EIGHT YEARS OF GLOBAL CIRRUS CLOUD STATISTICS USING HIRS

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1. INTRODUCTION

This paper reports on the ongoing investigation (now in the eighth year) of seasonal changes in semi-transparent or cirrus global cloud cover inferred from multispectral observations with the polar orbiting HIRS (High resolution Infrared Radiation Sounder). The HIRS measurements in the carbon dioxide absorption band at 15 microns are used to detect cloud and calculate both cloud top pressure and effective emissivity from radiative transfer principles. The HIRS cloud observations are compared with results from the International Satellite Cloud Climatology Project (ISCCP) and the Stratospheric Aerosol and Gas Experiment (SAGE).

2. TECHNIQUE

Cirrus clouds continue to be the focus of many efforts characterizing global cloud cover. Their occurrence has been underestimated in past work restricted to longwave infrared window (10-11 microns) radiances (Rossow and Lacis, 1990; Stowe et al., 1988). In more than 40% of the global infrared window observations, clouds appear warmer than the ambient air temperature at their altitude because they are transmitting radiation from below. Roughly half of these clouds are misinterpreted as being lower opaque clouds. Multispectral techniques have been more successful in discriminating cirrus from other clouds in global (Wu and Susskind, 1990, Wylie et al., 1994) and North American (Menzel et al., 1992) cloud studies. Using the HIRS infrared bands with partial CO_2 absorption (13.3 - 14.2 microns) , partially transmissive clouds can be distinguished during daylight and night over water and land. The technique and details of its application with HIRS data are described in Wylie et al. (1994).

In this work and our previous papers, effective emissivity refers to the product of the fractional cloud cover, N, and the cloud emissivity, ε, for each observational area (roughly 20 km by 20 km). When $N\varepsilon$ is less than unity, HIRS may be observing broken cloud ($N < 1, \varepsilon = 1$), overcast transmissive cloud ($N = 1, \varepsilon < 1$), or broken transmissive cloud ($N < 1, \varepsilon < 1$). All of these possibilities imply an observation where the HIRS radiometer detects radiation from below a cloud layer as well as from the cloud top. All observations where $N\varepsilon < 0.95$ (infrared optical depth less than 3.0) are labeled as "cirrus" in this paper; observations where $N\varepsilon > 0.95$ are called opaque clouds. When $N\varepsilon < 0.50$ (infrared optical depth less than 0.7), the cirrus clouds are considered to be thin; when $0.50 < N\varepsilon < 0.95$, the cirrus clouds are categorized as thick.

The implicit assumption in this work is that the semi-transparency of a cloud in a given field of view (FOV) is due more to cloud emissivity being less than one and due less to the cloud not completely covering the FOV. Studies with 4 km global AVHRR data have indicated that this assumption is reasonable for thick clouds in most synoptic regimes (especially in the tropics and subtropics); thin clouds were found to cover about 72% of the HIRS FOV on average. Figure 1 shows AVHRR cloud coverage within a HIRS FOV plotted against HIRS effective emissivity for clouds above 700 hPa in the tropics from 20 N to 40 N latitude for July 1994. AVHRR cloud cover is determined using the visible and infrared screening described in Frey et al. (1996). The HIRS FOVs with effective emissivity greater than 50% (thick clouds) are found to have an AVHRR cloud coverage of 100 % (all AVHRR FOVS within the HIRS FOV are found to be cloud covered); the HIRS FOVs with effective emissivities less than 50% (thin clouds) have a variety of AVHRR cloud coverage (72% of the AVHRR FOVS within the HIRS FOV are found to be covered with cloud on the average).

