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Trends in Global Cloud Cover in 22 Years of HIRS Observations

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Summary

All of the HIRS data from the polar orbiting NOAA satellites from 1979 through 2001 were processed for cloud height information. This included 11 satellites from TIROS-N to NOAA 16. All of the HIRS data were included in the processing. Unfortunately this grant ran out before all of these data could be closely examined and published. One paper was written, "Trends in Global Cloud Cover in 22 Years of HIRS Observations", which has been submitted to the Journal of Climate for publication. It describes the trends in cloud cover found over this period. It used only part of the data that were analyzed - only the satellites in the 2 pm/am orbit and only the data from the near nadir parts of the scan. These restrictions were applied to form a consistent record which would be scientifically trusted. The off-nadir data were analyzed along with the NOAA satellites in the other orbit, 8 am/pm. These data will eventually be used in later publications. The following report is a copy of the paper submitted to the Journal of Climate.

Trends in Global Cloud Cover in 22 Years of HIRS Observations

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Abstract

Cloud cover information and the frequency of upper tropospheric clouds have been extracted from NOAA/HIRS polar orbiting satellite data from 1979 to 2001. The HIRS-2 sensor was flown on nine satellites from TIROS-N through NOAA 14 during this time forming a consistent 22-year record. CO2 slicing was used to infer cloud amount and height. Trends in cloud cover and high cloud frequency are small in these data. High clouds show small but statistically significant increasing trends in the tropics and Northern Hemisphere. The HIRS analysis contrasts from the ISCCP which shows decreasing trends in both total cloud cover and high clouds during most of this period.

1. Introduction

There is interest in all factors of the earth's energy budget and whether they are showing trends in time. Cloud cover is one variable that could magnify or offset the warming affect of CO_2 increases in the atmosphere. The International Satellite Cloud Climatology Project (ISCCP, Schiffer and Rossow, 1983; Rossow and Schiffer, 1999) started analyzing cloud cover globally in 1983. The ISCCP took advantage of the spectral channels common to the operational weather satellites - the 0.5 μm visible channel and the 11 μm longwave infrared window channel. These channels have been on the imaging sensors of the four to five geostationary satellites and the NOAA polar orbiting satellites from the 1980s to the present time.

The High resolution Infrared Radiometer Sounder (HIRS) instruments also were flown on the same NOAA polar orbiting weather satellites during this time but were not used in the ISCCP because they were not available on all geostationary satellites. The longwave IR channels of HIRS provide an alternative way of finding the upper tropospheric cirrus clouds that often elude detection with the two channels used by the ISCCP. Upper tropospheric clouds that transmit terrestrial radiation appear warmer in the 11 μm infrared window channel than the ambient temperature at their altitude. This causes many of them to be diagnosed incorrectly as lower altitude clouds. The ISCCP identifies these clouds and quantifies their IR transmission using their visible reflectance measuremments. This limits detection of transmissive cirrus clouds to only day light data and to clouds that have sufficient reflection to be separated from their background reflection. In contrast to the ISCCP, the longwave temperature sounding channels of HIRS do not depend on visible reflectance measurements and thus provide both a day and night cirrus detection capability. Because of these features, an analysis of HIRS sounder data was undertaken by the University of Wisconsin (UW) as a complement to ISCCP's much larger program.

Part of the HIRS record from 1986 to 1998 analyzed by UW and was reported in Wylie et al. (1994) and Wylie and Menzel (1999). A comparison to the ISCCP showed that the HIRS reported 10-15% more cloud cover than the ISCCP (Jin et al., 1996), mainly due to increased detection of radiatively thin cirrus clouds. Because of this difference the NOAA Pathfinder program processed the full HIRS record which they had extracted from NOAA's archives. This analysis was made in conjunction with UW and is the topic of this paper. The first HIRS-2 sensor was flown on TIROS-N in 1978 and has been continued through the flight of NOAA 14. This paper presents a re-analysis of the HIRS-2 data from 1979 to 2001. Minor changes were made from the analysis of Wylie and Menzel (1999) that are summarized in the next section. A statistical summary of the Pathfinder analysis of the 22-year HIRS is presented in the following sections.

2. The method of analysis of HIRS data

Cloud analyses are performed on HIRS data using the CO2 Slicing Method; the name alludes to the fact that each of the sounding channels views a different vertical layer of the atmosphere. Clouds are detected and their heights estimated by the amount that each CO2 channel (between 13 and 15 microns) is affected by the clouds. The details of the cloud analysis were reported in Wylie and Menzel (1999) and are not repeated here. This UW Pathfinder analysis of HIRS data introduces some changes from the 1999 UW HIRS analysis; these are summarized in Table 1.

The largest change is in the determination of the cloud mask used to separate clear from cloudy HIRS fields of view (FOV). The UW Pathfinder analysis uses spatial and temporal variances in the 11 μm window channel following Jackson and Bates (2001). Clear FOVs have low variances between neighboring FOVs and report the warmest data in each location over five days. This method of clear FOV identification is similar that used in the ISCCP. The earlier UW HIRS study compared the 11 μm window channel blackbody radiance temperature (after allowing for water vapor absorption using a split window correction) to the estimate of surface temperature (Tsfc) found in the NCEP daily operational analysis. The current UW Pathfinder analysis is independent of the NCEP Tsfc.

After establishing the cloud mask, measurements in clear FOVs are compared to forward model calculations of clear channel radiances using NCAR/NCEP Reanalysis Project temperature soundings. The resulting radiance biases are catalogued in a global grid with cell sizes of 2.5° latitude by 2.5° longitude. Calculated minus observed clear radiances are averaged over 30 days in each grid cell. Separate bias grids are used for the ascending and descending orbits on each satellite to isolate opposite parts of the diurnal cycle.

The method of estimating the channel clear radiance is different in two ways with respect to the earlier UW HIRS analysis. The first difference is the use of 30-day mean biases where the earlier analysis determined clear radiance from only 12 hours of data; thus the UW NOAA Pathfinder clear radiance fields are more stable. The second difference is the use of CO2 Slicing to identify FOVs with thin cirrus from clear FOVs. A description of this process will be given later.

The UW NOAA Pathfinder analysis uses temperature and moisture soundings from the NCAR/NCEP Reanalysis Project. The previous UW HIRS analysis used the operational analysis taken from NCEP daily files. The differences between these soundings is small but the Reanalysis Project is expected to have better fields because it included more data than the NCEP operational analysis and used consistent methods over the 22 years of this study. Changes made to improve the operational analysis can affect long term trends. Reanalysis data, while not perfect, are not affected by changes in the analysis model physics.

