daytime results that discriminate between opaque and transmissive clouds. The analysis uses both geostationary and polar orbiting ra-

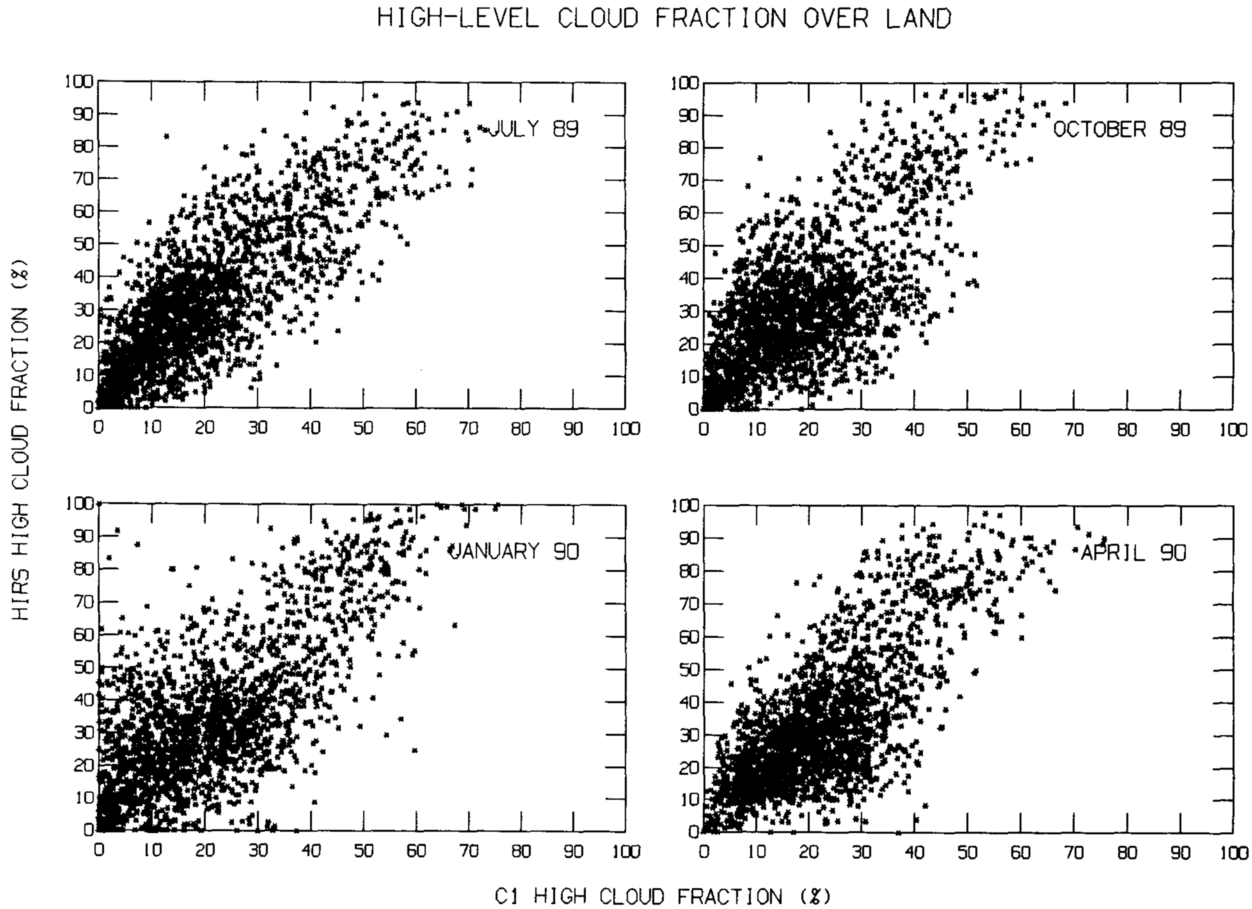

FIG. 4. (*Continued*)

diances measured at ~0.6 and ~11 μm wavelengths, common to all weather satellites. (Infrared radiances are given as brightness temperatures and visible radiances are given as a fraction of the response of the instrument when viewing a surface with reflectivity = 1 at the mean sun–earth distance.) The original radiance measurements in FOVs of 4–7 km in size at the nadir are sampled at intervals of about 30 km and 3 h (no time sampling of polar orbiter data) (Schiffer and Rossow 1985).

The ISCCP analysis involves three passes through all the data, the first two for cloud detection and the third for retrieval of cloud properties (Rossow et al. 1991). First, a set of space and time variation tests is performed for a variety of scales to identify clear radiances at each wavelength for each FOV (Rossow and Garder 1993a). This set of clear radiance values for each time and place is derived solely from satellite data (although some ancillary information is used to classify surface types). The accuracy of the inferred clear-sky radiances has been quantified (Rossow and Garder 1993b). In the second pass, all FOV radiances are compared with the corresponding clear values: if either the infrared radiance is smaller than the clear value by more than some threshold amount or the visible radiance is larger than the clear value by more than some threshold amount, that FOV is labeled cloudy. A key feature of the ISCCP algorithm is that the thresholds depend on the type of surface (Table 1); for most ocean areas the infrared threshold is 2.5 K and the visible threshold is 0.03, and for most land areas these thresholds are 6.0 K and 0.06, respectively (Rossow and Garder 1993a).

The cloud-top temperature (T_c) and visible optical thickness (τ) of clouds (as well as the surface temperature and visible reflectance) are retrieved in the third pass by comparing the observed radiances with those calculated by a radiative transfer model (Rossow et al. 1991). The cloud optical thickness and surface reflectance are retrieved only in daytime. When τ is small enough, the cloud transmits a significant portion of infrared radiation emitted by the surface and lower atmosphere, making the brightness temperature larger than the physical temperature of the cloud top. The value of T_c is recalculated to account for this transmission, using the retrieved value of τ_{vis} (Rossow et al.

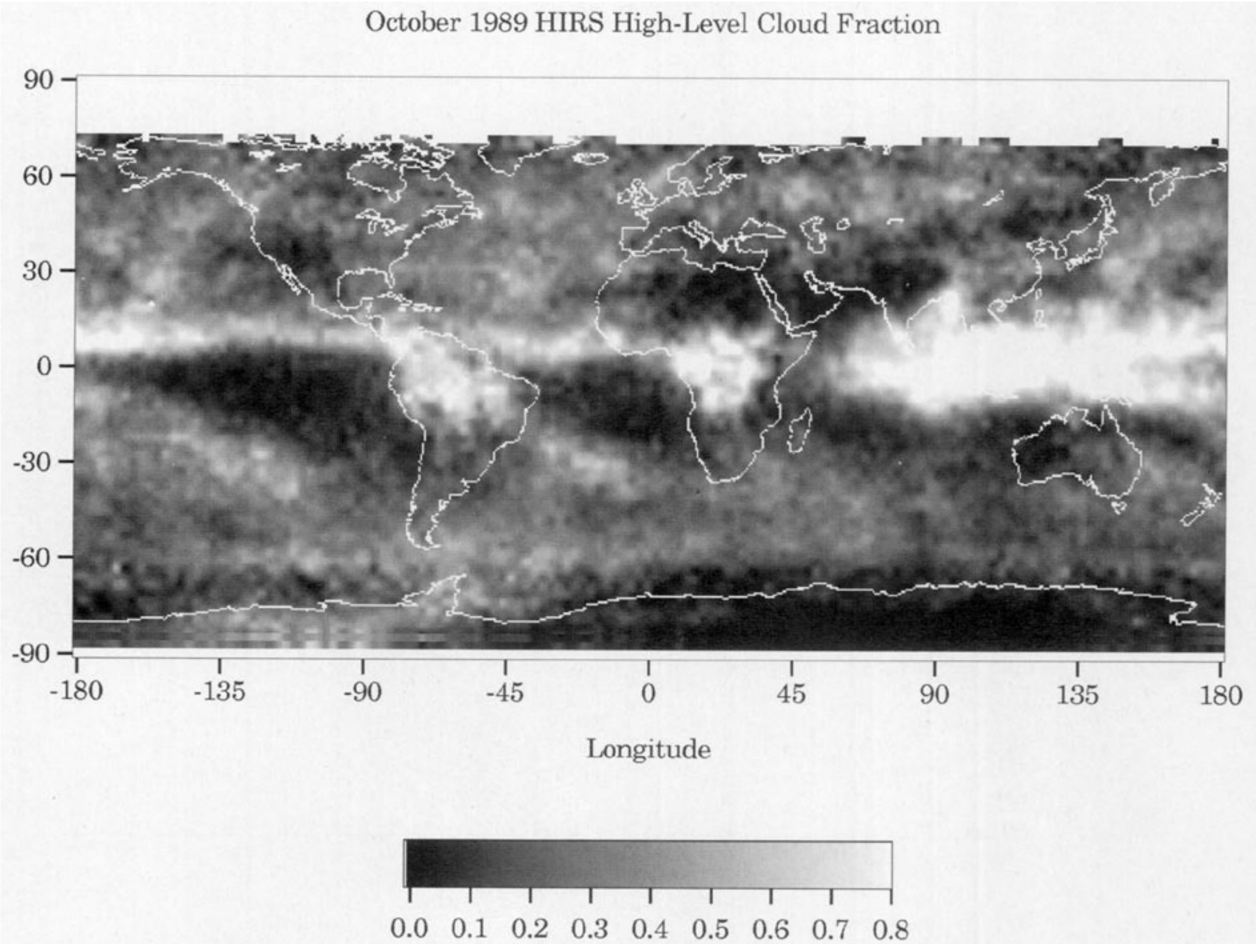

FIG. 5. Geographic distribution of monthly mean high-level cloud amounts for October 1989 from HIRS and ISCCP. These results are from daily datasets that have individually matched observations at 280-km resolution. Note that the same gray scale is applied to different ranges: 0–0.8 for HIRS and 0–0.5 for ISCCP.

1991), where $\tau_{IR} = \tau_{VIS}/2.0$ (Platt and Stephens 1980; Stephens and Webster 1981). The revised cloud-top temperature is used to locate the cloud-top pressure, using a local temperature profile. Transmissive high-level clouds cannot be identified at night with only a single infrared radiance measurement and the adjustment of T_c cannot be performed.

c. Mapping, matching, and transformation

Four months of global HIRS data and ISCCP data are compared: July 1989, October 1989, January 1990, and April 1990. To facilitate this comparison, the results from individual HIRS FOVs are collected into a mapped form, similar to the ISCCP C1 dataset, as described below.

The ISCCP C1 data give statistics from the analysis of individual FOVs at 3-h intervals in a global equal-area map grid, equivalent in resolution to 2.5° at the equator (Rossow and Schiffer 1991; Rossow et al. 1991). We use these data in an equal-angle map form [see Rossow et al. (1991) for details]. For daytime locations the C1 data provide the fractional amount of clouds in 35 categories defined by seven intervals in P_c and five intervals in τ. The P_c intervals are surface pressure or 1000–800 mb, 800–680 mb, 680–560 mb, 560–440 mb, 440–310 mb, 310–180 mb, and 180–50 mb or tropopause pressure. Note that the highest pressure is given by the surface pressure derived from the topographic altitude and the lowest pressure is given by the tropopause pressure obtained from the operational temperature analysis of the HIRS data by NOAA. There are five optical thickness intervals: 0.02–1.32, 1.32–3.63, 3.63–9.38, 9.38–23.08, and 23.08–125. High-level clouds are defined by $P_c \leq 440$ mb. The amount of cloud in each category, together with the retrieved surface temperature, is averaged over local daytime to form "daily" mean global maps.