CO_2 slicing cloud top pressures are calculated when the cloud forcing (clear minus cloudy radiance) is greater than five times the instrument noise level; otherwise the infrared window temperature is used to determine an opaque cloud top pressure. Fields of view are determined to be clear if the moisture corrected 11.1 micron brightness temperature is within 2.5 C of the known surface temperature (over land this is inferred from the NMC Medium Range Forecast (MRF) model analysis; over ocean this is the NOAA NESDIS sea surface temperature analysis). HIRS data from NOAA 10, 11, 12, and 14 are sampled to include only data from every third FOV on every third line with zenith angle less than 10 degrees. With two satellites, about one half of the Earth is sampled each day. Morning orbits over land are rejected because a good estimate of the morning land surface temperature is unavailable and therefore discerning cloudy from clear FOVs is difficult. In the Arctic and Antarctic, the HIRS bands are inspected for the presence of surface temperature inversions which are assumed to be indicators of clear sky. In multiple cloud layers, the height and emissivity of a single cloud layer best representing the radiative mean of the scene is estimated.

3. RESULTS OF GLOBAL CLOUD STUDY

A statistical summary of over 60 million cloud observations from HIRS between June 1989 through February 1997 is shown in Table 1. Little variation is found in the global boreal summer versus winter cloud statistics. A few percent more cirrus and less clear sky are found in the boreal winter. High clouds above 400 hPa comprise 26% of the observations. Summer to winter, 25 to 27% of the observations are of mid-level clouds between 400 hPa and 700 hPa. Low clouds below 700 hPa are found 23 to 25% of the time. Cloud free conditions are found 23 to 25% of the time. Cirrus and transmissive clouds (with effective emissivities less than 0.95) are found in 43 to 45% of the observations; they range from 100 to 800 hPa. Many of the mid level and all of the low level transmissive observations are most likely broken clouds. Clouds opaque to infrared radiation (with effective emissivities greater than 0.95) are found 32 to 33% of the time. The global average cloud cover is found to be 0.70 (thin cloud detection is scaled by 0.72 to account for their average cloud fraction within the HIRS FOV); Warren et al. (1988) report a global cloud fraction of 0.61 from ground observations.

The CO_2 slicing technique is subject to some errors that have been discussed in Menzel et al. (1992). The large observation area (20 km by 20 km) produces results where transmissive cloud observations are over-estimated; cloud edges and clear sky within a FOV are incorrectly estimated to be transmissive cloud in roughly 5% of the FOVs. Conversely, the HIRS is insensitive to very thin clouds in roughly 5% of the FOVs causing transmissive clouds to be incorrectly classified as lower opaque clouds (Wylie and Menzel, 1989). And finally, the top down view of the satellite reveals high clouds in preference to lower occluded clouds. These errors are largely offsetting. Overall, the frequency of clear sky observations in Table 1 is believed to be valid within 3%.

Table 1. Types of Clouds Found in HIRS CO2 Slicing Study from Jun 1989 - Feb 1997

Summer (Jun, Jul, Aug)

	thin	thick	opaque
hi	12.1	9.9	3.7
mid	10.7	9.6	4.6
low	0.5	0.4	24.2
	clear	cirrus	opaque
	24.3	43.2	32.4

Winter (Dec, Jan, Feb)

	thin	thick	opaque
hi	12.3	10.6	3.5
mid	10.4	11.2	6.0
low	0.5	0.4	22.7
	clear	cirrus	opaque
	22.5	45.3	32.2

