# Using 22 years of HIRS Observations to Infer Global Cloud Trends

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## Abstract

The frequency of occurrence of upper tropospheric clouds have been extracted from NOAA/HIRS polar orbiting satellite data from 1979 to 2001. A consistent 22-year record is available from the HIRS-2 sensor flown on nine satellites from TIROS-N through NOAA 14. CO2 slicing is used to infer cloud amount and height. Since 1979, HIRS measurements have found clouds most frequently in two locations; (1) the Inter-Tropical Convergence Zone (ITCZ) in the deep tropics where trade winds converge and (2) the middle to high latitude storm belts where low pressure systems and their fronts occur. In between are latitudes with fewer clouds and rain called sub-tropical deserts over land and sub-tropical high pressure systems over oceans. Globally averaged frequency of cloud detection (excluding the poles where cloud detection is less certain) has stayed relatively constant at 75%; there are seasonal. fluctuations but no general trends. High clouds in the upper troposphere (above 6 km) are found in roughly one third of the HIRS measurements; a small increasing trend of ~ 2% per decade is evident. The decadal average cloud cover has not changed appreciably from the 1980s to the 1990s; high cloud cover has changed some with increases of 10% in the western Pacific, Indonesia, and over Northern Australia. The most significant feature of these data may be that the globally averaged cloud cover has shown little change in spite of dramatic volcanic and El Nino events. During the four El Nino events winter clouds moved from the western Pacific to the Central Pacific Ocean, but their global average in the tropics did not change. El Chichon and Pinatubo spewed volcanic ash into the stratosphere that took 1-2 years to fall out, but cloud cover was not affected significantly.

The HIRS analysis differs from ISCCP which shows decreasing trends in both total cloud cover and high clouds during most of this period; HIRS detection of upper tropospheric thin cirrus accounts for most of the difference. GLAS observations of high thin clouds are found to be largely in agreement with the HIRS.

## 1. UW NOAA PATHFINDER HIRS CLOUD ANALYSIS

High resolution Infrared Radiation Sounders (HIRS) have flown on operational satellites from 1979 to the present, data from these instruments contain important indicators of variability as well as trends in temperature, moisture, cloudiness. 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 technique and details of its application with HIRS data are described in Wylie et al. (1994), Wylie and Menzel (1999), and Wylie et al. (2004). The data included in the re-processing of the UW NOAA Pathfinder HIRS data set is summarized in Table 1. Clear sky radiances are culled using infrared window threshold and temporal and spatial variance tests (Jackson and Bates, 2001); a second pass screens thin cirrus with the CO2 channels. Radiance bias adjustments are calculated for the clear fields of view in every 2.5 x 2.5 degree lat-lon grid box so that calculated and measured radiances are kept in concert. CO2 slicing is attempted for every field of view. The NCEP/NCAR Reanalysis is used for the cloud top pressure calculation. The HIRS data have a higher sensitivity to semi-transparent cirrus clouds than visible and infrared window techniques; the threshold for detection appears to be at IR optical depths greater than 0.05 (in general visible optical depths are twice the IR optical depth).

Since 1978 data has been available from nine different HIRS instruments (version 1, 2, or 2I) that were maintained in either a morning (8 am local time) or afternoon (2 pm local time) local overpass. Table 2 indicates the morning and afternoon satellite instruments (prior to NOAA 15 where the HIRS instrument was upgraded to version 3).

## 2. UW PATHFINDER HIRS PROCESSING OF 22 YEARS OF CLOUD DETECTION

UW NOAA Pathfinder HIRS cloud statistics for the whole globe (for observations within 18 degrees of satellite nadir) from 1979 through 2001 are shown in Table 3a. They are separated by cloud type into clear sky (infrared window optical depth $\tau_{IR} < 0.05$), thin ($\tau_{IR} < 0.7$), thick ($\tau_{IR} > 0.7$), and opaque ($\tau_{IR} > 3.0$) clouds and separated by level in the atmosphere above 440 hPa, between 440 and 700 hPa, and below 700 hPa. On the average for summer and winter, HIRS finds thin clouds in 20% of all observations, thick clouds in 23%, and opaque clouds in 32%. These HIRS observations imply that clouds are found in 75% of all HIRS observations. High clouds are observed in 33% of the observations. Table 3b shows the same cloud statistics corrected for the fact that HIRS does not observe lower cloud layers where higher cloud layers are found. This random overlap assumption yields more representative of lower cloud coverages. Cloud frequency statistics are reported both ways in the literature, with and without correction for high cloud blockage. Accounting for blockage by high clouds, low clouds are inferred to be observed in 49% of the observations.