Each HIRS FOV is mapped into the ISCCP 2.5° equal-angle grid and assigned to one of the 35 cate-

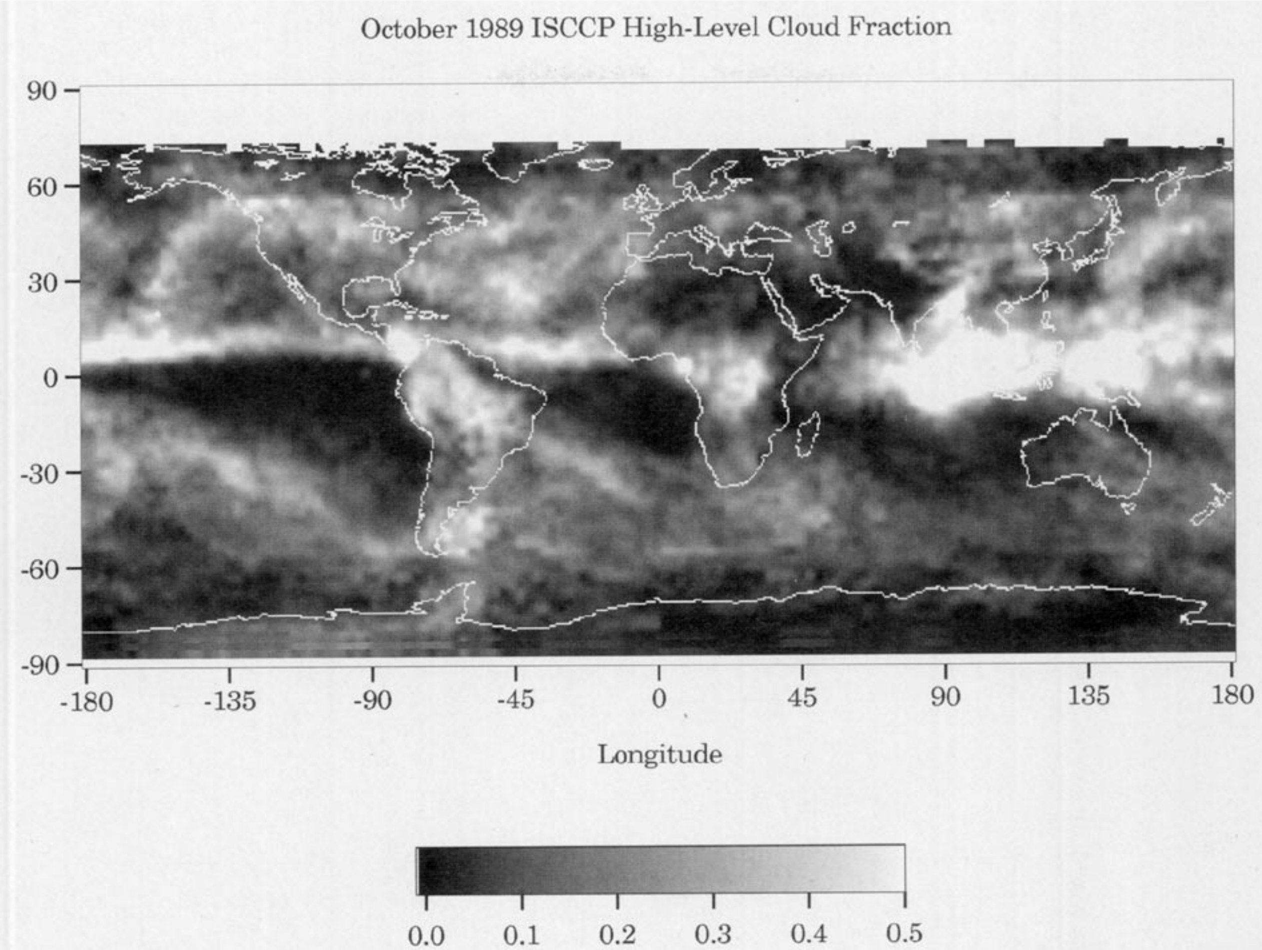

FIG. 5. (*Continued*)

gories by the values of P_c and ϵ reported from the CO_2-slicing analysis. This classification makes the assumptions 1) that each HIRS FOV is completely covered by a single cloud layer, so that the "effective" emissivity (the product of emissivity and cloud cover fraction) is taken to be the *actual* emissivity [Wylie et al. (1994) provide strong support for the validity of this assumption], and 2) that the visible optical thickness can be calculated from the infrared emissivity, using the same ratio of infrared to visible optical thickness as used by ISCCP:

$$\tau_{VIS} = 2\tau_{IR} = 2[-\ln(1 - \epsilon)], \qquad (1)$$

where the factor of two is an empirically derived relationship (Platt and Stephens 1980; Wylie et al. 1995). Minnis et al. (1993a) obtain a theoretical value of 2.13 for this factor for ice crystal clouds that appears successful in comparisons of satellite retrievals and lidar observations (Minnis et al. 1993b). However, the ISCCP retrieval of τ_{VIS} uses a liquid water droplet model that causes an overestimate. We return to this point in section 4. The emissivity ranges corresponding to the lowest three ISCCP optical thickness categories are 0.01–0.483, 0.483–0.837, and 0.837–0.991, and the last two categories correspond to emissivities = 1. The detection sensitivity of transmissive clouds increases with increasing cloud-top height (cf. Wielicki and Parker 1992). Practical consideration of the sensitivity of the HIRS analysis suggests a detection limit of $\epsilon \geqslant 0.1$ for clouds with $P_c < 700$ mb (Wylie et al. 1994), so the limit should be least $\epsilon \geqslant 0.05$ for clouds with $P_c \leqslant 440$ mb. For ISCCP, the detection sensitivity of ϵ is between 0.05 and 0.1 over ocean and between 0.1 and 0.2 over land for cloud with P_c between 440 mb and 200 mb (cf. Wielicki and Parker 1992; Rossow et al. 1993; Liao et al. 1995a).

HIRS cloud amounts are determined by counting the number of FOVs in each category divided by the total number (clear and cloudy). This may lead to a small overestimate of cloud amounts by HIRS relative to ISCCP because of the larger FOV size for HIRS (Wylie et al. 1994; Wylie and Menzel 1989; Menzel et al. 1992; cf. Wielicki and Parker 1992). Wylie et

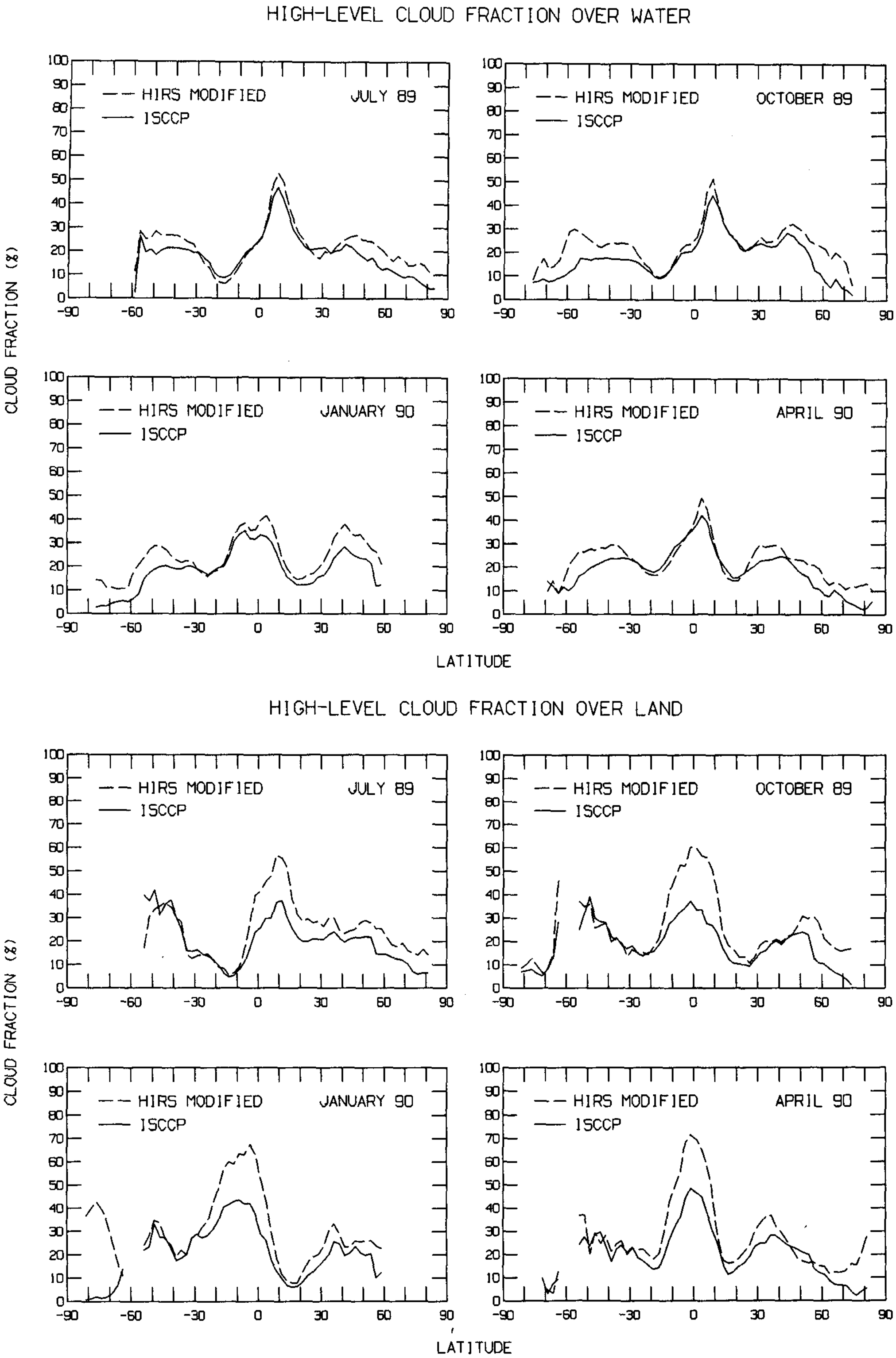

FIG. 6. Same as in Fig. 1 except that very thin ($\tau_{VIS} \leq 0.5$) clouds have been removed from the HIRS results (dashed lines).

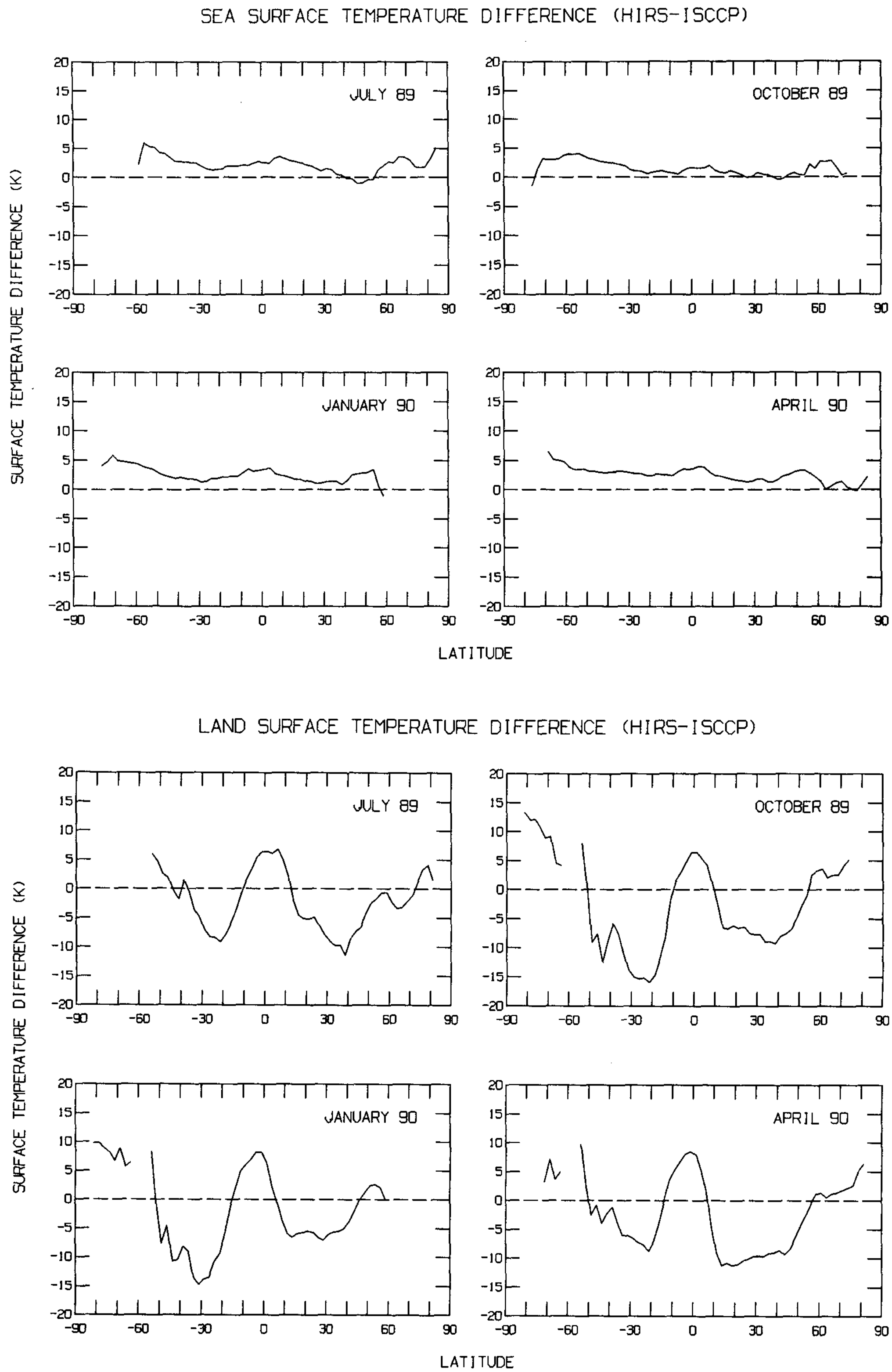

FIG. 7. Zonal monthly mean differences (HIRS–ISCCP) of surface temperatures over oceans and land for July and October 1989, and January and April 1990.