Figure 2 shows the geographical distribution of cirrus clouds in the summer and winter seasons (darker regions indicate more frequent cloud occurrence). The months of December, January, and February were summarized for the boreal winter (austral summer) and the months of June, July, and August were used for the boreal summer (austral winter). The seasonal summaries were compiled using a uniformly spaced grid of 2 degree latitude by 3 degree longitude. Each grid box for each season has at least 1000 observations. The major features of the eight year summary have not changed appreciably from those reported in the four year summary (Wylie et al., 1994). The Inter-Tropical Convergence Zone (ITCZ) is readily discernible as the region of more frequent cirrus (darker band in the tropics); the mid-latitude storm belts are also evident. The ITCZ is seen to move north with the sun. The subtropical high pressure systems are seen in the regions of less frequent cirrus cover. Over the Indonesian region the ITCZ expands in latitudinal coverage from boreal winter to summer. In the central Pacific Ocean, the ITCZ shows both a southern and northern extension during the boreal winter months. In the southern hemisphere, the eastern Pacific Ocean off South America and the eastern Atlantic Ocean off Africa remain relatively free of cirrus clouds throughout the year. The southern hemispheric storm belt is evident throughout the year. In the northern hemisphere mid-latitude storm belts, the frequency of cirrus clouds increases during the winter with the strengthening of the Aleutian Low in the north Pacific Ocean and the Icelandic Low in the north Atlantic Ocean. The North American cirrus cloud cover shows little seasonal change. Large convective development occurs during the austral summer (boreal winter) in South America and Africa, which is readily apparent in the increased occurrence of high cirrus clouds.

Figures 3a and 3b indicate the trends in cloud detection from 1989 to 1997 from one year to the next. Semitransparent high cloud has increased from 17% to 24%, or about 1% per year. Increase in high thin clouds (Nε < 0.5) accounts for more than half of this increase. High level opaque cloud has decreased slightly (by 1%). Mid-level semi-transparent cloud detection increased initially to a high of 23% but has tapered off at about 21%, while mid-level opaque cloud detection has decreased (possibly due to obscuration inherent with increased detection of higher cirrus).

Comparison with the results of ISCCP reveal that this HIRS multispectral analysis is finding roughly twice as many transmissive clouds than the ISCCP visible and infrared window analysis. Jin and Rossow (1994) studied collocated ISCCP and HIRS results for four months (July 1989, October 1989, January 1990, and April 1990); HIRS finds clouds 76% of the time (80% over water and 65% over land) while ISCCP finds 63% cloud cover (68% over water and 51% over land). Most of this difference is attributed to HIRS detection of thin clouds; if thin clouds are excluded from the HIRS data (roughly 20 % of the observations) and low opaque clouds in the HIRS data are increased (adding roughly 5%), all adjusted HIRS cloud categories would agree with Jin and Rossow (1994) to within a few percent. Figure 4 shows the monthly trends of ISCCP and this HIRS work from 1983 through 1996 for total cloud cover (which remains roughly constant in both) and ISCCP cirrus and HIRS thin cirrus and thin plus thick cirrus (all increase about 1% per year). While the detection of thin cirrus separates the ISCCP and HIRS plots, the trends are the same; there is an increasing amount of semi-transparent clouds in the atmosphere. It is noteworthy, that the dominance of northern hemisphere winter cloudiness shows up more clearly in the annual variations of the HIRS total cloud cover. Also, it seems that the HIRS detection of cirrus peaked in 1994 and is beginning to come down somewhat.

It is likely that HIRS is not exaggerating the presence of thin cirrus. Recent aircraft experiments have confirmed the continual presence of nearly invisible layers of small ice crystals (visible optical depths around .05) that are mostly transparent near 10 microns but are highly absorbing toward 12 microns (Smith et al., 1996). These ice crystal layers are not detectable in visible or infrared window observations; they become obvious in the longer wavelengths as radiative attenuation increases to more than 50%. The layers may be remnants of jet contrails where the small particles remain undisturbed in the stable tropopause.

Comparison with SAGE II data from the summers of 1989-1990 and the winters of 1990 and 1991 (Wylie and Wang, 1997) reveal good correlation (greater than 0.8) in the geographical distribution of clouds above 5 km (Figure 5). This must be considered in the context of the differing observing characteristics of the two systems (SAGE limb scanning over 2.5 by 200 km footprints versus HIRS nadir scanning over 20 km footprints); in addition SAGE can detect clouds with visible optical depths of 0.0002 while HIRS begins seeing clouds when visible optical depths exceed 0.1. There is good comparison in the winter hemispheres and the tropics (within 5%), but in the summer hemispheres SAGE finds more clouds (up to 15%). On the global average, SAGE finds 87% cloud cover, while HIRS finds 76%; SAGE is expected to find more clouds given its limb scanning and larger footprint. Overall, there are more similarities than differences in these two cloud data sets.