The geographical distribution of clouds in summer and winter seasons is shown in Figure 1. Since 1979, HIRS measurements have found clouds most frequently in two locations; (1) the Inter-Tropical Convergence Zone (ITCZ) in the deep tropics where trade winds converge and (2) the middle to high latitude storm belts where low pressure systems and their fronts occur. In between are latitudes with fewer clouds called sub-tropical deserts over land and sub-tropical high pressure systems over oceans. The outline of the Rocky Mountains, the Himalayas, and the Tibetan Plateau also appear in Figure 1; this is a result of difficulties in the cloud retrieval system in high altitude mountains.

## 3. HIRS TROPICAL CLOUD TRENDS

Time trends are studied for three latitude belts, 20 to 60 N, 20 to 60 S, and the tropics from 20 S to 20 N. The time series are derived from the NOAA satellite in the 2 am/pm orbit; the 8 am/pm orbit has gaps of several months to 1.5 years in duration. Cloud frequencies for the two orbits (not shown) are found to be similar. Monthly averages in each latitude belt are subdivided into separate time series for land and ocean areas (six cloud trends in all). However before calculating the time trends, corrections for orbit drift, $CO_2$ increase, and anomalous satellites must be applied.

## 3a. Corrections for Orbit Drift

The local passage of the 2 am/pm satellites over the lifetime of each satellite drift as much as 3.8 hours (see Table 4a). The effects of orbit drift are summarized in Table 4b. In the 20 to 60 S land belt, the frequency of all clouds reported the largest drop by 0.013 per hour of orbit drift; other changes in cloud frequency were 0.01 or less per hour of orbit drift. In general all cloud detection decreases over land with orbit drift, while detection increases with orbit drift over oceans. The diurnal cycle of most clouds over land follows the sun and peaks in early afternoon; as the satellite orbits drifted in to the later afternoon, they sampled after the diurnal cycle peaks. High cloud detection was found to increase with orbit drift significantly over land and much less over ocean. High cloud cover peaks later in the day because of cirrus generated by cumulonimbus clouds (Wylie and Woolf, 2002).

These cloud frequency data are from both the daytime (descending) and night (ascending) orbits. For high clouds over land, the effect of orbit drift differed between the orbits. High cloud reports decreased with orbit drift for the nighttime pass while it increased for the daytime orbit. The daytime increase was stronger than the nighttime decrease dominating the average. This occurred on all latitude belts. Total cloud cover (all clouds of all altitudes) generally decreased in both the day and night orbit passes with orbit drift.

The cloud statistics were adjusted with a linear extrapolation to a 1400 ascending node for all satellites.

## 3b. Corrections for Changing $CO_2$ Concentration

From 1979 to 2001, atmospheric concentrations of $CO_2$ increased from 335 to 375 ppm on the global average. The UW NOAA Pathfinder HIRS analysis assumed the $CO_2$ concentration 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 in the calculation of cloud altitude. 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 function from high to low concentration of $CO_2$, the exponential form of the transmittance function suggests that $\tau$dry(335,p,ch) = $\tau$dry(380,p,ch)**{335/380} where $\tau$dry(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. Total transmission ($\tau$) is the product of dry air transmission ($\tau$dry), water vapor transmission ($\tau$H2O), and ozone transmission ($\tau$O3); thus $\tau$(p,ch) = $\tau$dry(p,ch)*$\tau$H2O(p,ch)*$\tau$O3(p,ch).

Lower $CO_2$ concentrations increase atmospheric transmission, so radiation is detected from lower altitudes in the atmosphere. For January and June 2001, 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 in less high clouds than reported with the more opaque atmospheric transmission functions (CO2 at 380 ppm). This implies that the frequency of high cloud detection in 1979 and the early 1980s are likely reported to be too large (by using $CO_2$ at 380 ppm) and that the trends for increasing high cloud detection are likely larger than shown in the constant $CO_2$ analysis. The effect was larger outside of the tropics; the average increase was 0.028 in high cloud frequency poleward of 20° latitude equally in each hemisphere while in the tropics the average increase in was only 0.018.