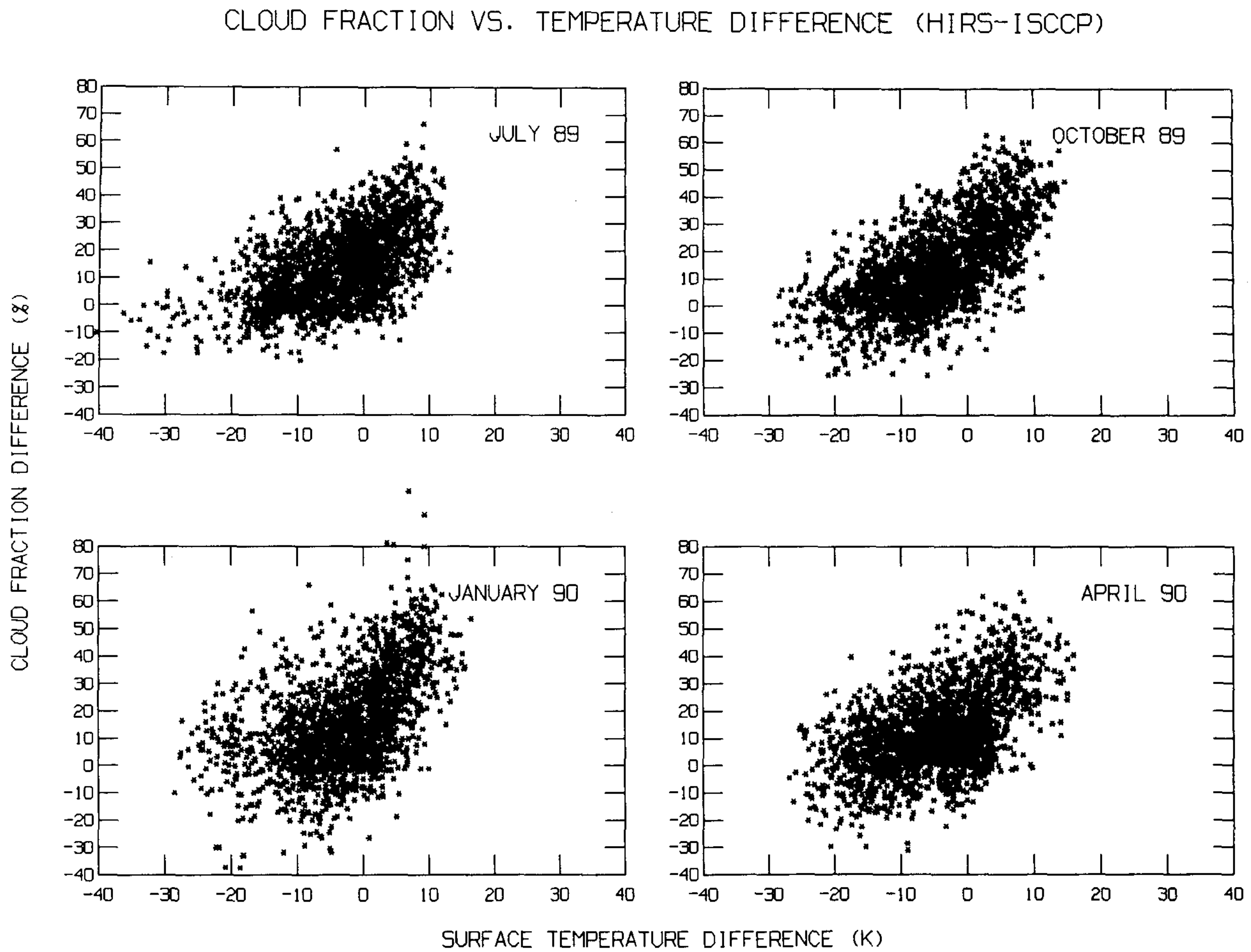

FIG. 8. Scatterplots of differences over land between individually matched map grid cell values from HIRS and ISCCP of monthly mean high-level cloud fraction against their surface temperature differences (HIRS–ISCCP) for July and October 1989, and January and April 1990. Results are restricted to "transmissive" clouds ($\tau_{VIS} < 9.4$) and to latitudes equatorward of 60°.

al. (1994) compared Advanced Very High Resolution Radiometer (AVHRR) 1-km resolution cloud cover determinations with HIRS values of cloud effective emissivity determined by assuming total cloud cover at 17-km resolution. (FOVs with cloud tops below 700 hPa are not included in the comparison because the CO_2-slicing algorithm is not used below this level.) They found that for HIRS effective emissivities > 0.50, almost all of the variation from one FOV to another is caused by changes of actual emissivity and not of subpixel cloud fraction; for effective emissivities < 0.50, most of the variation is still being caused by changes in cloud emissivity, but some is caused by changes in subpixel cloud fraction. For most synoptic regimes, especially in the Tropics and subtropics, most of the semitransparency for individual FOVs is due to cloud emissivities < 1 rather than partial cloud cover. Wielicki and Parker (1992) studied the general effects of sensor spatial resolution on the determination of cloud cover and also found that cirrus cloud amount exhibited little dependence on sensor spatial resolution up to 8 km. Menzel et al. (1992) estimated that a change of the observation area for the geostationary VAS [Visible–Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder] data from 10×10 km^2 to 10×30 km^2 (close to the HIRS FOV 17×17 km^2) increases total transmissive cloud amount by 0.05. Together, these results suggest an upper limit of a bias of HIRS high-level transmissive cloud amount ≈ 0.05.

All available HIRS results, up to four per day, are averaged to form daily mean global maps. The NCEP and NESDIS surface temperatures used in the HIRS analysis are also mapped and averaged. Finally, all individual daily mean maps from HIRS and ISCCP are compared to find all coincident and colocated observations. These matched daily results and their differences are then averaged to produce monthly mean values.

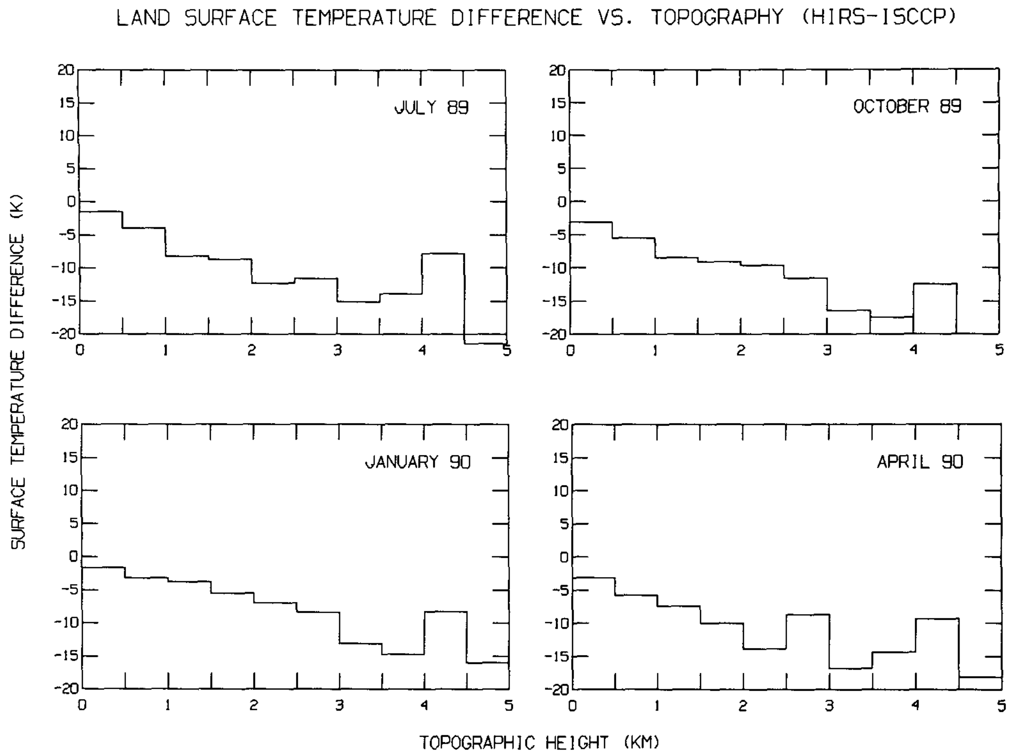

FIG. 9. Average land surface temperature differences between HIRS and ISCCP analyses as a function of topographic altitude in kilometers for July and October 1989, and January and April 1990. Regions poleward of 60° are excluded.

3. Comparison of high-level cloud distributions and variations

a. Global annual-mean statistics

To provide a context for discussing the high-level cloud results, we first give a brief survey of total, high ($P_c \leq 440$ mb), middle (440 mb $< P_c \leq 680$ mb), and low (680 mb $< P_c \leq 1000$ mb) cloud amounts obtained from HIRS and ISCCP (Table 2). All cloud amounts will be given as fractions from zero to one. Note that the cloud amounts shown in Table 2 differ somewhat from the published versions of these climatologies because they are averages only over 4 particular months, they exclude the polar regions, the ISCCP results are only for daytime, and the cloud amounts represent only the matched observations. Hence, these values should not be interpreted as proper estimates of the average cloud amounts; they are used only to assess differences between the two analyses.

For convenience, we will call "cirrus" all high-level clouds that are transmissive enough that they increase the net radiative heating of the earth, defined approximately by an infrared emissivity $\epsilon < 0.84$ (or visible optical thickness $\tau_{VIS} < 3.6$). We also define "thin cirrus" as high-level clouds with $\epsilon < 0.5$ (or $\tau_{VIS} < 1.3$). Since detection of polar clouds is more difficult (e.g., Rossow and Garder 1993b), the polar regions (60° to 90° in both hemispheres) are excluded in this section, but discussed in section 4c.

Over the oceans, the HIRS total cloud amount is 0.80, which is about 0.12 higher than the ISCCP value. Both climatologies indicate almost no seasonal variation of global means over the oceans (range about 0.01–0.02). Over land the HIRS total cloud amount is 0.65, which is about 0.14 higher than the ISCCP value. Both climatologies indicate larger seasonal variations of global means over land than over ocean with the maximum in April, but the amplitude of the ISCCP variations (0.07) is several times larger than that for HIRS (see section 4).