Forward calculations of clear radiances are made using the NCEP atmospheric transmission model (Van Delst et al., 2000) that is derived from the OPTRAN radiative transfer model. The previous UW HIRS analysis used the transmission model from the International TOVS Processing Project (ITPP). The differences between the two are very small.

The UW Pathfinder analysis includes more HIRS FOVs than the previous UW HIRS analysis. All FOVs within 18° scan angle of nadir are used, whereas the UW HIRS analysis sampled FOVs from every 3rd pixel on every 3rd line within 10° of nadir. The UW Pathfinder also uses all measurements over land whereas the previous UW HIRS analysis discarded the descending orbits at 2 am and 8 am because the model derived Tsfc did not track the diurnal cycle well and thus caused difficulties in the cloud mask. The inclusion of these orbits significantly improved coverage of continental areas. The last difference is that the UW Pathfinder analysis processes measurements in the polar regions; the previous UW HIRS analysis was limited to measurements between 65° N and 65° S latitude.

Three passes are made through the HIRS data. The first pass identifies clear FOVs and generates a first guess analysis of the biases in the forward calculation of clear radiances. The second pass through the data uses CO2 Slicing from Wylie and Menzel (1999) to identify high clouds. All HIRS data are subjected to the second pass including the FOVs marked clear by the cloud mask on the first pass. The CO2 Slicing high cloud analysis considers any FOV to be cloudy when two of the four sounding channels from 13-15 μm have radiance observations more than 1 mw/m^2/steradian/wavenumber colder than the clear FOV estimate from the forward calculation after bias removal. If the CO2 Slicing identifies a cloud in the troposphere, the FOV is considered to be cloudy regardless of any clear assignments made by the cloud mask on the initial pass through the data. About 2% of the data change from clear to cloudy in this pass.

Using the clear FOVs remaining after the second pass through the data (i.e. after purging the clear FOVs of any FOVs in which the CO2 Slicing found clouds), the 30-day radiance bias averages are re-calculated. Then the CO2 Slicing is re-applied to the whole data set in a third pass. This three-pass analysis differs from the two-pass analysis used in Wylie and Menzel (1999) where a clear radiance analysis was immediately followed by the cloud height analysis. The previous HIRS analysis processed all data within two days of acquisition and did not revise clear radiance fields using the CO2 Slicing cloud detection. The data processing decisions of the previous analysis were based on the need to move large amounts of data through small communication channels. The UW Pathfinder analysis did not have this handicap.

3. Global Averages

The UW Pathfinder HIRS global averages are similar to those reported in Wylie and Menzel (1999) and are summarized in Table 2a. Clouds were found in 75% of the data. High clouds (over 440 hPa) were found in 33% and IR transmissive clouds were found in 43% of the data. These values are within 2% of Wylie and Menzel (1999). The earlier Wylie-Menzel study reported cloud frequencies slightly differently because middle and low cloud layer cloud frequencies were corrected for the fact that HIRS does not observe these layers in FOVs where higher clouds are found. The middle and lower layers are only observed when higher clouds are not present. For consistency with Wylie and Menzel (1999), the cloud frequency statistics are re-tabulated and presented in Table

2b. Other cloud studies have not accounted for high cloud blockage of middle and low levels so we present both forms of statistics in Tables 2a and 2b. The blockage-corrected statistics show that low level clouds (below 700 hPa) are the most common occurring 49% of the time that this level was observed.

The geographical distribution of clouds also follows Wylie and Menzel (1999) and is shown in Figure 1. Clouds are most frequently found in the Intertropical Convergence Zone (ITCZ) and the mid-latitude storm belts of the North Atlantic, North Pacific, and Antarctic oceans. In between are the subtropical high pressure zones over the oceans and the subtropical deserts over land where clouds are less frequent. These features move north and south following the sun with the seasons.

4. Time trends

Time trends are reported for three latitude belts, 20 to 60 north, 20 to 60 south, and the tropics from 20 south to 20 north. The time series are taken only from the NOAA satellite in the 2 am/pm orbit. The other orbit, 8 am/pm, has gaps of several months to 1.5 years in duration, so it is treated separately from the 2 am/pm satellites. Cloud frequencies for the two orbits are similar and the most continuous orbit, 2 am/pm, generally represents the trends found in this UW Pathfinder HIRS analysis.

Before presenting the time series, changes in cloud frequencies with respect to the time drift of the sun synchronous orbits are described. The local passage of the 2 am/pm satellites over the lifetime of each satellite drift as much as 3.8 hours (see Table 3). To evaluate the effect of orbit time drift on the cloud frequency data, monthly means for each satellite are plotted against the local time of passage (equator crossing time). Figure 2 shows the changes in 20° to 60° south latitude over land, as an example. For all six satellites, the frequency of all cloud detection drops by 0.0127 per hour of orbit drift. Table 4 shows that most of the orbit drift cloud detection changes are less than 0.01 per hour. Over land all cloud detection decreases with orbit drift, while over oceans all cloud detection increases with orbit drift. High cloud detection increases with orbit drift significantly over land and much less over ocean. High clouds peak later in the day because of cirrus generated by cumulonimbus clouds (Wylie and Woolf, 2002) which is why more high clouds were reported with orbit drift.

The 22-year trends in the UW NOAA Pathfinder HIRS detection of cloud cover are generally small. Statistically significant trends after removing the annual cycle, are believed to be only those greater than 1% per decade; significant trends are shown in Table 5. The time series for 20 to 60 north latitude over oceans is shown in Figure 3. The ISCCP shows a strong decrease in cloud cover (-4.2 % per decade) while the HIRS shows no discernible change. For high clouds, HIRS and the ISCCP also disagree on the trends. The HIRS data show a modest increase (2% per decade) while the ISCCP shows a slight decrease (-0.7% per decade). A large part of the HIRS increase in high clouds comes from the dip in high cloud frequency from 1982-1984 detected with NOAA 7. NOAA 8, in the 8 am/pm orbit, also shows a similar dip of lesser magnitude during this time (see Figure 4). From 1995 onward the high clouds show further increases.

Over land from 20 to 60 north, high clouds also show an increasing trend (1.8% per decade) while all clouds show a negligible decreasing trend (Figure 5). The dip during NOAA 7 is smaller over land than oceans, so most of the HIRS high cloud 1.8% increase per decade is from the late 1990s. The ISCCP shows strong decreasing trends in all cloud cover (-3.1% per decade) and slight decreases in high clouds (-1.5% per decade).