Each of the six time series was adjusted to represent a linear increase in $CO_2$ from 335 ppm to 375 ppm in that latitude belt.

## 3c. Corrections for Anomalous Satellites

The corrected 22-year trends in the UW NOAA Pathfinder HIRS detection show a dip in high cloud frequency from 1982 to 1985 during the flight of NOAA-7. NOAA-7, in the 2 am/pm orbit, shows high cloud frequencies that are lower than NOAA-5 before and NOAA-9 after. NOAA-8, in the 8 am/pm orbit, also shows a similar dip of lesser magnitude during this time along with an increase by its successor, NOAA-10. In the absence of an explanation for this dip, we do not use the NOAA-5 and -7 data in calculation of trends. Thus, UW NOAA Pathfinder HIRS trends are reported for 1985 to 2001. Trends in the ISCCP data were calculated from its beginning of July 1983 through September 2001.

## 3d. Corrected Cloud Trends

The orbit drift and $CO_2$ increase corrections to the HIRS data had only minor affects on the calculated trends. The corrected 16-year trends in the UW NOAA Pathfinder HIRS detection of cloud cover are shown in Table 5. Statistically significant trends, after removing the annual cycle, are believed to be only those greater than 0.01 per decade. Table 5 also shows the trends (1985-2001) for the data before applying the orbit drift and $CO_2$ change corrections. The corrections increased the high cloud trends slightly in the northern hemisphere by 0.006/decade on the average but decreased the trends in the tropics and southern hemisphere up to 0.008/decade. This occurred because the orbit drift correction was often opposed to the $CO_2$ correction.

Figure 2 shows the monthly average frequency of clouds and high clouds (above 6 km) from 70 south to 70 north latitude from 1979 to 2002.

# 4. COMPARISONS WITH ISCCP AND GLAS

Table 5 also shows the decadel trends found in the International Satellite Cloud Climatology Project (ISCCP). The HIRS indicates no significant trends in total cloud cover but a slight increasing trend in high cloud cover of 0.02 (2%) per decade in mid-latitudes. In the tropics a trend in high clouds was found only over oceans. The ISCCP shows decreasing trends in total cloud cover of 0.03 to 0.04 (3 to 4%) per decade but little high cloud trend except for mid-latitude land areas in both hemispheres where the ISCCP reported slight decreasing trends.

Differences between UW HIRS analysis and the ISCCP are primarily (a) ISCCP uses visible reflectance measurements with the infrared window thermal radiance measurements, which limits transmissive cirrus detection to only day light data; (b) UW HIRS analysis uses only longwave infrared data from 11 to 15 µm which is more sensitive to transmissive cirrus clouds, but is relatively insensitive to low level marine stratus clouds. Campbell and VonderHaar (2005) suspect that ISCCP may be showing fewer clouds as satellite coverage (and hence more nadir viewing coverage) increases in later years.

Table 6 summarizes the total cloud and high cloud detection for HIRS (1979 – 2001), ISCCP (1983-2001), and GLAS (March 2003). ISCCP detects 10 % fewer high clouds than HIRS, probably because ISCCP uses only visible and infrared window measurements which limit transmissive cirrus detection to only day light data. The Geoscience Laser Altimeter System (GLAS) reports nearly the same high cloud frequencies as HIRS. HIRS reports more clouds over land than GLAS, probably because GLAS at 70 meter resolution sees holes in low cumulus that HIRS at 20 km resolution does not. GLAS seems to confirm that high clouds in the upper troposphere are common.

## 5. GEOGRAPHICAL LOCATIONS OF DECADAL CHANGE

The geographical locations of the cloud cover changes are studied using the difference of the average of the last 8 years of the HIRS record subtracted from the average of the first 8 years (see Figure 3a). The decadal average cloud cover has not changed appreciably from the 1980s to the 1990s. Small increases occurred in the tropics, mainly in the Indonesian Islands. Small decreases occurred in the sub-tropics, the eastern Sahara and in the central Pacific Ocean from Hawaii westward. The decreasing trend in Antarctica is uncertain because cloud detection itself is very difficult in the cold temperatures of Antarctica.