4. CONCLUSIONS

Global upper tropospheric transmissive cirrus cloud cover has been charted for the past eight years (June 1989 - May 1996) using NOAA polar orbiting HIRS multispectral infrared data. Cloud occurrence, height, and effective emissivity are determined with the CO_2 slicing technique that accounts for clouds partially filling the sensor field of view and semi-transparency of some clouds. More than 40% of the HIRS observations find cirrus clouds; their presence appears to be gradually increasing about one percent per year. This unprecedented high detection of cirrus clouds is supported by recent aircraft experiments that found nearly continual presence of nearly invisible layers of small ice crystals mostly transparent near 10 microns but highly absorbing toward 12 microns. Comparisons with cloud studies conducted by ISCCP reveal similar trends from year to year, but the ISCCP cirrus detection is less than half that of HIRS. Comparisons with SAGE high cloud frequency distributions are quite good; global patterns are well correlated.

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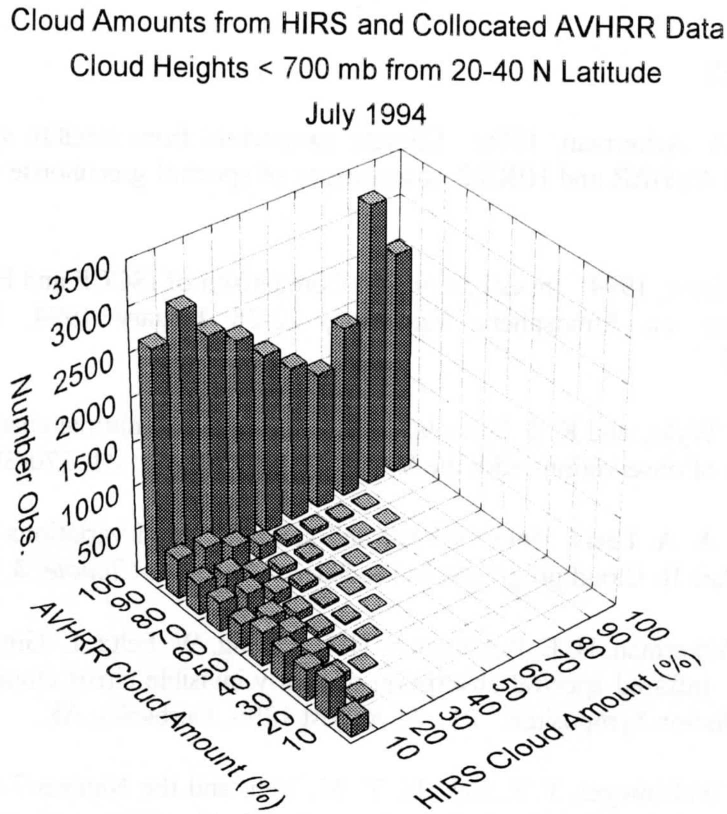


Fig. 1 AVHRR cloud coverage within a HIRS FOV plotted against HIRS effective emissivity (effective cloud amount) for clouds above 700 hPa in the tropical oceans from 20 N to 40 N latitude for July 1994.