In the tropics HIRS trends are small (Figures 6 and 7). Over ocean, both all clouds (0.8 % per decade) and high clouds (0.9 % per decade) increase. Over land, all clouds decrease (-0.8 % per decade) and high clouds increase recognizably (1.9% per decade). On the contrary, over oceans the ISCCP shows a significant decrease of all clouds (-3.7 % per decade) and a small decrease of high clouds (-0.5 % per decade). Over land, ISCCP shows decreasing trends for all clouds (- 2.1 % per decade) and slight decreases for high clouds (-0.7 % per decade).

In the southern mid-latitudes similar trends are seen (Figures 8 and 9). HIRS finds no trends in all clouds (less than 0.4 % per decade) but increases in high clouds of 1.7 % (land) and 2.4% (ocean) per decade. The ISCCP decreases all clouds by 1.7 % (oceans) and 1.0 % (land) per decade; for high clouds decrease of 0.9 % over oceans and 2.0 % over land are found.

The geographical locations of the cloud cover changes are studied using the difference of the average of the last 10 years of the HIRS record subtracted from the average of the first 10 years (see Figure 10). All clouds show their largest increases over tropical oceans - the Atlantic, the eastern tropical Pacific, and the northern Indian Oceans. Other small increases are found in Asia. Small areas of cloud cover decreases are found over oceans in the subtropics in both hemispheres. High clouds (Fig. 10b) show large increases in the tropics and over central Asia while small decreases are found in the southern sub-tropics. Large decreases in both the all cloud and high categories are found over eastern Antarctica.

5. The effect of CO_2 changes

From 1979 to 2001, atmospheric concentrations of CO_2 increased from 335 ppm to 375 ppm. For this analysis, the CO_2 concentration is assumed to be constant at 380 ppm to be consistent with NCEP's radiative transfer code. The amount of CO_2 affects atmospheric transmission in the sounding channels used to find thin cirrus clouds. To estimate the impact of an assumption of constant CO_2 concentrations on our cloud trends, one month of HIRS data was reprocessed with transmission functions representative of a lower CO_2 concentration of 335 ppm. To adjust the transmission functions, the exponential form of the transmittance function suggests that the following formula can be used.

$$\tau dry(335,p,ch) = \tau dry(380,p,ch)^{**}\{335/380) \quad (1)$$

where τdry(380,p,ch) is the transmission from pressure level (p) to the top of the atmosphere for HIRS channel (ch) considering only dry air with CO2. The total transmission (τ) is the product of the dry air transmission (τdry), the water vapor transmission (τH2O), and the ozone transmission (τO3):

$$\tau(p,ch) = \tau dry(p,ch)^{*}\tau H2O(p,ch)^{*}\tau O3(p,ch) \quad (2)$$

where τdry(335,p,ch) is an estimate of the transmission for a lower CO_2 concentration (335 ppm) in the atmosphere. Lower CO_2 concentrations increase the atmospheric transmission, so radiation is detected from lower altitudes in the atmosphere. For January 2001 the clouds detected by NOAA 14 in the more transparent atmosphere (CO2 at 335 ppm) are found to be lower by 13-50 hPa; this results in HIRS reporting 0.02 less high clouds than found in the more opaque atmosphere (CO2 at 380 ppm). This implies that the frequency of high cloud detection in the early 1980s are likely reported to be too large by using high CO_2 estimates and that the trends for increasing high cloud detection are likely larger than reported here.

6. Summary and conclusions

In summary, the HIRS data reveal the following.

a) Total cloud cover remains relatively steady over the 22 years studied with roughly 75% of all HIRS observations indicating clouds.

b) High clouds are observed in one third of the HIRS observations. High cloud cover shows an annual cycle mainly over land with the maximum in the summer of each hemisphere. In tropical land areas the maximum is from December to February.

c) High cloud cover has a modest increase in the second decade over the first decade (about 2%).

d) Orbit drift in some of the satellites is affecting the trends. The frequency of all cloud detection over land drops by more than 1% per hour in the afternoon; over oceans the increase of high cloud detection is less than 0.5% per hour.

e) The modest increase in HIRS detection of high clouds over the past two decades will likely become stronger when CO2 concentrations are allowed to vary seasonally and annually.

f) Volcanic eruptions as well as El Nino Southern Oscillation events in the past twenty years do not seem to influence the global HIRS cloud detection trends significantly.

g) HIRS finds more cloud cover and high clouds than ISCCP. HIRS shows different cloud trends than ISCCP.

This HIRS analysis contrasts with the time trends of the ISCCP which reports significant decreases in the general cloud cover (the all cloud category) with very small and insignificant decreases in high clouds. The UW NOAA Pathfinder HIRS analysis reports nearly constant general cloud cover with significant increasing trends in high clouds. These increases occur mainly over tropical oceans.

Searching for a cause for these contrasting trends, the earlier Jin et al.(1996) comparison of the ISCCP to the UW HIRS analysis found that HIRS detected more upper tropospheric thin clouds in most areas. This accounted for the 10-15% difference in total cloud cover reported by these two analyses. The same difference also is apparent in these data.

The most significant difference between this HIRS analysis and the ISCCP is the methods used to detect upper tropospheric transmissive cirrus clouds and estimate their heights. The ISCCP uses visible reflectance measurements with the infrared window terrestrial radiance measurements. This limits transmissive cirrus detection to only day light data. The UW NOAA Pathfinder HIRS analysis uses only longwave infrared data from 11 to 15 μm which is more sensitive to transmissive cirrus clouds. It finds more upper tropospheric clouds than the ISCCP different time trends because of the inclusion of these clouds.

Acknowledgements

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References

Jackson, D.L. and J.J. Bates 2001: Upper tropospheric humidity algorithm assessment. *J. Geophys. Res.*, **106**, 32259-32270.

Jin, Y., W. B. Rossow, and D. P. Wylie, 1996: Comparison of the climatologies of high-level clouds from HIRS and the ISCCP. *J. Climate*, **9**, 2850-2879.

Rossow, W. B., and R. A. Schiffer, 1999: Advances in understanding clouds from the ISCCP. *Bull. Amer. Meteor. Soc.*, **80**, 2261-2287.

Schiffer, R. A. and W. B. Rossow. 1983: ISCCP: The first project of the World Climate Research Program. *Bull. Amer. Meteor. Soc.*, **64**, 770-784.

Van Delst, P., J. Derber, T. Kleespies, L. McMillin, and J. Joiner, 2000, "NCEP Radiative Transfer Model", Proceedings of the 11th International ATOVS Study Conference, Budapest, Hungary, 20-26 Sept. 2000.