High cloud cover has changed some in the northern hemisphere winter season. Increases of 10% in the last decade for clouds above 6 km altitude occurred in the western Pacific, Indonesia, and over Northern Australia. Other fairly large increases occurred in western North America, Europe, the Caribbean, Western South America, and the Southern Ocean north of Antarctica. Decreases in high clouds occurred mainly in the tropical South Pacific, Atlantic and Indian Oceans south of the ITCZ.

Figure 3b confirms that most of the cloud changes in high cloud are from high thin cirrus (with effective emissivity less than 0.50). Jet aircraft have been suspected of increasing cirrus cloud cover from their contrails, but these data do not reveal much correlation between jet air traffic and increases in high thin cirrus. Increases of high cirrus seem to occur in areas of high air traffic, such as central and western North America and Europe, as well as areas of rare air traffic, such as the Southern Ocean around Antarctica. It is likely that high cloud cover changes are mostly caused by larger weather systems.

The most significant feature of these data may be that the globally averaged cloud cover has shown little change in spite of dramatic volcanic and El Nino events. During the four El Nino events winter clouds moved from the western Pacific to the Central Pacific Ocean, but their global average in the tropics did not change (see Figure 4). El Chichon and Pinatubo spewed volcanic ash into the stratosphere that took 1-2 years to fall out, but cloud cover was not affected significantly.

## 6. CONCLUSIONS

In summary, the UW NOAA HIRS Pathfinder cloud 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; this is in good agreement with GLAS but 10 % more than ISCCP. 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) HIRS trends in all clouds were small and not significant while ISCCP found a decrease of about 3 to 4 % per decade; HIRS found a 2 % per decade increase in high clouds while ISCCP found no significant change. (d) 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.

## 7. ACKNOWLEDGMENTS

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**Table 1:** UW Pathfinder HIRS Cloud Processing Summary

Record length - 22 years
Orbits processed - all orbits (ascending and descending)
View angles considered - 18 deg from nadir
Coverage - contiguous fovs over whole globe processed
Cloud mask - based on spatial & temporal variances of IRW plus $CO_2$ screening of thin cirrus
Clear radiances – based on forward radiance calculation with bias correction interpolated from nearby fovs (using NCEP/NCAR Reanalysis)

**Table 2:** Local overpass times for the NOAA satellites since 1978. The asterisk indicates NOAA 11 and 14 drifted from 14 UTC to 18 UTC over 5 years of operation.

| morning (8 am LST) | afternoon (2 pm LST) |
|---|---|
| NOAA 6 HIRS/2 | NOAA 5 HIRS |
| NOAA 8 HIRS/2 | NOAA 7 HIRS/2 |
| NOAA 10 HIRS/2 | NOAA 9 HIRS/2 |
| NOAA 12 HIRS/2 | NOAA 11 HIRS/2 * |
| | NOAA 14 HIRS/2 * |

**Table 3a:** The distribution of UW NOAA Pathfinder HIRS cloud reports by cloud height and density from 1979-2001. $N\varepsilon$ refers to effective emissivity, and $\sigma$ refers to the corresponding visible optical depth. Over 76,000,000 HIRS observations from 9 NOAA satellites are included. Percentages of all observations are reported.

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

**Table 3b**: Table 3a statistics which have been corrected for the number of times the middle and low layers were actually observed by HIRS using the random overlap assumption.