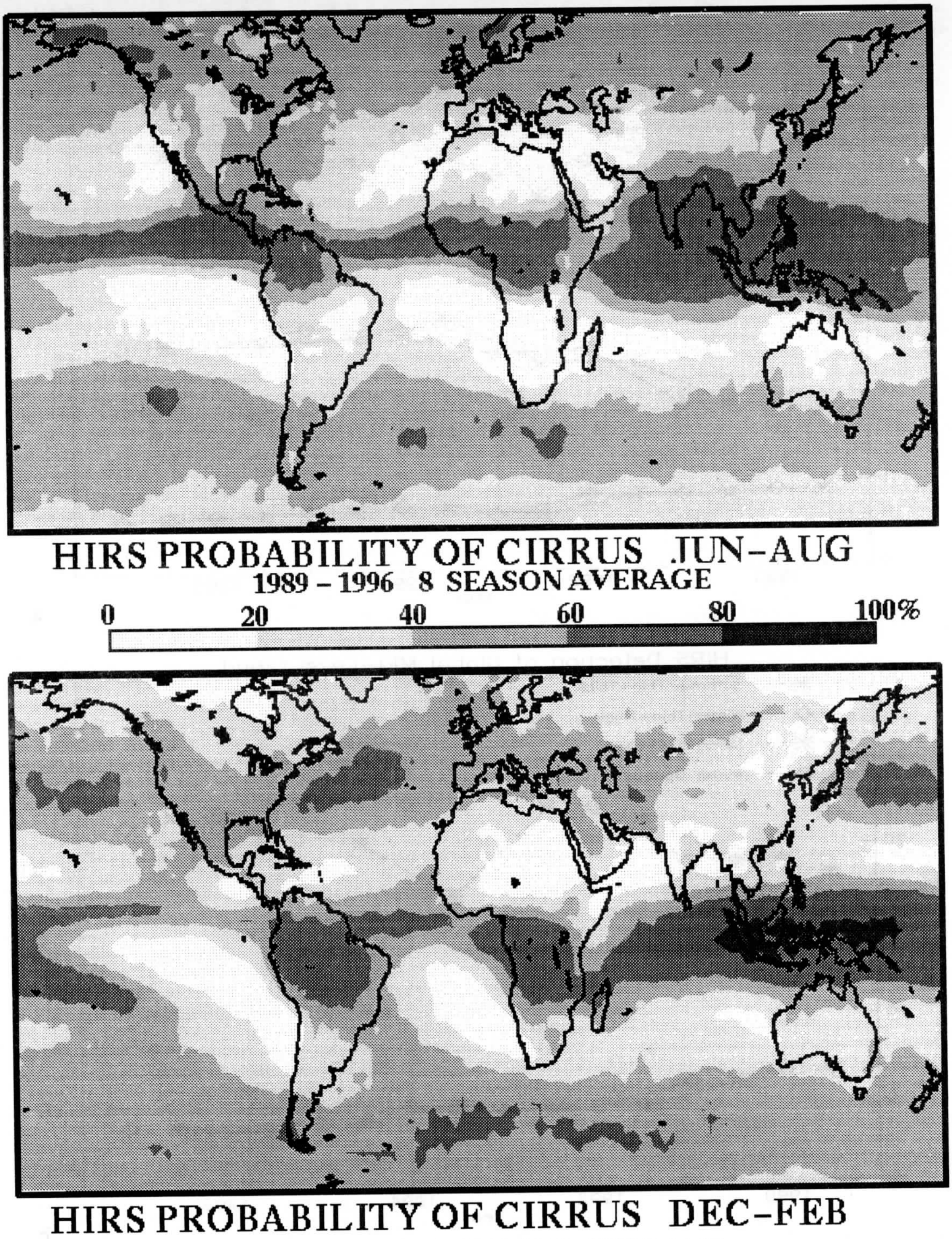
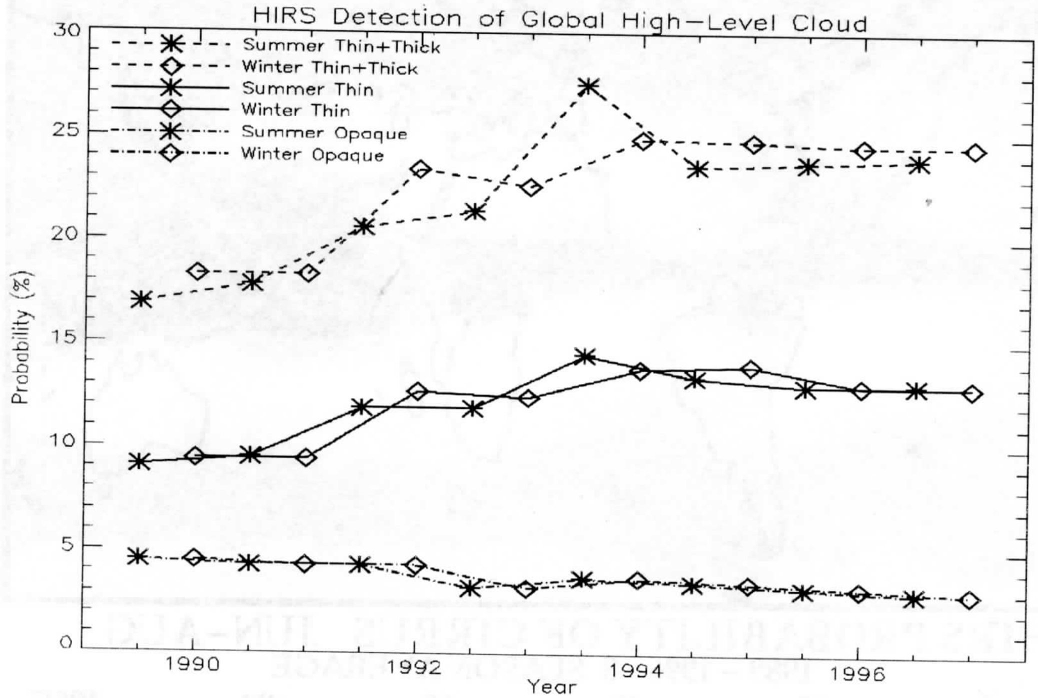