Wylie, D. P., and H. M. Woolf, 2002: The diurnal cycle of upper-tropospheric clouds measured by GOES-VAS and the ISCCP., *Monthly Wea. Rev.*, **130**, 171-179.

Wylie, D. P., and W. P. Menzel, 1999: Eight years of high cloud statistics using HIRS. *J. Climate*, **12**, 170-184.

Wylie, D. P. W. P. Menzel, and K. I. Strabala, 1994: Four years of global cirrus cloud statistics using HIRS. *J. Climate*, **7**, 1972-1986.

Tables

Table 1: The differences between the Wylie and Menzel (1999) HIRS analysis and the present Pathfinder analysis.

	Current UW Pathfinder	Earlier UW HIRS
Record length	22 years	8 years
Orbits processed	Both ascending and descending	Over land only ascending 2 and 8 pm LST
With of scan swath	18° from nadir	10° from nadir
Coverage	Contiguous FOVS over whole globe	Every 3rd element on every 3rd line between 60N – 60S
Basis of Cloud Mask	Spatial and temporal variances of window channel data plus CO2 Slicing to eliminate thin Ci	Window channel comparison to NCEP Tsfc with split window water vapor correction
Channel Clear radiance estimate	From explicit forward radiance calculation with bias correction	Interpolated from nearest clear FOV

Table 2a: The distribution of HIRS Cloud reports by cloud height and density from 1979-2001. Nε refers to effective emissivity, and σ refers to the corresponding visible optical depth. Over 76,000,000 HIRS observations from 8 NOAA satellites are included. Percentages of all observations are reported.

	Cloud Density			
	Thin	Thick	Opaque	
	$N\varepsilon < 0.5$	$0.5 < N\varepsilon < 0.95$	$N\varepsilon > 0.95$	
Cloud Level	$\sigma_{vis} < 1.4$	$1.4 < \sigma_{vis} < 6$	$\sigma_{vis} > 6$	All Densities
High (<440 mb)	15 %	15 %	3 %	33 %
Middle (440-700 hPa)	5 %	7 %	6 %	18 %
Low (>700 hPa)		1 %	23 %	24 %
Total	20 %	23 %	32 %	75 %

Table 2b: Table 2a statistics which have been corrected for the number of times the middle and low layers were actually observed by HIRS.

	Cloud Density			
	Thin	Thick	Opaque	
	$N\varepsilon < 0.5$	$0.5 < N\varepsilon < 0.95$	$N\varepsilon > 0.95$	
Cloud Level	$\sigma_{vis} < 1.4$	$1.4 < \sigma_{vis} < 6$	$\sigma_{vis} > 6$	All Densities
High (<440 mb)	15 %	15 %	3 %	33 %
Middle (440-700 hPa)	7 %	10 %	9 %	26 %
Low (>700 hPa)		2 %	47 %	49 %
Total	20 %	23 %	32 %	75 %

Table 3: The local time of the ascending node equator crossing at the beginning and ending of the flights of each NOAA satellite.

	Beginning of Flight			End of Flight		
Satellite	Month	Year	Time (hrs)	Month	Year	Time (hrs)
NOAA 5	Jan.	1979	15.32	Jan.	1981	15.88
7	Jul.	1981	14.51	Jan.	1985	15.93
9	Jan.	1985	14.37	Oct.	1988	16.12
11	Nov.	1988	13.71	Dec.	1994	17.28
14	Jan.	1995	13.73	Dec.	2001	17.53

Table 4: The change in cloud frequency per hour of orbit drift.

	Orbit drift corrections.			
	All Clouds		High Clouds	
	Land	Sea	Land	Sea
20-60 North	-0.004	0.002	0.007	0.004
Tropics 20 S - 20 N	-0.010	0.006	0.010	0.004
20-60 South	-0.013	0.003	0.006	0.000

Units are cloud fraction/hour.

Table 5: The statistically significant trends in cloud frequency change per decade.

	HIRS					
	20-60 N		20 S - 20 N		20-60 S	
	Ocean	Land	Ocean	Land	Ocean	Land
High Clouds	0.020	0.018	none	0.019	0.024	0.017
All Clouds	none	None	none	none	none	none
	ISCCP					
High Clouds	none	-0.015	none	none	none	-1.0
All Clouds	-0.042	-0.031	-0.037	-0.021	-0.017	-0.020

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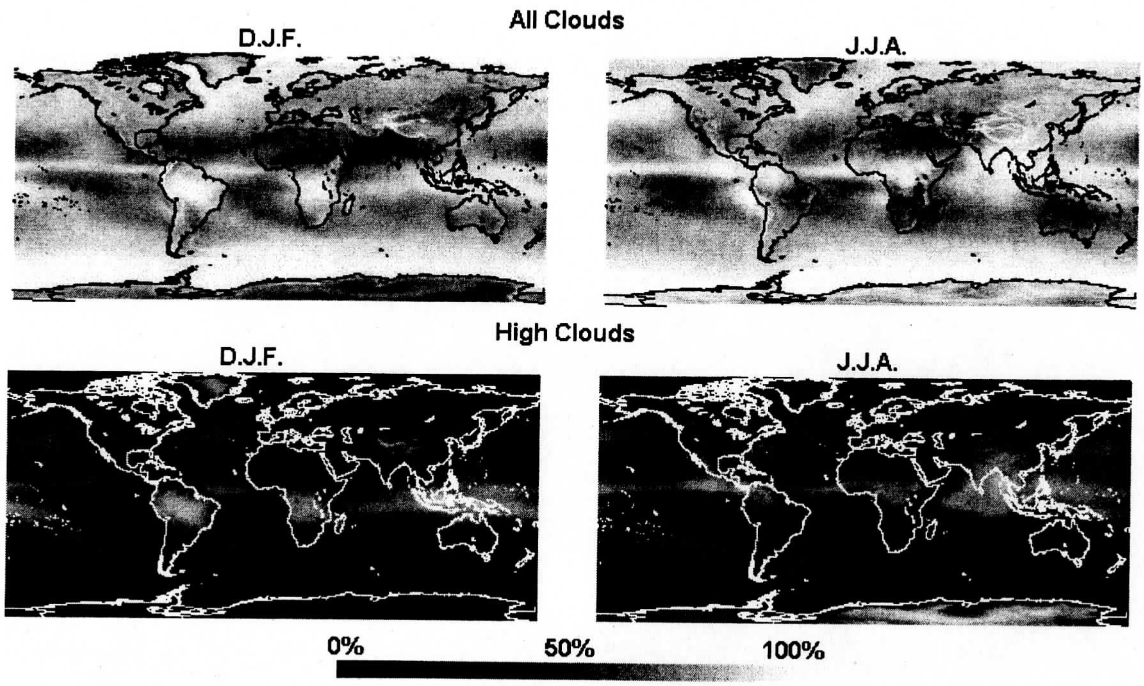

Figure 1: The frequency of all clouds and high clouds above 440 hPa from 1979 to 2001 found in HIRS data during winter (D, J, F) and summer (J, J, A).