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

**Table 4a:** The local time of the ascending node equator crossing at the beginning and ending of the flights of each NOAA satellite in the 2 am/pm orbit.

| Satellite | First Month | Time (hrs) | Last Month | Time (hrs) |
|---|---|---|---|---|
| NOAA 5 | Jan. 1979 | 15.32 | Jan. 1981 | 15.88 |
| NOAA 7 | Jul. 1981 | 14.51 | Jan. 1985 | 15.93 |
| NOAA 9 | Jan. 1985 | 14.37 | Oct. 1988 | 16.12 |
| NOAA 11 | Nov. 1988 | 13.71 | Dec. 1994 | 17.28 |
| NOAA 14 | Jan. 1995 | 13.73 | Dec. 2001 | 17.53 |

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

| | Orbit drift corrections. | | | |
|---|---|---|---|---|
| | All Clouds | | High Clouds | |
| | Land | Sea | Land | Sea |
| 20-60 N | -0.004 | 0.002 | 0.007 | 0.004 |
| Tropics 20 S - 20 N | -0.010 | 0.006 | 0.010 | 0.004 |
| 20-60 S | -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 from 1985-2001.

| | 20 to 60 N | | 20 N to 20 S | | 20 to 60 S | |
|---|---|---|---|---|---|---|
| | Ocean | Land | Ocean | Land | Ocean | Land |
| HIRS uncorrected | | | | | | |
| High Clouds | 0.013 | 0.014 | none | 0.017 | 0.014 | 0.021 |
| All Clouds | none | none | 0.018 | none | none | none |
| HIRS corrected | | | | | | |
| High Clouds | 0.023 | 0.021 | none | 0.017 | 0.027 | 0.029 |
| All Clouds | none | none | 0.014 | none | none | none |
| ISCCP | | | | | | |
| High Clouds | none | -0.015 | none | none | none | -0.020 |
| All Clouds | -0.042 | -0.031 | -0.037 | -0.021 - | 0.017 | -0.010 |

**Table 6:** HIRS, ISCCP, and GLAS Global Cloud Detection

| | All Clouds | | High Clouds | |
|---|---|---|---|---|
| | Ocean | Land | Ocean | Land |
| HIRS (1979-2001) | 77 | 71 | 32 | 34 |
| ISCCP (1983-2001) | 70 | 56 | 20 | 25 |
| GLAS (Mar 2003) | 80 | 66 | 31 | 34 |

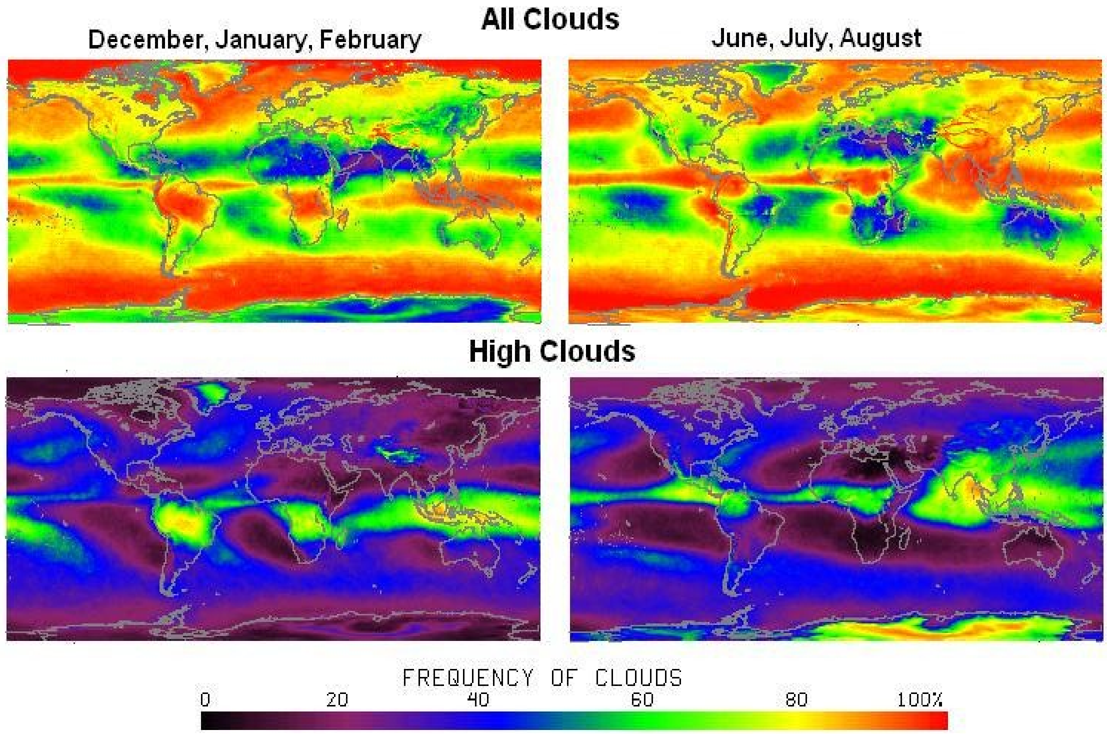


**Figure 1:** The frequency of all clouds and high clouds above 440 hPa from 1979 to 2001 found in HIRS data during winter (D, J, F) and summer (J, J, A).