Middle-level and low-level cloud amounts are nearly the same in the two climatologies. HIRS reports about 0.19 middle-level clouds over the oceans and about 0.17 over land, while ISCCP reports about 0.17 over both oceans and land. Seasonal variations of middle-level clouds are about 0.02 in both climatologies, with better agreement in phase over oceans. ISCCP reports about 0.29 low-level cloudiness over ocean, about 0.05 more than HIRS reports. The ISCCP daytime cloud amounts are almost 0.10 larger because the visible radiance threshold detects low-level clouds missed by the IR threshold. Over oceans the HIRS IR radiance threshold is the same as that used by ISCCP, but the clear-

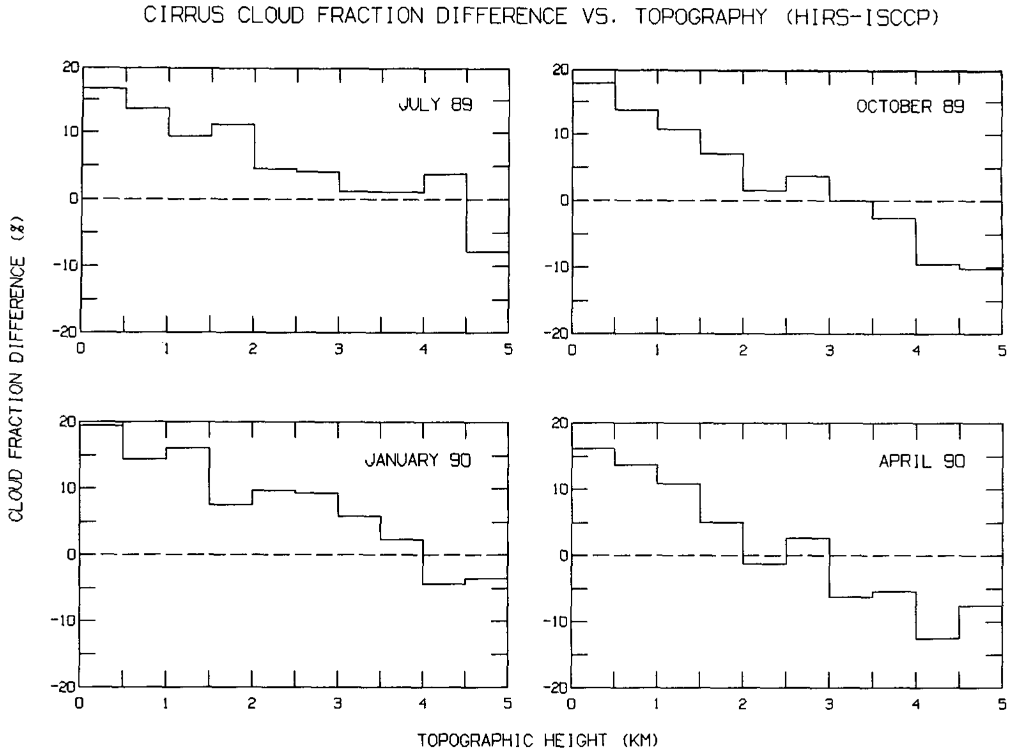

FIG. 10. Same as in Fig. 9 but for the average differences of cirrus cloud amounts between HIRS and ISCCP.

sky temperature is slightly larger (see section 4), so that HIRS amounts are closer to ISCCP amounts. Nevertheless, the difference in low-level cloud amounts over oceans appears to be consistent with the lower sensitivity of infrared instruments (cf. Wielicki and Coakley 1981; Wielicki and Parker 1992). Over land both climatologies report about 0.14 low-level cloudi-

TABLE 4. Globally averaged fraction of all HIRS data that change from cloudy to clear and from clear to cloudy when ISCCP clear radiances and the IR threshold are used in the first stage of the HIRS analysis. Results are from *NOAA-10* (morning satellite) and *NOAA-11* (afternoon satellite), separately and together, for July 1989 and January 1990 over ocean, land, and land and ocean combined.

	July 1989			January 1990		
	NOAA-10	NOAA-11	Both	NOAA-10	NOAA-11	Both
			Cloudy to clear			
Ocean	0.19	0.19	—	0.15	0.16	—
Land	0.28	0.16	—	0.36	0.20	—
Global	0.21	0.18	0.20	0.20	0.17	0.18
			Clear to cloudy			
Ocean	0.01	0.01	—	0.00	0.00	—
Land	0.00	0.04	—	0.00	0.04	—
Global	0.01	0.02	0.02	0.00	0.01	0.00
			Original HIRS clear			
Ocean	0.20	0.21	0.21	0.20	0.20	0.20
Land	0.28	0.40	0.34	0.20	0.40	0.30
Global	0.22	0.26	0.24	0.20	0.25	0.22

TABLE 5. Average amounts of thin cirrus ($\epsilon < 0.5$, $\tau_{VIS} < 1.3$) and all cirrus including thin ($\epsilon < 0.84$, $\tau_{VIS} < 3.6$) from ISCCP (differences with HIRS are indicated in parentheses) for July and October 1989, January and April 1990, and all 4 months together. Regions poleward of 60° latitude are excluded.

	July and October 1989	January and April 1990	"Annual"
		Thin cirrus	
Ocean	0.06 (+0.12)	0.07 (+0.12)	0.07 (+0.12)
Land	0.06 (+0.06)	0.07 (+0.06)	0.07 (+0.06)
Difference	0.00 (+0.06)	0.00 (+0.06)	0.00 (+0.06)
		All cirrus	
Ocean	0.09 (+0.19)	0.10 (+0.19)	0.09 (+0.19)
Land	0.09 (+0.14)	0.10 (+0.14)	0.09 (+0.14)
Difference	0.01 (+0.05)	−0.01 (+0.05)	0.00 (+0.05)
		Total high level	
Ocean	0.21 (+0.15)	0.22 (+0.15)	0.22 (+0.15)
Land	0.19 (+0.12)	0.23 (+0.12)	0.21 (+0.12)
Difference	0.02 (+0.03)	−0.01 (+0.03)	0.01 (+0.03)

TABLE 6. Spatial correlations of high-level clouds classified by optical thickness. The first two groups show results from HIRS and ISCCP for oceans, and the second two groups show the results for land. The first three columns show correlations with thinner to thicker cloud types. The cloud types are defined by the ranges of visible optical thicknesses given. The last column in the HIRS results shows the spatial correlations of differences between HIRS and ISCCP total high-level cloud amounts with each type of cloud in the HIRS dataset. All results use monthly mean distributions and are averages of results for the 4 months.

	Correlated with			
Target type	1.2–3.6	3.6–9.4	>9.4	HIRS–ISCCP
		HIRS ocean		
<1.2	0.31	0.09	0.27	0.66
<3.6	—	0.32	0.44	0.74
3.6–9.4	—	—	0.47	0.28
>9.4	—	—	—	0.30
		ISCCP ocean		
<1.2	0.55	0.39	0.14	—
<3.6	—	0.60	0.26	—
3.6–9.4	—	—	0.64	—
>9.4	—	—	—	—
		HIRS land		
<1.2	0.34	0.20	0.08	0.70
<3.6	—	0.39	0.28	0.79
3.6–9.4	—	—	0.34	0.38
>9.4	—	—	—	0.34
		ISCCP land		
<1.2	0.39	0.17	−0.08	—
<3.6	—	0.47	0.13	—
3.6–9.4	—	—	0.68	—
>9.4	—	—	—	—

ness, despite larger differences in the detection thresholds (the reasons for this result are discussed in more detail in section 4). Comparison of the ISCCP climatology with that from surface observations over land (Warren et al. 1986) suggests that ISCCP underestimates low cloud amounts by about 0.05, by almost 0.10 in winter (Rossow et al. 1993); hence, both these climatologies may underestimate low-level cloud amounts over land (aside from the effects of obscuration by upper-level clouds).

Table 2 shows that almost the entire difference in total mean cloud amounts between these two climatologies appears in the difference of high-level cloud amounts. Over oceans HIRS reports 0.36 mean high-level cloud amount compared to 0.22 for ISCCP, while over land HIRS reports 0.34 mean high-level cloud amount compared to 0.21 for ISCCP. Both climatologies indicate similar, small, seasonal cycles in global-mean high-level cloud amount of about 0.02 over oceans and about 0.04 over land, with similar phases (cf. Carlson et al. 1996, manuscript submitted to *J. Climate*). The difference of mean high-level cloud amounts is about 0.02 smaller over land than over oceans, but, overall, the differences of mean high-level cloud amounts are nearly the same over oceans and land in all seasons and at all latitudes.

Separating the high-level cloud category into thin cirrus and all other high-level clouds (Table 3) shows that the difference between HIRS and ISCCP high-level cloud amounts appears predominantly as a difference in thin cirrus cloud amounts. Over oceans HIRS reports roughly equal amounts of thin cirrus and denser high-level clouds, whereas ISCCP reports about half as much thin cirrus as denser high-level clouds. Consequently, HIRS has about 0.12 more thin cirrus than ISCCP, while the difference in the remaining high-level cloud amounts is only about 0.03. Over land HIRS has slightly more than half as much thin cirrus as denser high-level cloud, whereas ISCCP has slightly less than half as much. Consequently, HIRS has both more thin cirrus and denser high-level cloud than ISCCP by about 0.06.

Table 3 also shows that HIRS obtains 0.06 more thin cirrus over oceans than over land, whereas ISCCP reports about equal amounts of thin cirrus over oceans and land. The surface-based cloud climatology (Warren et al. 1986, 1988) indicates that there is more cirrus over land than over oceans, but there are different problems with observing cirrus at sea than on land, including different amounts of obscuration by lower-level cloudiness. Moreover, we cannot define what range of optical thickness is equivalent to what the surface observer calls cirrus. This question is considered in section 4.

b. Geographical distribution and seasonal variations

Plots (not shown) of zonal monthly mean middle-level and low-level cloud amounts show excellent quantitative agreement between the detailed geographic distributions of these types of cloud in the HIRS and ISCCP datasets, except that the ISCCP low-level cloud amounts are somewhat higher than the HIRS values over subtropical marine stratus regions. Since essentially all of the disagreement between these two datasets is represented by the differences in high-level cloud amounts, illustrated in the next several figures, the remainder of the discussion in this paper concentrates on high-level cloudiness.

Figure 1 shows the zonal monthly mean high-level cloud amounts from HIRS and ISCCP for all 4 months. (Since the HIRS data are matched with daytime ISCCP results, no results are shown for the unilluminated portions of the polar regions.) Over oceans both datasets show a maximum in high-level cloud amount near the equator, associated with the location of the ITCZ, and broad, secondary maxima in the midlatitudes, associated with the zones of cyclonic storms. Notably, the differences between HIRS and ISCCP cloud amounts

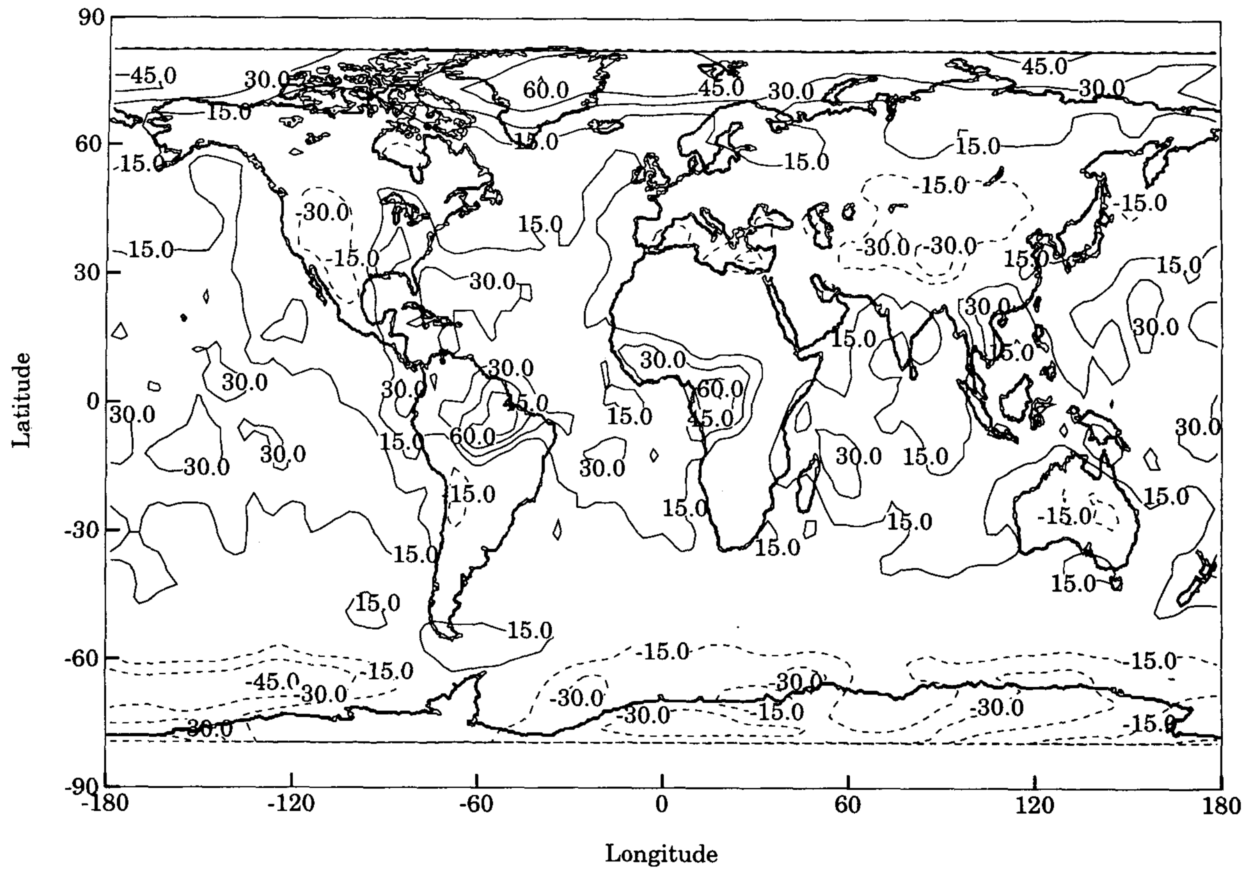

FIG. 11. Geographic distribution of changes in HIRS frequency of clear observations for July 1989, caused by substituting the ISCCP clear IR radiances and the threshold in the first step of the HIRS analysis. Positive values (solid lines) indicate changes from cloudy to clear, and negative values (dashed lines) indicate changes from clear to cloudy.

are roughly constant with latitude, except that the ITCZ feature in the HIRS results is more prominent. HIRS also has more high-level cloudiness than ISCCP at almost all latitudes over land, but the difference is much larger in the ITCZ (except for summertime Antarctica) and smaller in the midlatitudes. The same seasonal shifts of the maxima and minima appear in both the HIRS and ISCCP high-level cloud amounts over oceans and land.