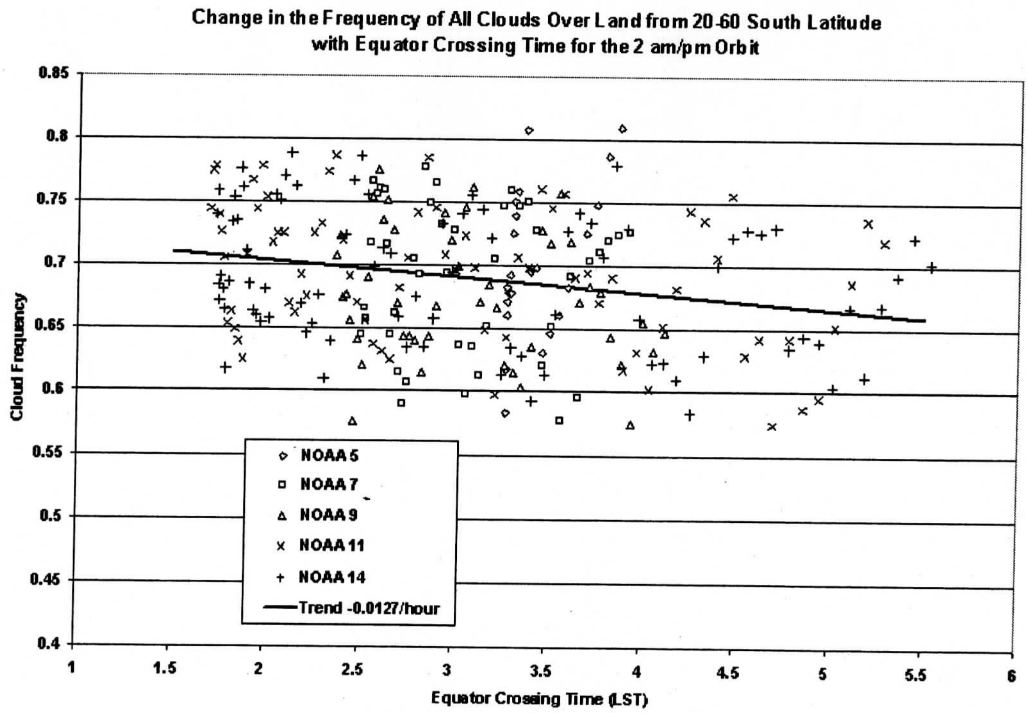

Figure 2: The monthly averaged frequency of clouds over land as a function of the equator crossing time for each satellite in each month studied.

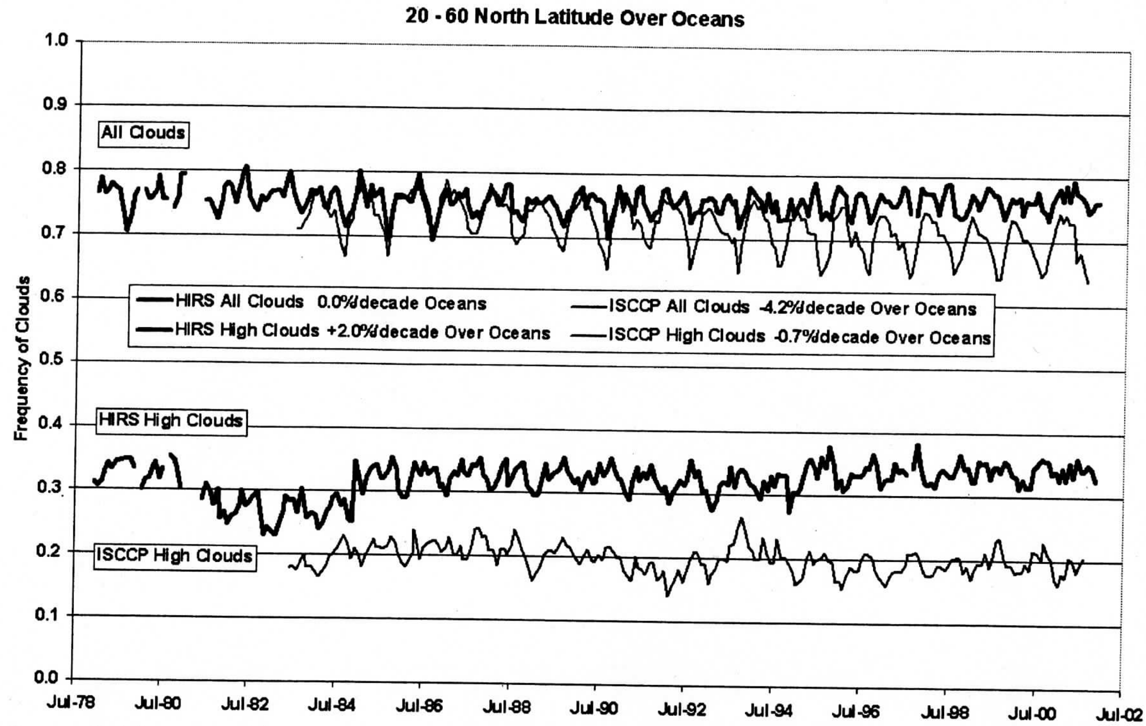

Figure 3: The monthly average frequency of clouds and high clouds (above 440 hPa) from 20-60 north latitude over oceans.