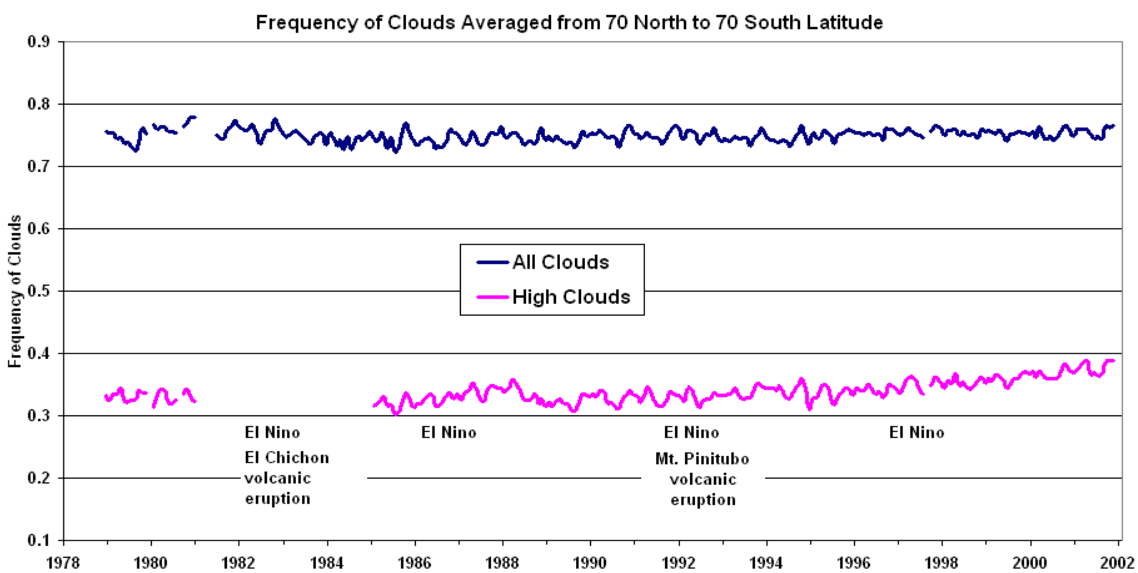


**Figure 2:** The monthly average frequency of clouds and high clouds (above 6 km) from 70 south to 70 north latitude from 1979 to 2002.