Excluding the thin cirrus shows that the latitudinal distributions of the remaining high-level clouds from HIRS and ISCCP match even better (Fig. 2), with HIRS cloud amounts slightly larger than ISCCP amounts over the midlatitude oceans and over the ITCZ on land (the large difference over Antarctica is discussed in section 4c). Seasonal variations are very similar to those of the total high-level cloud amount in both datasets. Thus, almost all of the difference between HIRS and ISCCP high-level cloud amounts is concentrated in the thin cirrus category. Figure 3 shows the zonal monthly mean distributions of thin cirrus over oceans and land. Over oceans HIRS amounts of thin cirrus are larger than those of ISCCP by about 0.08 in the midlatitudes and by more than 0.20 in the Tropics. In contrast, HIRS thin cirrus amounts over land are similar to ISCCP values in the midlatitudes but larger by about 0.15 in the Tropics. Seasonal variations of thin cirrus are small in both datasets; however, both agree that there is more thin cirrus in the January–April half of the year than in the July–October half over both oceans and land (Table 3). Both datasets also agree that the pattern of seasonal variations of thin cirrus mirror those of the remaining high-level clouds (Table 3).

Comparison of the detailed geographic patterns and seasonal changes of high-level cloud amounts from HIRS with those of ISCCP shows the same behavior as illustrated in Figs. 1, 2, and 3—namely, excellent agreement of the *pattern* of variation with an offset in magnitude that is roughly constant with location (somewhat larger in the Tropics than in the midlatitudes, more so over land than over oceans). Correlations of monthly mean maps range from 0.79 to 0.86 over oceans and from 0.66 to 0.79 over land, giving an average correlation of 0.81. Figure 4 shows scatterplots of high-level cloud amounts for individually matched map grid cells over oceans and land (excluding the

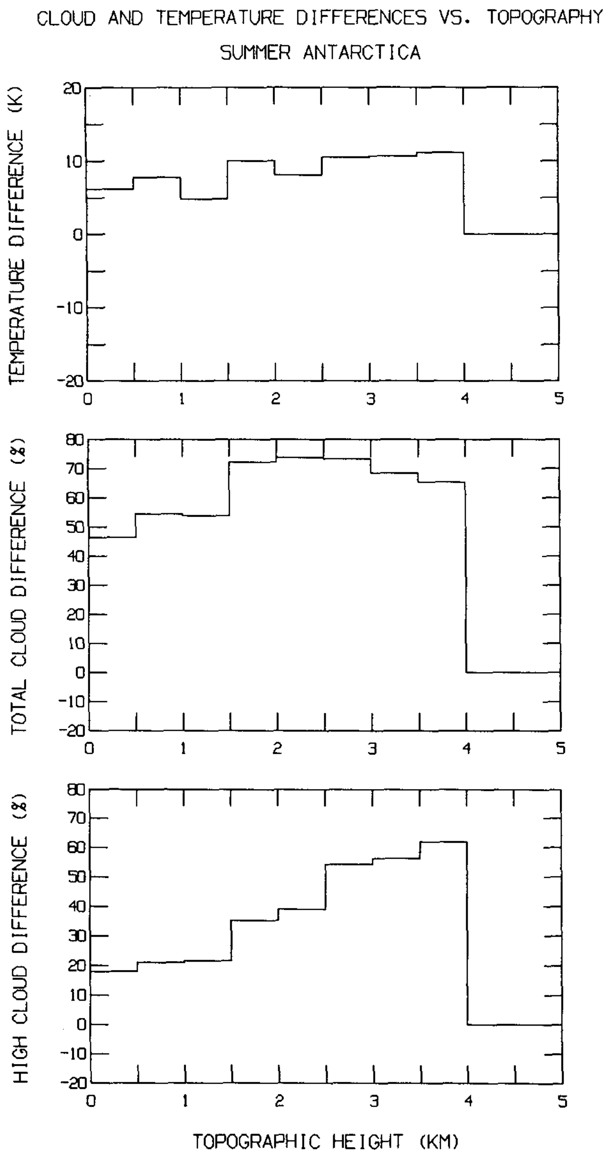

FIG. 12. Average differences in surface temperature (upper panel), total cloud amount (middle panel), and high-level cloud amount (lower panel) between HIRS and ISCCP results for Antarctica in January 1990, as a function of topographic height in kilometers.

polar regions) for each of the 4 months. Linear least squares fits to each of these plots have slopes from 1.04 to 1.20, offsets from 0.07 to 0.13, and rms differences from 0.08 to 0.16. The rms differences are smaller by about 0.05 over oceans, but the mean difference is smaller by about 0.02 over land.

To illustrate the detailed agreement in geographical distributions, Fig. 5 shows an example of the monthly mean high-level cloud amounts from HIRS and ISCCP (for October 1989). The same gray scale is applied to a slightly different range of values to enhance visual similarity. There are three tropical maxima: central Africa, Brazil, and the largest feature, extending from the central Indian Ocean to the western Pacific. There are four extensive minima at subtropical latitudes: from southern Africa to the subtropical South Atlantic, from Chile into the subtropical eastern Pacific, from the subtropical south Indian Ocean into Australia, and from North Africa to northern India. The HIRS maxima and minima are both larger in magnitude than the ISCCP maxima and minima, making the spatial contrasts slightly larger in the ISCCP results. Another notable detail that appears in both results is the set of subtropical jet streams marked by somewhat larger high-level cloud amounts. In the Northern Hemisphere, there are four features, extending from the Bay of Bengal into northern China, from near Papua New Guinea into the central North Pacific, from the central equatorial Pacific into western Canada, and from the equatorial Atlantic into Spain. In the Southern Hemisphere there are only two well-developed features, extending from the equatorial western Pacific to the southern tip of South America and from Brazil to south of Africa. Both datasets show a general decline of high-level cloud amounts toward the poles, but this decline is more extreme in the ISCCP results.

4. Reasons for differences

The discussion in section 3 shows that, although the HIRS high-level cloud amounts are larger than the ISCCP values, the geographical and seasonal patterns of variation in these two climatologies are very well correlated. This suggests some systematic difference in the two analysis schemes. However, we also noted that the agreement is poorer over land than over oceans and in the polar regions, which suggests that other factors can also contribute to the differences in detected high-level cloud amounts. In this section we present results from investigations of possible causes for both the systematic and specific regional differences.

a. Differences in sensitivity to thin cirrus clouds

Table 3 shows that most of the difference between HIRS and ISCCP high-level cloud amounts occurs in the thin cirrus ($\epsilon < 0.5$, $\tau_{VIS} < 1.3$) category, especially over oceans. Since the multiwavelength CO_2-slicing analysis of HIRS can infer cloud-top pressures independently of the transmissivity of the cloud, this technique can detect very thin cirrus clouds that might be missed or confused with some broken low-level clouds by other techniques (Wylie and Menzel 1989). In particular, a threshold method like that used by ISCCP cannot reliably detect the thinnest cirrus because they do not produce large enough changes of the observed infrared and/or visible radiances from the clear-sky values. Wielicki and Parker (1992) show that for very thin high-level clouds, the IR threshold determines the detection sensitivity. Over oceans, where the IR thresh-

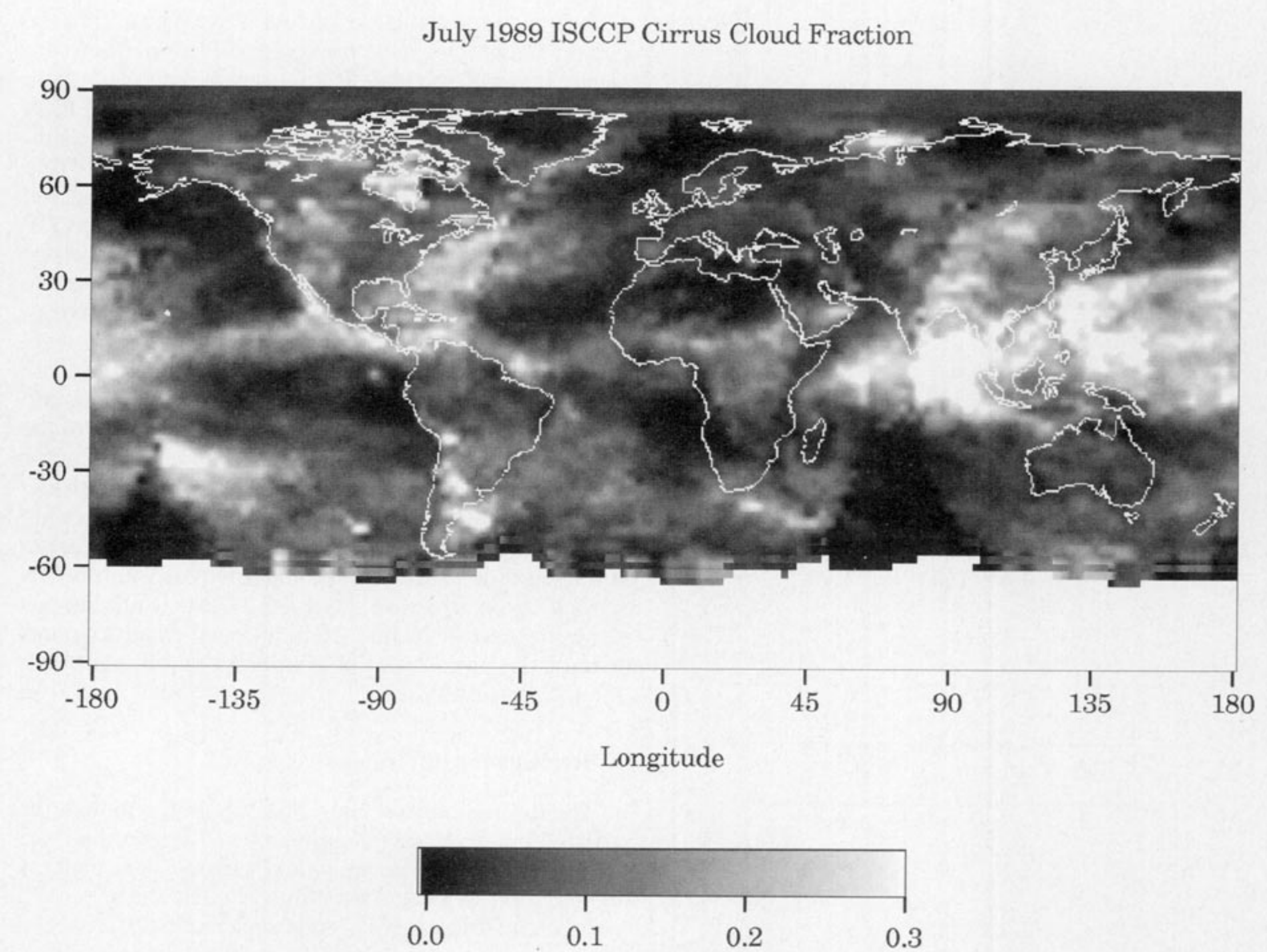

FIG. 13. Geographic distribution of monthly mean fraction of cirrus and cirrostratus clouds ($P_c \leqslant 440$ mb, $\tau_{VIS} < 9.4$) from ISCCP for July and October 1989, and January and April 1990 (cf. Fig. 5). Gray scale is applied to a range of cloud amounts from 0 to 0.3.

old used by ISCCP is smallest, the minimum value of τ_{VIS} that can be detected for high-level clouds is estimated to be 0.1–0.2 (Rossow et al. 1993; Liao et al. 1995a), equivalent to $\epsilon \approx 0.05$–0.1. Over land, the ISCCP cutoff is estimated to be about $\tau_{VIS} \approx 0.2$–0.4 ($\epsilon \approx 0.1$–0.2). In the HIRS analysis, some channels see infrared emission primarily from the atmosphere, rather than from the surface, so that the wavelength dependence of high-level cloud emission allows for identification of thinner cirrus ($\epsilon \approx 0.05$). Thus, we expect the HIRS analysis to be more sensitive to the presence of thin cirrus than the ISCCP analysis, especially over land. A comparison of ISCCP with the more sensitive SAGE II measurements suggests that about 0.10 very thin cirrus exist in the upper troposphere (Liao et al. 1995) that are below the detection limit for ISCCP. Thus, a difference in the sensitivities of the HIRS and ISCCP analyses should also produce a systematic difference in high-level cloud amount between these two datasets.