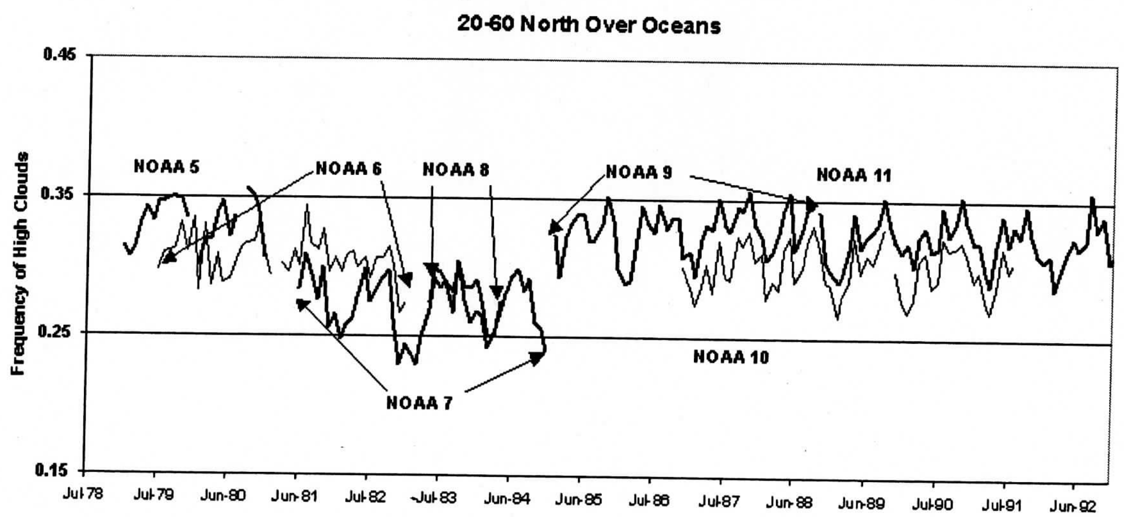

Figure 4: The monthly average frequency of high clouds from 20-60 N showing the time period of individual satellites.

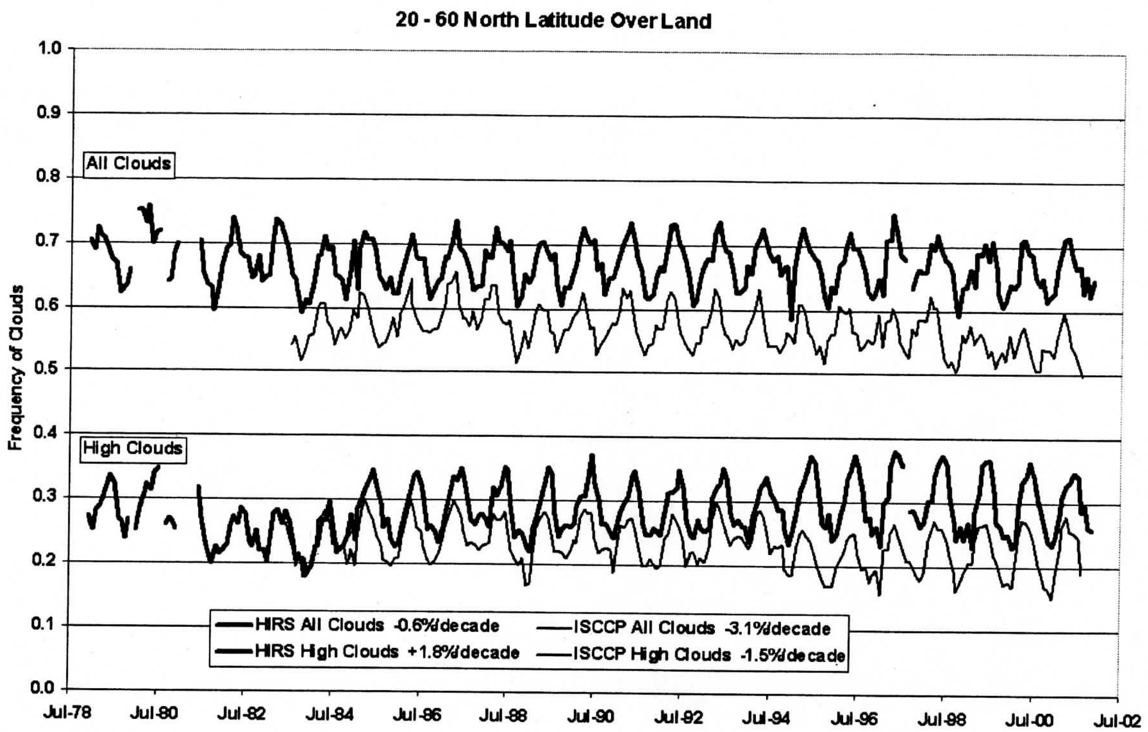

Figure 5: The monthly average frequency of clouds from 20-60 N over land.

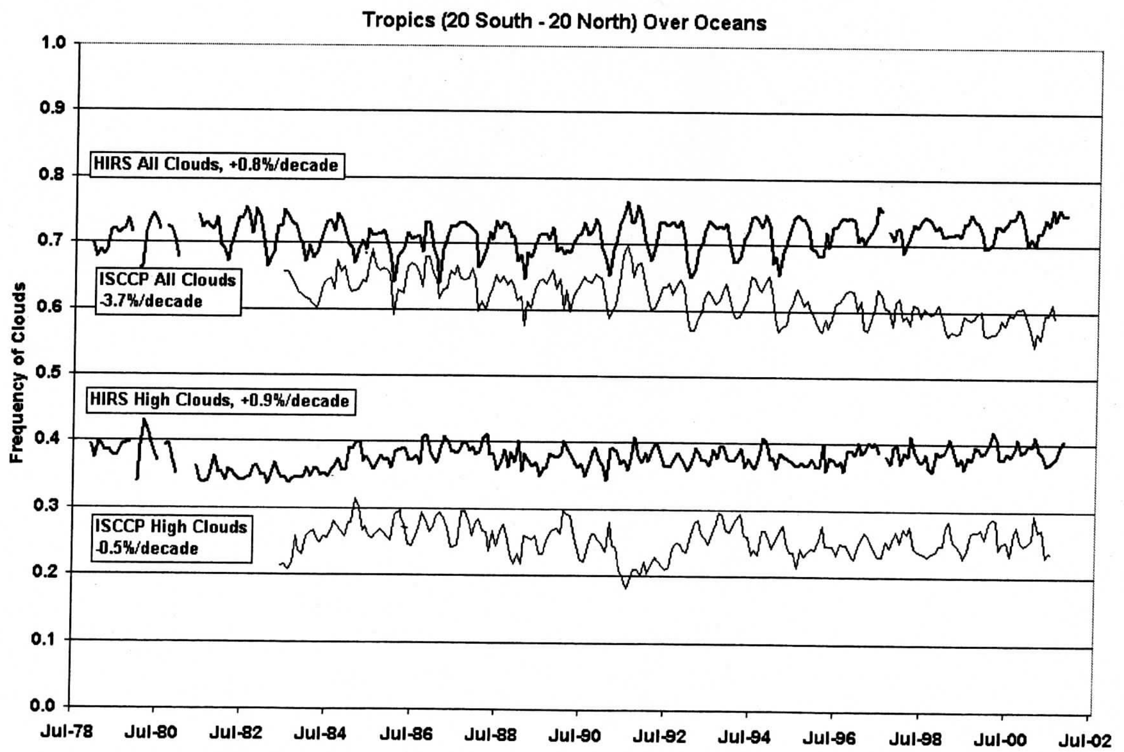

Figure 6: The monthly average frequency of clouds from 20 S to 20 N over oceans.