Fig. 2. Geographical distribution of cirrus clouds in the summer (Jun, Jul, Aug) and winter (Dec, Jan, Feb) seasons from June 1989 through April 1997 (darker regions indicate more frequent cloud occurrence).



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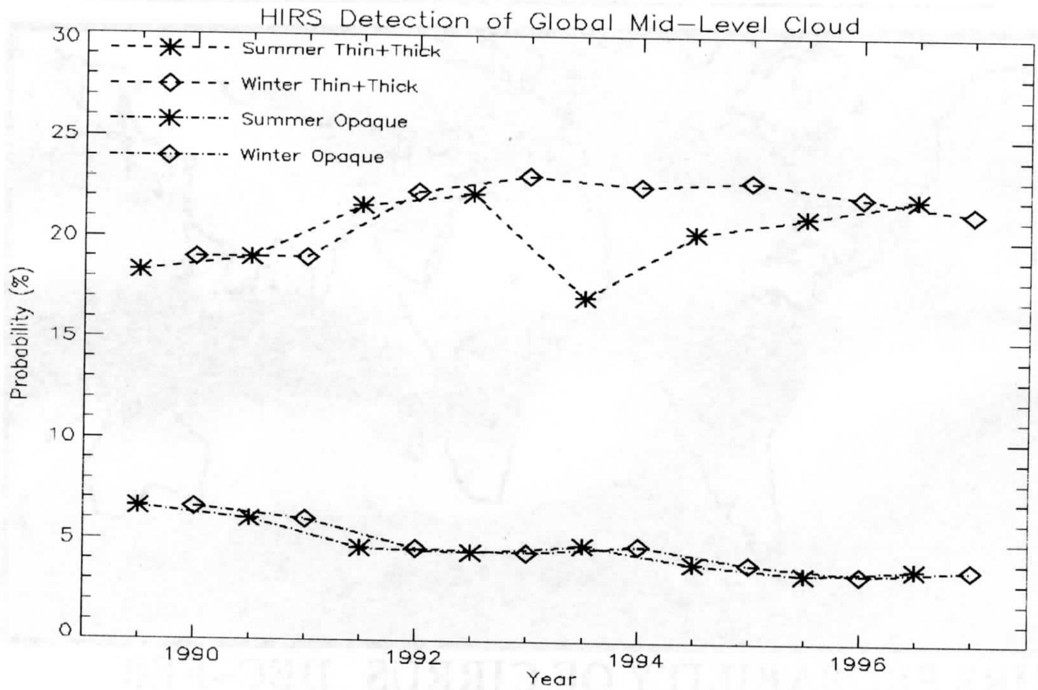

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Fig. 3. Trends in probability of detection of high (a) and mid (b) level cloud from 1989 to 1997.