To illustrate the possibility that the differences in high-level cloud amounts are produced by differences in thin cirrus detection sensitivity, the optically thinnest high-level clouds ($\epsilon < 0.22$, $\tau_{VIS} < 0.5$) are removed from the HIRS results. Figure 6 compares the zonal monthly-mean *total* high-level cloud amounts from the reprocessed HIRS with ISCCP over oceans and land. Over oceans most of the differences between these two datasets disappear (cf. Fig. 1), with zonal-mean differences of *thin* cirrus reduced to $\leqslant 0.02$; a slight increase in the cutoff value of τ_{VIS} would improve the match still further. The remaining differences of thicker cloud amounts in midlatitude regions may be caused by ISCCP values of SST being too low (Rossow and Garder 1993b). The larger sensitivity of the HIRS results over oceans may seem surprising, given that the infrared detection threshold used in the HIRS analysis is the same as the ISCCP threshold. However, as discussed in section 4b, the ocean surface temperatures used in the HIRS analysis are also 1–2 K larger than

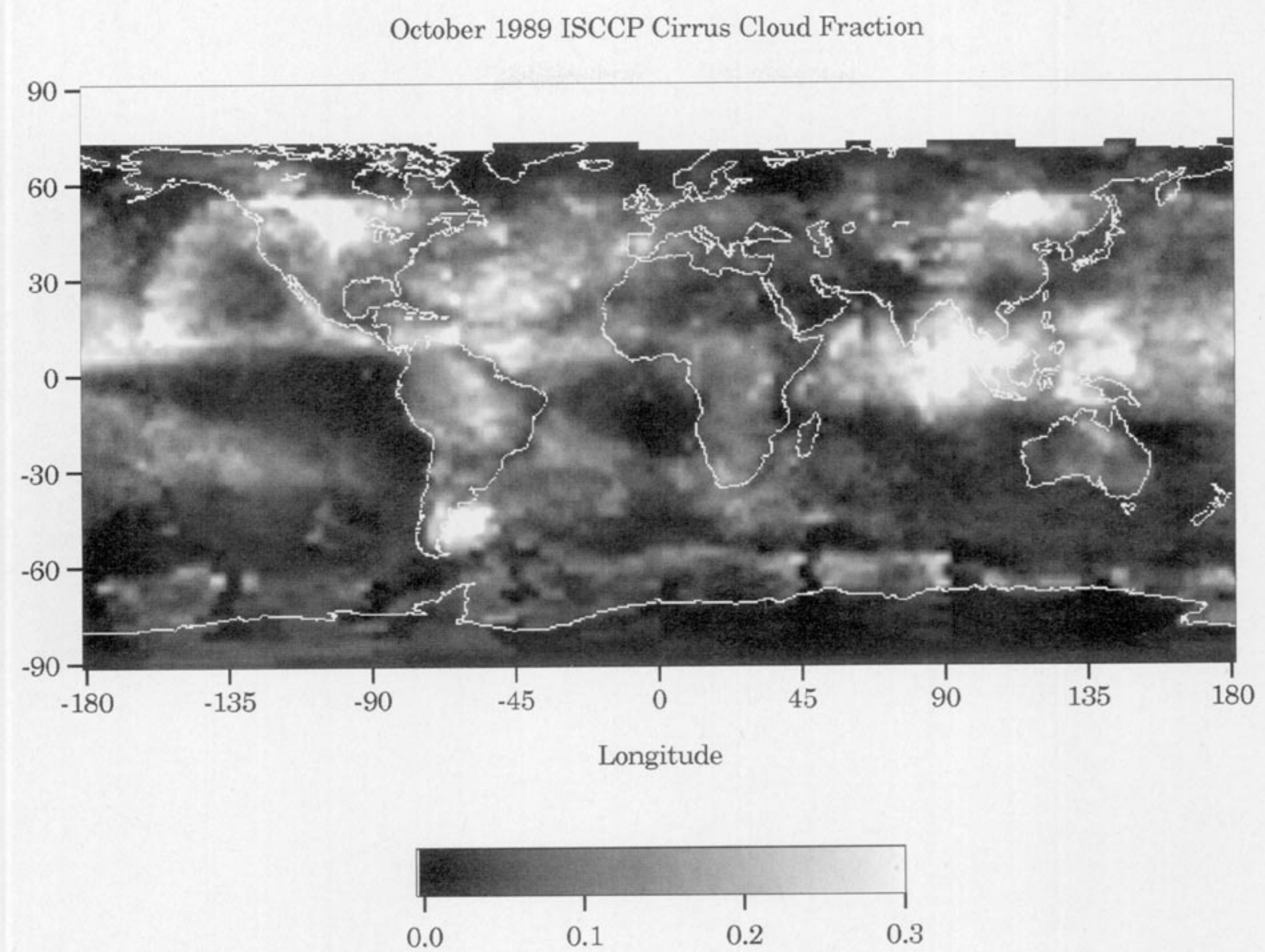

FIG. 13. (*Continued*)

those used in the ISCCP analysis, but the latter appear to be more accurate by comparison with other measurements. Consequently, the effective temperature threshold used by HIRS may be $\leqslant$1 K, which can increase the sensitivity of the detections in the first step of the HIRS analysis.

Over land, the differences between HIRS and ISCCP have also been reduced, especially in the midlatitudes, and the differences in the remaining mean *thin* cirrus (τ_{vis} < 1.3) are $\leqslant$0.01; however, the HIRS cloud amounts for the denser clouds (τ_{vis} > 1.3) are still much larger than the ISCCP values in the Tropics. Hence, we conclude that, while differences in detection sensitivities can explain most of the 0.12 difference between HIRS and ISCCP high-level cloud amounts over oceans, they can only explain 0.06 of the difference over land. It will be shown in section 4b that the remaining difference over land is explained by the larger detection threshold used in the ISCCP analysis, offset by larger surface temperature differences in the two analyses. Note that in a new version of the ISCCP analysis, the IR detection threshold over land has been decreased to 4 K (cf. Rossow and Garder 1993b), which increases the ISCCP high-level cloud amount by approximately 0.03.

The quantitative comparison of HIRS and ISCCP is also affected in a small way by a systematic bias of the ISCCP optical thickness values for high-level clouds, produced by using liquid water spheres with an effective radius of 10 μm in the retrieval model when these clouds are presumably composed of larger ice crystals (Minnis et al. 1993b). The effect is an overestimate of ice cloud optical thicknesses, which reduces the amount of thin cirrus and produces an underestimate of cloud-top heights, which reduces total high-level cloud amount. A new version of the ISCCP datasets is now being produced that retrieves optical thickness values for cold-topped clouds (temperature < 260 K) using a scheme based on the results of Minnis et al. (1993a). Comparison of 1 year (July 1990–June 1991) of the new version of ISCCP with the old version shows an increase in high-level cloud amounts by ~0.02 because of the smaller optical thickness values. Moreover, there is also a shift of clouds from the thicker into the thinner cirrus category. Both of these

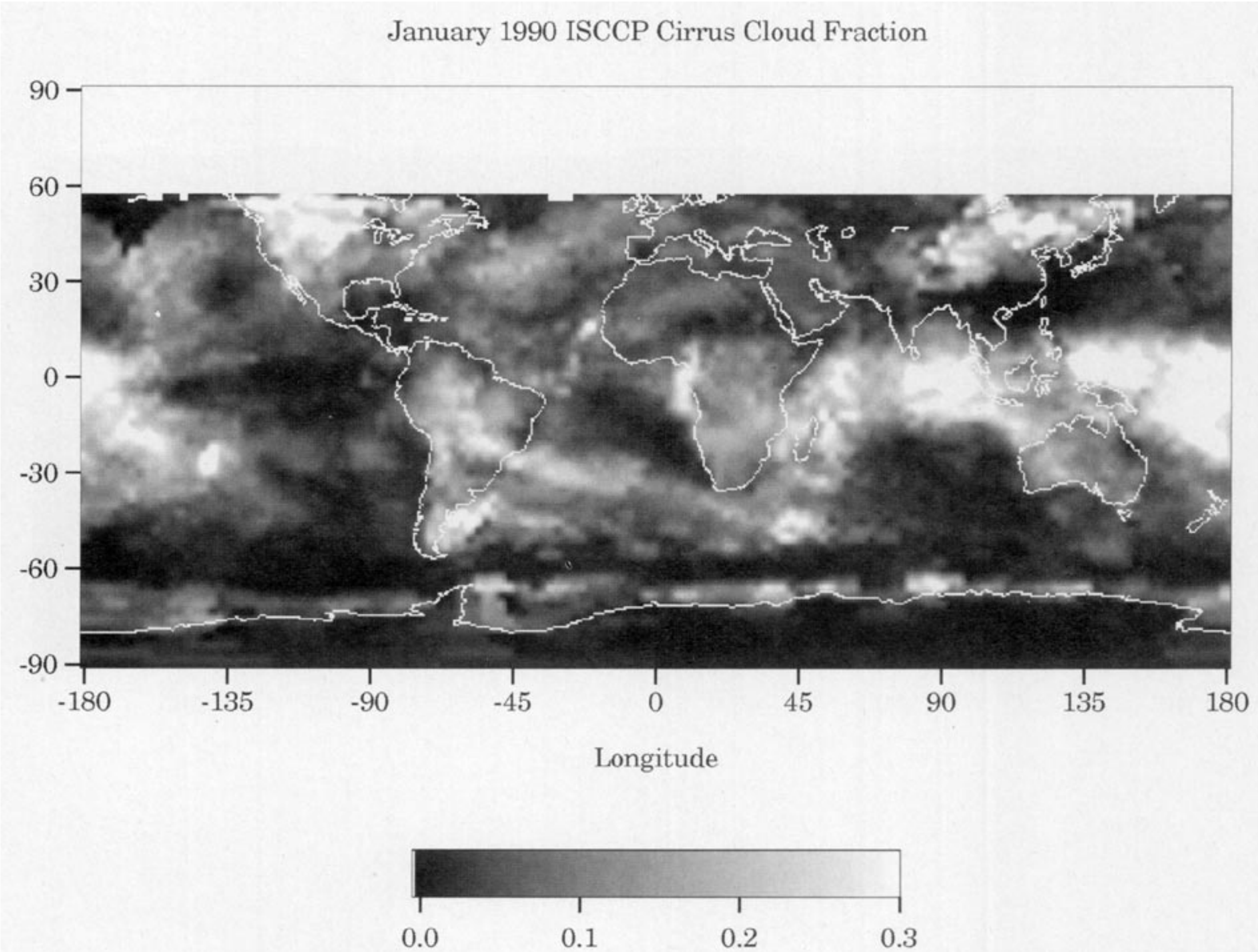

FIG. 13. (*Continued*)

changes improve the agreement of ISCCP with HIRS thin cirrus and high-level cloud amounts.

b. *Differences in surface temperatures*

The accuracy of both the HIRS and ISCCP cloud detection procedures relies on the accuracy of the estimates of clear-sky radiances, and hence, some of the differences in cloud amount (especially thicker clouds) may be caused by differences in the clear-sky radiances. The HIRS cloud detection procedure compares satellite radiances, measured at 11.1 μm and corrected for atmospheric absorption (equivalent to the retrieval of a surface brightness temperature), with surface temperatures specified by the NOAA/NESDIS SST retrievals over oceans and by the NCEP meteorological analyses over land. The NOAA/NESDIS SSTs are retrieved from AVHRR radiances with an empirical procedure that is tuned to agree with bulk temperatures of the ocean mixed layer measured by ships and buoys (McClain et al. 1985; Walton 1988), whereas the NCEP temperatures are based on observations of, and represent the temperature of, the near-surface air without consideration of diurnal variations. Both of these quantities can differ significantly from the surface "skin" temperature that the satellite radiometers sense, particularly over land near local noon (cf. Rossow and Garder 1993b), so there may be systematic errors that affect HIRS cloud detection. In contrast, the ISCCP cloud detection procedure estimates clear infrared ($\sim$11 μm) and visible ($\sim$0.6 μm) top-of-atmosphere radiances from among the measured values over a variety of space and time domains. Although there are also some sources of error in the ISCCP values (particularly cloud contamination), using directly observed infrared radiances avoids the systematic difference between surface skin temperatures and either bulk ocean temperatures or near-surface air temperatures and also avoids any error introduced by correcting for atmospheric effects. We examine the possibility of systematic differences in HIRS and ISCCP cloud amounts caused by systematic differences in clear-sky radiances first by comparing the surface temperatures used in the HIRS analysis with the surface brightness temperatures