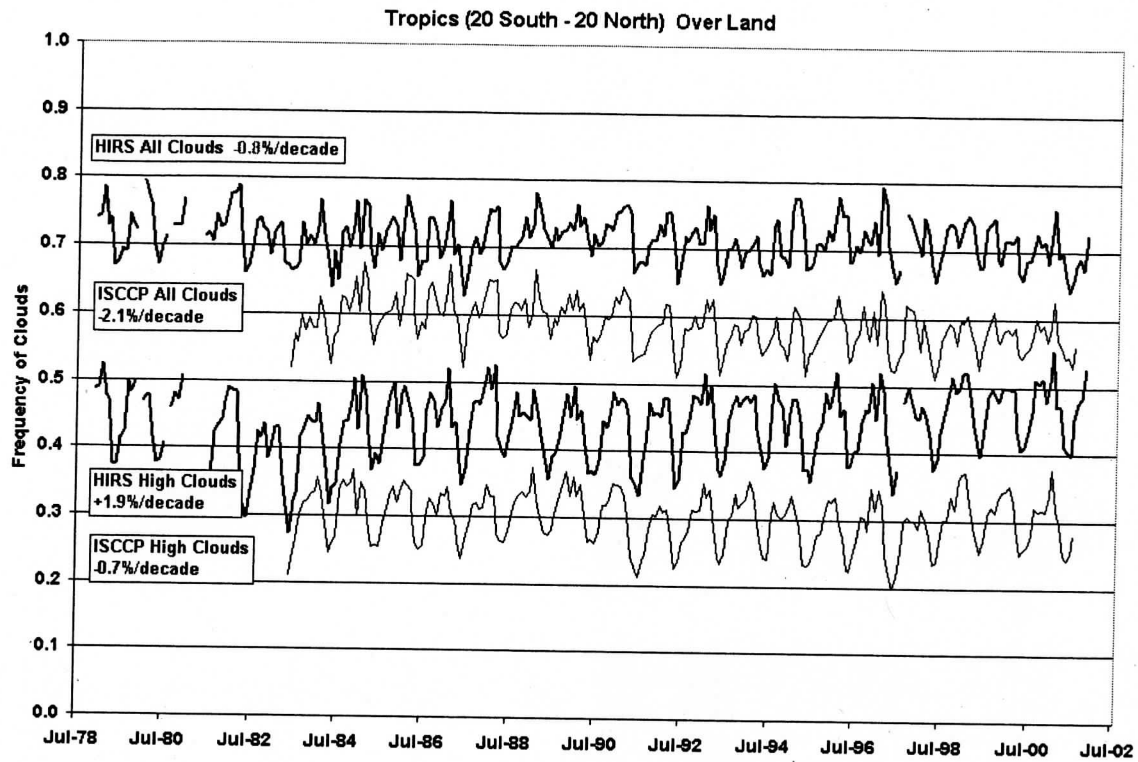

Figure 7: The monthly average frequency of clouds from 20 S to 20 N over land.

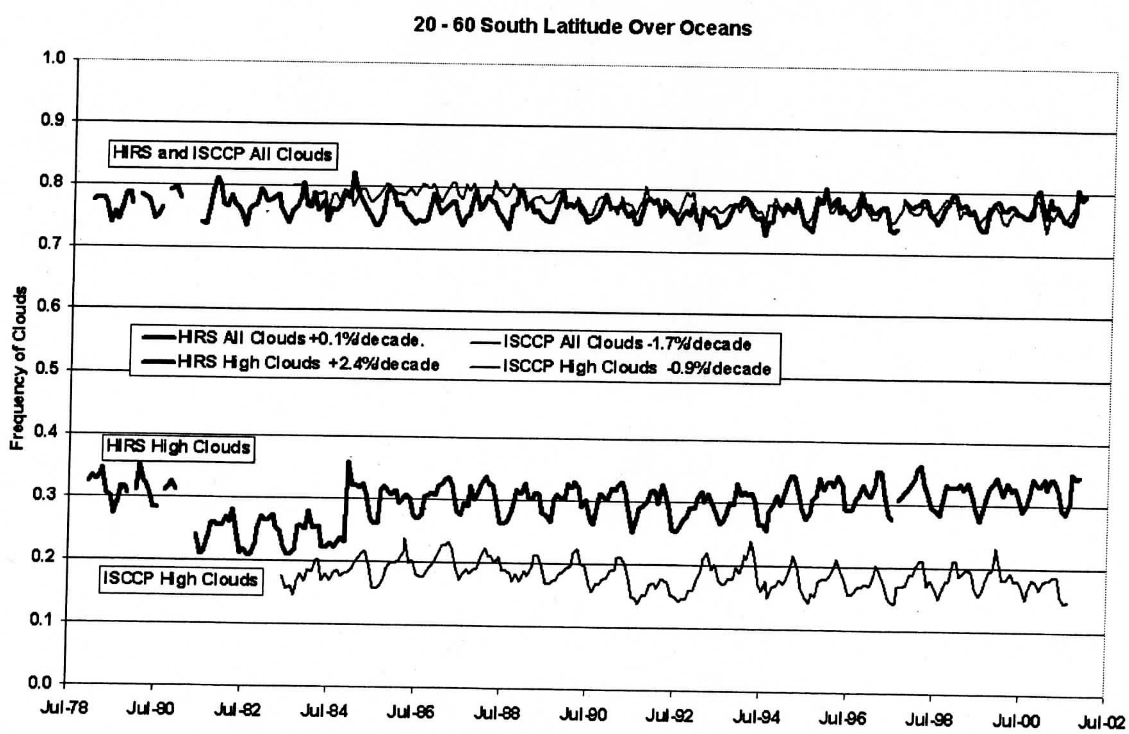

Figure 8: The monthly average frequency of clouds from 20-60 S over oceans.