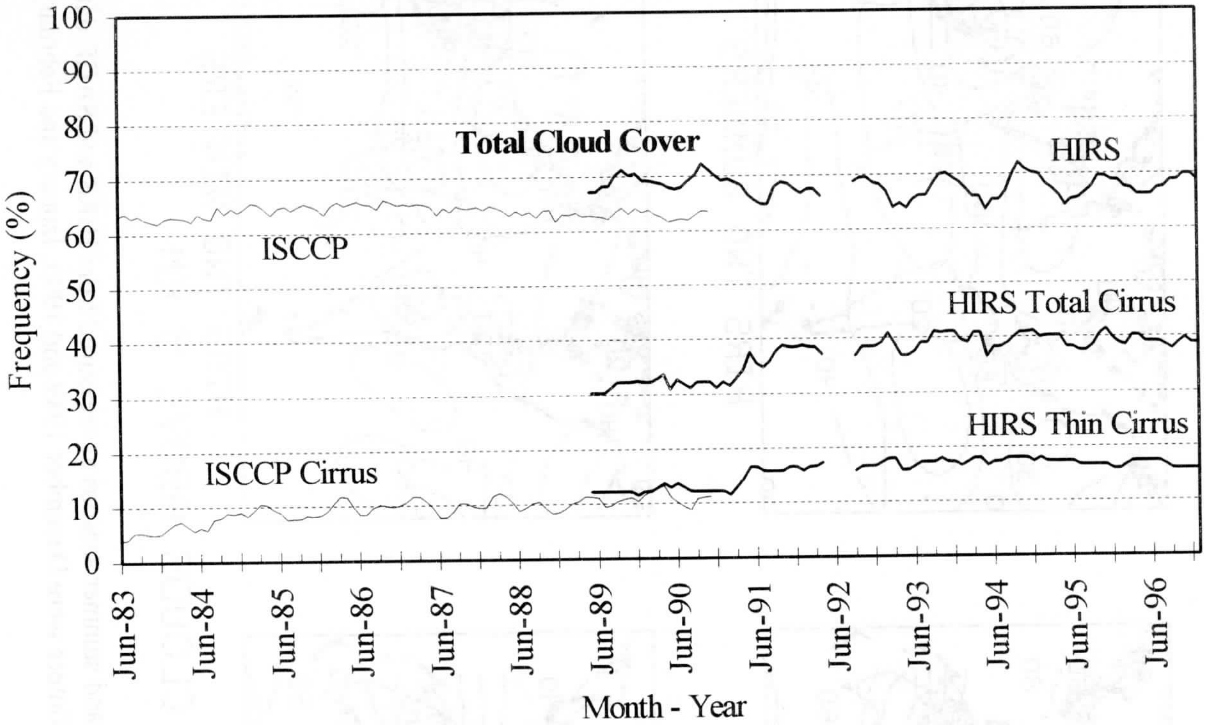

Fig. 4. Monthly trends for ISCCP total cloud cover and cirrus (thin lines) and HIRS total cloud cover, thin cirrus, and thin plus thick cirrus (thick lines) from 1983 through 1997.