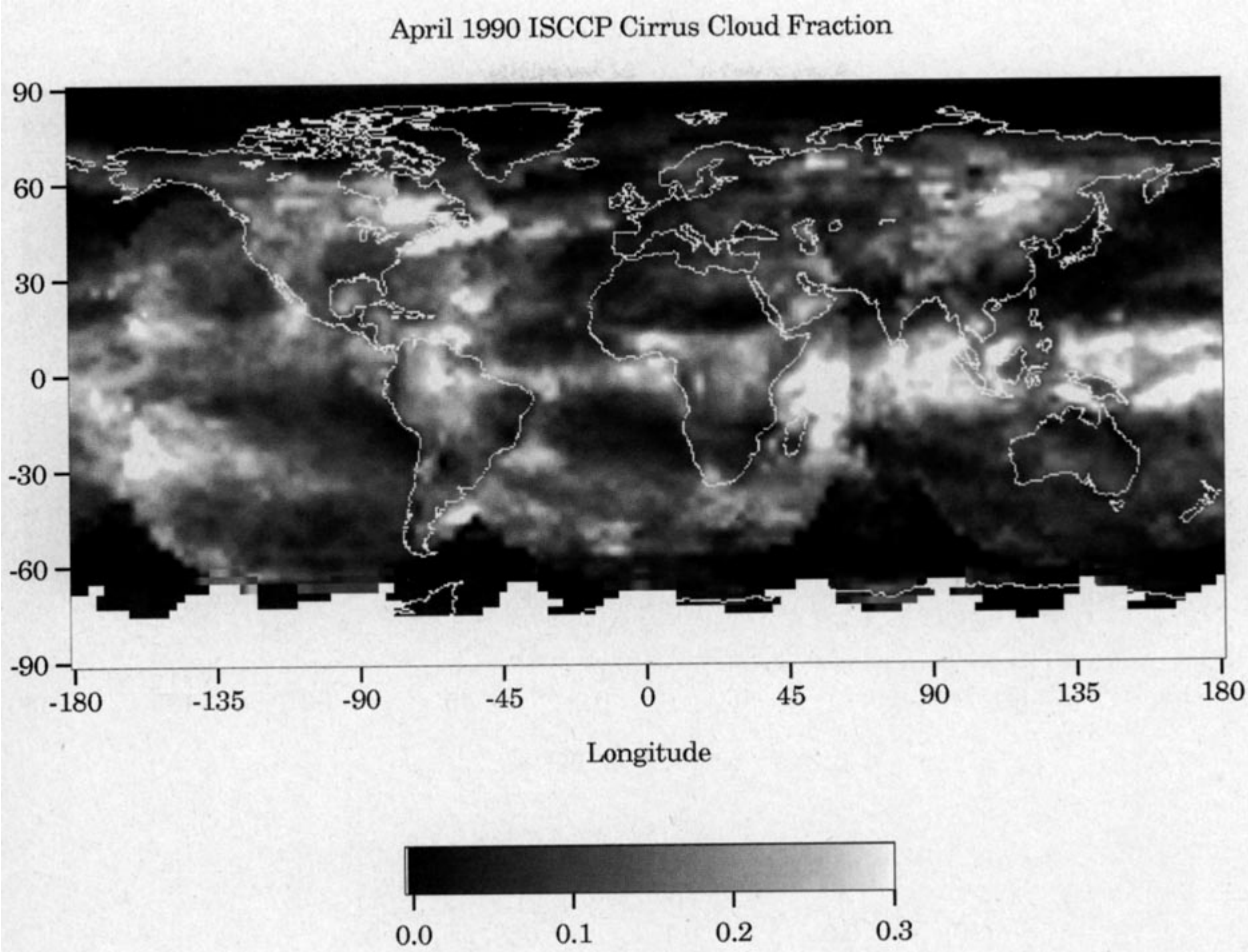

FIG. 13. (*Continued*)

(emissivity is assumed to be unity) retrieved from the clear radiances in the ISCCP analysis.

Figure 7 shows latitudinal distributions of the surface temperature differences (HIRS–ISCCP) over oceans and over land. Over oceans upper HIRS has larger surface temperatures than ISCCP by about 2 K at low latitudes and by almost 5 K at high latitudes; the difference is reduced by about 1 K if the correct emissivity for water is used in the ISCCP retrieval. Comparison of the ISCCP SSTs with the blended analysis, which adjusts the NOAA/NESDIS satellite values with ship observations (Reynolds 1988), shows that the ISCCP values are larger by about 1 K near the equator but smaller by about 3–4 K at higher latitudes (Rossow and Garder 1993b). When the surface emissivity is corrected, the tropical difference between the ISCCP and the blended SST increases by 0.5 K and the higher latitude differences decrease by almost 1 K. The colder ISCCP values at high latitudes appear to be caused, in part, by persistent cloud contamination at these latitudes; however, some of the difference can be caused by the effects of the sea ice boundary condition on the blended analysis (cf. Reynolds and Marsico 1993). All of these comparisons together imply that the unadjusted NOAA/NESDIS SST values used in the HIRS analysis are about 2 K warmer than the blended satellite ship values, which is within the range of uncertainty in the calibration of the AVHRR radiances used in the NOAA/NESDIS analysis. For example, a comparison of six different SST datasets shows that the NOAA/NESDIS analysis was about 0.5–1.0 K colder than the blended analysis in 1982–84 because of the effects of the El Chichón volcanic aerosol (Folland et al. 1993). In the HIRS analysis this high bias of the SSTs just makes the HIRS cloud detections more sensitive to high-level thin clouds because any false detections are eliminated later by the CO_2-slicing analysis in the second step (this second step may discard some low-level clouds, however). Thus, the small bias of temperatures over the oceans works to increase the sensitivity of the HIRS method relative to the ISCCP method, even though the detection thresholds have the same value in both methods.

FIG. 14. Same as in Fig. 13 except that the ISCCP cloud amounts have been averaged over July, October, January, and April for 8 years (1983–91). The gray scale and range are the same as in Fig. 13.

Figure 7 shows that the situation is more complex over land: the HIRS near-surface air temperatures are generally 5–15 K smaller than the average *daytime* ISCCP surface skin temperatures, except in the ITCZ and in the polar regions where HIRS values are larger. Correcting for lower land emissivities increases the ISCCP temperatures by another 2–6 K, which can account for the HIRS–ISCCP differences in the Tropics (dense vegetation and large surface moisture make the surface emissivity generally larger over tropical land areas) but makes the differences at higher latitudes even worse. The smaller positive differences in the ITCZ may also indicate some cloud contamination of the ISCCP values, since cloudiness is very persistent (the polar regions are discussed separately). The large negative differences are consistent with the differences between the skin and near-surface air temperatures (cf. Rossow and Garder 1993b), particularly during the daytime and over arid land. Note also that the magnitude of the differences varies with latitude, being larger (smaller) in zones where cloud amount is smaller (larger); the reduction of surface solar insolation by clouds reduces the difference between the skin and air temperature in just this manner (see Rossow and Garder 1993b, their Fig. 7). The effect of these temperature biases on the HIRS results are complicated by the lack of a diurnal variation in the NCEP values, producing a bias that varies not only with time of day but also with longitude and season. The effect on the published HIRS results is reduced somewhat by discarding results over land from the 0730 LST orbits of *NOAA-10* and the 0230 LST orbits of *NOAA-11* (Wylie et al. 1994), but the effect of these large surface temperature differences on the matched results may explain the poorer agreement in the pattern of high cloud amounts over land.

A surface temperature bias affects the HIRS high-level cloud amounts differently depending on its sign. If the HIRS surface temperature is too low, the cloud detection procedure will miss some clouds, but these would be high-level clouds only if they are optically thin enough to appear as relatively warm clouds. If the HIRS surface temperature is too high, the CO_2-slicing

FIG. 14. (*Continued*)

procedure will eliminate the false detections but will retrieve cloud-top pressures that are too low (Menzel et al. 1992), which would increase the high-level cloud amount. In the ISCCP analysis, a low bias in the surface temperature will cause a loss of optically thin high-level clouds (since the visible channel still detects optically thicker low-level clouds) as well as an overestimate of cloud-top pressures for optically thin clouds, both of which reduce the high-level cloud amount. A high surface temperature bias causes some false detections that will be interpreted as high, optically thin clouds because the visible radiances do not detect any significant increase in reflectivity. Figure 8 confirms these effects of surface temperature differences in the HIRS and ISCCP results by showing the variations of the differences in high-level transmissive ($\tau_{VIS} < 9.4$, $\epsilon < 0.99$) cloud amounts with the differences in surface temperature (polar regions excluded). When the HIRS temperatures are larger than the ISCCP values, then the HIRS cloud amounts tend to be relatively larger; when the HIRS temperatures are smaller than the ISCCP values, then the HIRS cloud amounts are relatively smaller. Because of the overall higher sensitivity of the HIRS results, the ISCCP high-level cloud amounts do not exceed the HIRS cloud amounts unless the ISCCP surface temperatures are more than about 15 K larger than the HIRS values.

Aside from some desert locations, such large differences in surface temperatures occur preferentially in high topography, as shown in Fig. 9. This effect arises as a combination of the relatively crude representation of topography in the NCEP atmospheric model and the predominance of data input from low-altitude stations (cf. Giorgi et al. 1993). Moreover, at higher altitudes, the differences between the skin and near-surface air temperature increase because the infrared opacity of the atmosphere is much lower at lower pressure (higher altitude), which decreases the exchange of radiative energy between the surface and air that maintains a relation between the skin and air temperatures. Figure 10 shows the corresponding comparison of the HIRS and ISCCP amounts of high-level transmissive clouds: the ISCCP amounts exceed those of HIRS for topography higher than about 3 km. Indeed, this effect ex-

FIG. 14. (*Continued*)

plains the fact that when maps like Fig. 5 of high-level cloud amounts from HIRS and ISCCP are differenced, almost the only locations where the ISCCP cloud amounts exceed the HIRS amounts are over the major mountainous areas of the Himalayas, the Rockies, and the Andes.

The effect of clear radiance differences on high-level cloud amounts from the HIRS and ISCCP analyses is tested by reanalyzing 2 months (July 1989 and January 1990) of the HIRS data using the clear-sky radiances derived by ISCCP for each individual HIRS pixel (same time and location). Only the cloud detection step in the HIRS analysis was redone and the thresholds used were the same as those used by ISCCP—2.5 K over oceans and 6.0 K over land. Table 4 shows the changes in the HIRS cloud detections using the ISCCP clear radiances and cloud detection thresholds. About 0.18–0.21 of all the HIRS data originally classified as cloudy are changed to clear, but only 0.04–0.06 of these were originally classified as high-level clouds, notably all as thin cirrus. This illustrates part of the difference in detection sensitivity between HIRS and ISCCP. The sensitivity of the HIRS total cloud amounts over oceans to a very small change (<3 K) in the clear radiances is shown by the large fraction of the data changed to clear when using the lower ISCCP clear-sky radiances. Almost all of these cases are low clouds, however. A similar change over land is caused by use of the larger ISCCP threshold and is exaggerated for *NOAA-10* because the ISCCP and NCEP temperatures are closer in value at the times of day at which *NOAA-10* observes (cf. discussion in Rossow and Garder 1993b). These results show the advantage of the strict test for cloudiness in the HIRS analysis method: this strict test may overdetect cloudiness at first, but the second analysis step can eliminate most false detections using radiances that are relatively insensitive to the surface temperature (Wylie et al. 1994).