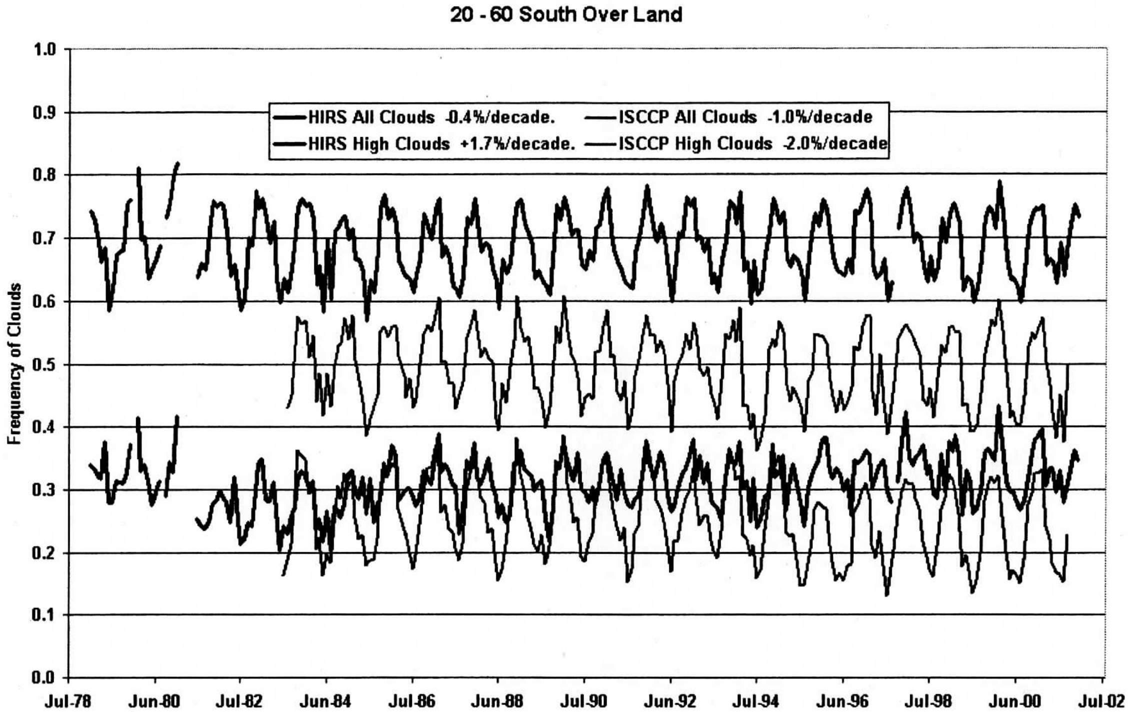

Figure 9: The monthly average frequency of clouds from 20-60 S over land.

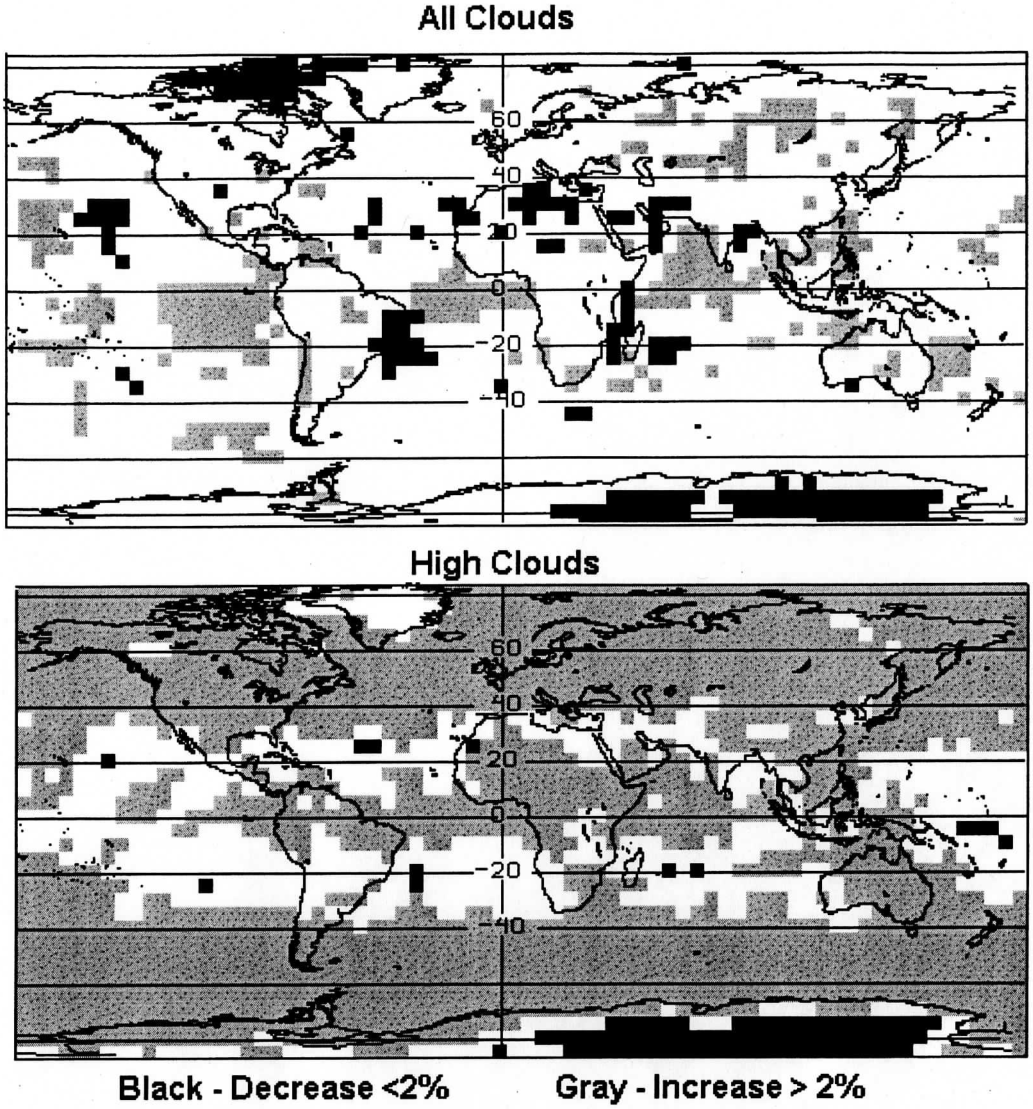

Figure 10: The geographical locations of changes in All Clouds and High Cloud frequency between the first and last decade of this study. Gray areas indicate increases in cloud frequency > 0.02 while black areas show decreases <0.02.