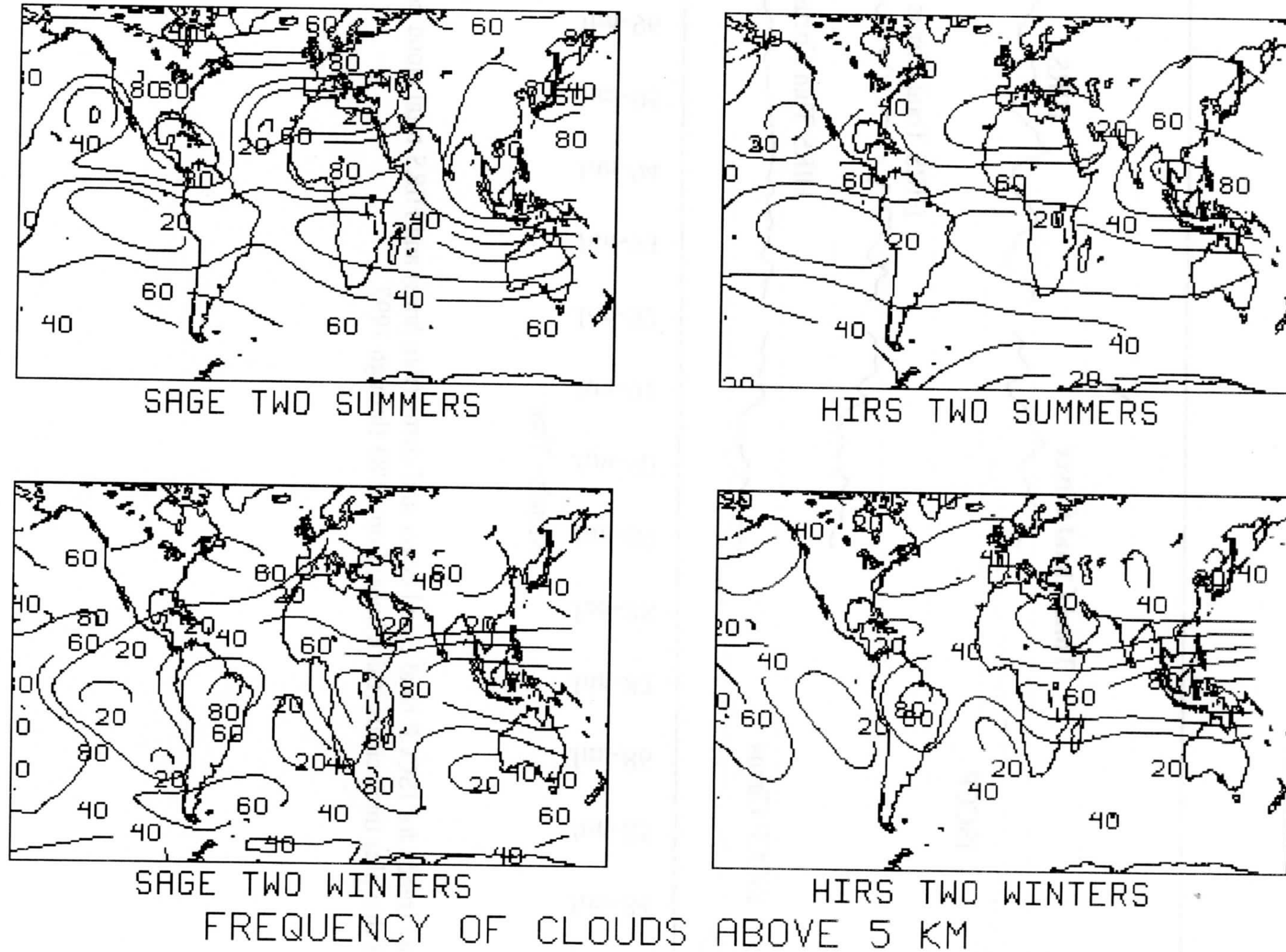

Fig. 5. The frequency of clouds above 5 km in two winter and summer seasons as measured from HIRS and SAGE data. Summers were the months of June, July, and August of 1989 and 1990. Winters were December 1989 and 1990, January and February of 1990 and 1991.

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