Overall, very few HIRS data classified as clear are reclassified as cloudy, but almost all of these are in the *NOAA-11* land dataset, which observes at times of day when the different diurnal cycles of the skin and air temperatures produce larger differences between the ISCCP and NCEP temperatures. Moreover, the 0.04

FIG. 14. (*Continued*)

population that changed from clear to cloudy over land occurs almost entirely over mountainous regions (Fig. 11). Thus, we conclude that the more complicated differences between HIRS and ISCCP over land arise from the additional differences in clear-sky radiances there. The ISCCP surface temperatures appear to capture diurnal and topographic variations better than the NCEP temperatures used in the HIRS analysis (cf. Rossow and Garder 1993b). These results suggest that the HIRS results underestimate the amount of high-level cloudiness, particularly the cirrus, over land. The same conclusion is supported by the disagreement of the HIRS and surface cloud climatologies on the land/ocean ratio of cirrus. The HIRS results implied more ocean than land cirrus, whereas the surface observations suggest more cirrus over land than ocean. Our test results suggest that a revised HIRS analysis using better surface temperature information would also find more cirrus over land than over oceans. The new ISCCP climatology is derived using a lower infrared detection threshold over land (4 K instead of 6 K), increasing the amount of high-level transmissive cloudiness relative to ocean areas in better agreement with the surface observations.

c. Polar regions

Comparison of the two climatologies in the polar regions has been neglected so far because the results are more difficult to interpret. Other comparisons of cloud climatologies have usually found some of the largest disagreements in polar regions (e.g., Rossow et al. 1993), and this is no exception. Figure 1 shows the daytime comparisons for high-level clouds only, and the only large disagreement is over Antarctica in summer (January 1990). In the Arctic the high-level cloud amounts from HIRS and ISCCP differ by about 0.10–0.15, similar to lower latitudes, suggesting the presence in the Arctic of similar amounts of very thin cirrus. However, the HIRS *total* cloud amount is much larger than the ISCCP amount (not shown), primarily in summertime. Comparison of ISCCP total cloud amounts for the summertime Arctic with surface observations (Rossow et al. 1993) also showed a significant low bias, caused mostly by missed low-level clouds. We note that the HIRS amounts in summer are 0.10–0.20 larger than surface-based estimates (Curry and Ebert 1992; Hahn et al. 1995).

The only large difference between HIRS and ISCCP high-level cloud amounts, about 0.40, occurs over Antarctica in summertime (Fig. 1) and is part of an even larger difference (>0.6) of total cloud amount (Fig. 12). The HIRS total cloud amount is 0.10 less than the ISCCP total amount in wintertime (not shown). To understand these differences, we compared the monthly mean clear-sky radiances from HIRS and ISCCP with monthly mean surface temperatures reported from 31 stations, 21 on the coast or at low elevation and 10 inland at elevations >1000 m (Keller et al. 1990, 1991; cf. Sanson 1989). It should be noted that at latitudes higher than 70°, the HIRS analysis procedure includes an extra test over high topography. 1) If the 13.3-μm channel radiance is greater than the 11.1-μm radiance, then a temperature inversion is assumed to be present, the location is labeled clear, the observed 11.1-μm radiance replaces the NESDIS surface temperature, and the regular threshold test is not performed; 2) if the two radiances are equal to within 1 K, the location is labeled cloudy and the regular threshold test is not performed; and 3) if the 13.3-μm radiance is colder than the 11.1-μm radiance by more than 1 K then the regular threshold test is performed (Wylie et al. 1994). We compare the resulting HIRS clear radiances and the ISCCP surface temperatures to the surface observations.

In January 1990 (summertime), we find that both the HIRS and ISCCP clear radiances are in fairly good agreement with the surface measurements (atmospheric effects are assumed to be <1 K and surface emissivities are assumed to be near unity for snow and ice covered surfaces). HIRS temperatures are about 2 K smaller (4 K rms) at low elevations (<1000 m) and about 8 K larger (9 K rms) at high elevations (>1000 m), whereas the ISCCP values are about 2 K larger (3 K rms) at low elevations and about 5 K larger (10 K rms) at high elevations. When all locations are included, the HIRS surface temperatures are 5–7 K larger than the ISCCP values, with a weak dependence on elevation (Fig. 12). The generally warmer HIRS temperatures imply that the first thresholding step will overdetect clouds but the second CO_2-slicing step will eliminate many of the false detections. This increased sensitivity of the HIRS analysis is reinforced by the much smaller temperature threshold used in the HIRS analysis as compared with the ISCCP analysis over Antarctica, 2.5 K versus 8 K (Table 1, see Rossow and Garder 1993a). In the experiment where ISCCP clear radiances and thresholds replaced HIRS values in the first step, about 0.60 of HIRS clouds in summertime changed to clear—almost the entire difference in total cloud amount. Thus, most of the underestimate of summertime cloudiness in the ISCCP results over Antarctica arises from the very large detection threshold used (slightly offset by an overestimate of surface temperature).

In July 1989 (wintertime) the ISCCP results appear to overestimate surface temperatures by about 10 K compared with surface observations (7 K at low elevations and 15 K at high elevations), which nearly eliminates the effects of the large detection threshold. However, there may be even more clouds present with no temperature contrast or even reversed temperature contrast (see discussion in Raschke et al. 1992; Rossow and Garder 1993b). Thus, the ISCCP cloud amounts have to be a lower limit. Yet the ''inversion'' procedure of HIRS detects 0.10 less cloud than ISCCP, which may be reflected in a HIRS underestimate by about 8 K of surface temperature compared with surface observations (10 K at low elevations but only 3 K at high elevations). An associated cold bias of HIRS surface temperatures over the oceans near Antarctica appears to cause a systematic underestimate of total cloud amount there by as much as 0.20.

These differences are interpreted as suggesting the presence of even larger amounts of transmissive (τ_{vis} < 9.4) cloudiness over Antarctica than at lower latitudes: Fig. 12 shows that the difference in high-level transmissive cloud amounts between HIRS and ISCCP grows with elevation even though the surface temperature discrepancy does not. However, the accuracy of the HIRS cloud amounts depends on how well the CO_2-slicing procedure works over high topography, where the shape of the weighting functions is altered by the high topography and the sensitivity of the analysis to the surface temperature is higher. More study of polar cloudiness is warranted.

5. High-level cloud properties

The ISCCP C1 dataset for July and October 1989, and January and April 1990 has about 0.21 high-level cloud amount over land and about 0.22 over oceans, excluding the regions polewards of 60°. The HIRS dataset has about 0.36 high-level cloud amount over land and about 0.34 over oceans for the same domain and months. Table 5 shows that about half of all high-level clouds in the ISCCP dataset and about two-thirds of all high-level clouds in the HIRS dataset are cirrus, defined as those clouds that have a net radiative heating effect—that is, infrared emissivity—$\epsilon < 0.84$ (or τ_{VIS} < 3.6). Almost all of the difference in high-level cloud amounts appears as a difference in thin cirrus defined by $\epsilon < 0.5$ or $\tau_{VIS} < 1.3$ (Table 5, cf. Table 3). The larger HIRS FOV may account for a difference of up to 0.05 in the transmissive high-level cloud amounts between HIRS and ISCCP (see section 2c).

Except for the effect of the difference in FOV size, it was shown in section 4 that most of the difference in ISCCP and HIRS cirrus amounts over oceans can be caused by the higher sensitivity of the HIRS analysis to optically thin clouds, aided by a small high bias of the sea surface temperatures used in the HIRS threshold step. Based on a comparison of ISCCP results that retrieve cloud optical thicknesses using a water droplet model (C1 dataset) and an ice crystal model (new ISCCP D1 dataset), about one-quarter to one-third of the difference of C1 with HIRS is produced by an overestimate of cirrus optical thicknesses and the consequent underestimate of cloud-top height (cf. Minnis et al. 1993b). Over land the higher detection sensitivity of the HIRS analysis was partially offset by the effect of large low biases in the surface temperatures used in the HIRS threshold step, most especially over high mountainous terrains. This effect also explains the large differences in high-level cloud amounts over Antarctica and Greenland (not shown). Based on the experiment in which we replaced the original land surface temperatures and detection threshold used in the HIRS analysis with the values used in the ISCCP analysis, we estimate that the differences shown in Table 5 between ISCCP and HIRS cirrus amounts over land are underestimates by about 0.03–0.05. Thus, from these two datasets it can be concluded that about one-third of the earth is covered by high-level clouds (tops above the 440-mb level) and that more than two-thirds of these clouds are cirrus.

The amount of extra-thin cirrus detected by the more sensitive HIRS analysis is quantitatively similar to that detected by SAGE II when compared with ISCCP (Liao et al. 1995a). After subtracting 0.05 to account for the possible effect of the larger HIRS FOV size, it is concluded that the HIRS detection sensitivity to thin cirrus is between those of SAGE II and ISCCP. The HIRS results exhibit similar latitudinal variations of the thinnest cirrus, as found in the SAGE II study (Liao et al. 1995a; Woodbury and McCormick 1986), indicating more very thin cirrus in the Tropics than in the midlatitudes. If the high-level clouds from HIRS and ISCCP are divided into several optical thickness ranges from thin to thick and spatial correlations of their global monthly mean distributions are calculated, the results shown in Table 6 are obtained. The correlations with the next-thicker cloud type in both datasets show a progressive increase for each cloud type as optical thickness increases. Correlations are generally higher in the Tropics and subtropics than in the midlatitudes (not shown). These correlations suggest that thin cirrus is slightly less often associated with thicker cirrus than thicker cirrus is with clouds that are thicker still. The best correlations are between moderate thickness high-level clouds ($3.6 < \tau_{VIS} < 9.4$) and the thickest high-level clouds ($\tau_{VIS} > 9.4$). Although providing only a crude test, these correlations suggest that not all cirrus are produced from storm systems (containing much thicker high-level clouds). That is, there is at least one more dynamic process (e.g., jet streams) that produces cirrus.

The last column in Table 6 shows that the differences between HIRS and ISCCP total high-level cloud amounts are very highly correlated with the presence of cirrus, even more so when HIRS indicates thin cirrus predominates. Taken together with the high correlations of total high-level cloud amounts of the two datasets, we conclude that the missed thin cirrus in the ISCCP dataset does not significantly alter the pattern of geographic and seasonal variations of cirrus. So we conclude this study by highlighting the most notable features of these variations, based on 8 years of ISCCP results.

Figures 13 and 14 show the monthly mean amounts of cirrus cloud for the individual months used in this study and for the same months averaged over all 8 years of ISCCP results.[1] Major concentrations of cirrus occur in association with storm systems in the ITCZ and midlatitude storm tracks. However, equally large or larger midlatitude concentrations appear over the major mountain ranges. The HIRS results show the same pattern except for the mountain concentration, but our investigation suggests that this results from an underestimate of cirrus by HIRS over mountains. Strong minima in cirrus concentration occur over the marine stratus regimes. These minima are confirmed by the HIRS results, which eliminates the possibility that ISCCP may significantly underestimate high cloud amount over these regions due to the persistent underlying marine stratiform clouds.

The tropical pattern of cirrus marks the upwelling and downwelling regimes of the mean circulation. However, "jet like" features, which are especially prominent in individual spring–autumn months, mark the jet streams of poleward flow into the subtropics from the ITCZ. Such features in the Northern Hemisphere extend from the eastern Pacific into North America, from the tropical Atlantic toward Europe, from the Indian Ocean into eastern Asia, and from Indonesia into the north-central Pacific; and in the southern hemisphere they extend from the central into the southeastern Pacific and from South America into the South Atlantic. The largest tropical concentration of cirrus appears in the Indian Ocean and western Pacific sector and is particularly extensive in July. The next largest concentration appears over the Amazon in the wet season (January–April).

[1] Notable quasi-circular features appear in the ISCCP distributions of cirrus (and other) cloud amounts caused by small, but systematic, errors in the retrieved cloud optical thicknesses and cloud-top temperatures with increasing satellite viewing zenith angle. While still under investigation, at least two causes of this effect have been proposed: an increase of cloud cover associated with increasing FOV area as the satellite zenith angle increases (e.g., Minnis 1989) and increased detection sensitivity for optically thin clouds with increasing satellite zenith angle (Rossow and Garder 1993b). In light of the evidence for a background of thinner cirrus missed by ISCCP, the latter effect could explain the ISCCP cirrus results and suggests a larger underestimate of cirrus amount at lower latitudes near the centers of the geostationary views.

In the midlatitudes the oceanic storm tracks are indicated by local enhancements of the concentration of cirrus that are smaller than in the Tropics (Wylie et al. 1994). However, this may be partly a matter of definition since cloud tops are generally lower in the midlatitudes than in the Tropics (cf. Rossow and Schiffer 1991). If we were to include middle-level clouds, which are probably mostly composed of ice, then the storm track concentrations would appear similar in prominence to the tropical features in Figs. 13 and 14. The notable concentrations of cirrus over the major mountain ranges in the midlatitudes suggest that they are produced by uplift of the generally eastward motions at these latitudes.

Finally, it is noted that the presence of large amounts of cirrus over both polar regions helps to explain both the agreements and disagreements between the ISCCP and HIRS datasets, but the quantitative accuracy of both the HIRS and ISCCP results over the poles is low.

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