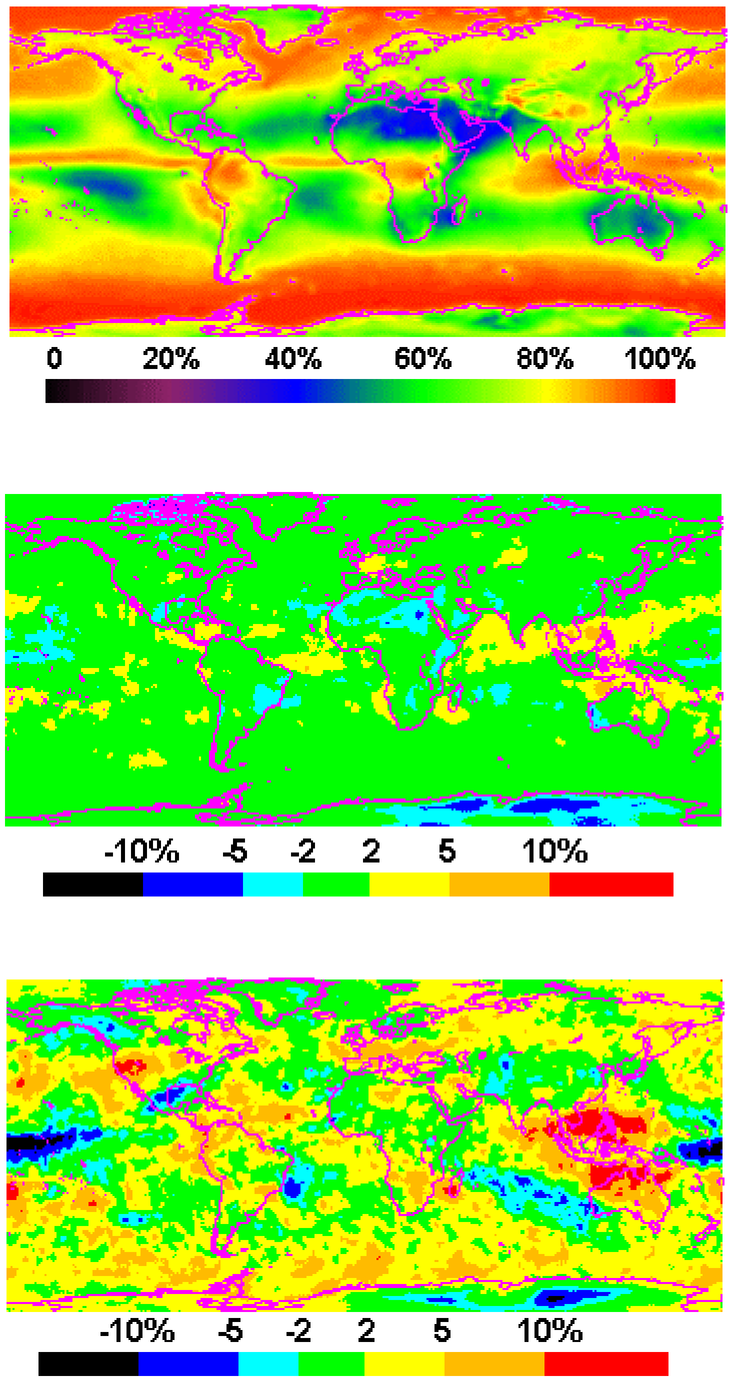


**Figure 3a:** (Top) Frequency of all clouds found in HIRS data since 1979. (Middle) Change in cloud frequency from the 1980s to the 1990s. (Bottom) Change in high cloud (above 6 km) frequency during northern hemisphere winters (December, January, and February) from the 1980s to the 1990s.

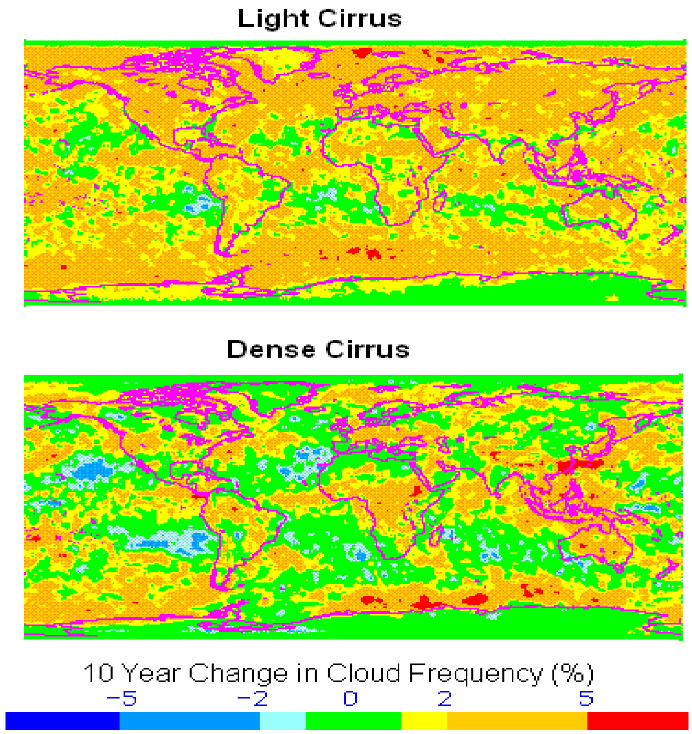


**Figure 3b:** (Top) Change in thin high cirrus frequency from the 1980s to the 1990s. (Bottom) Change in dense high cirrus frequency from the 1980s to the 1990s

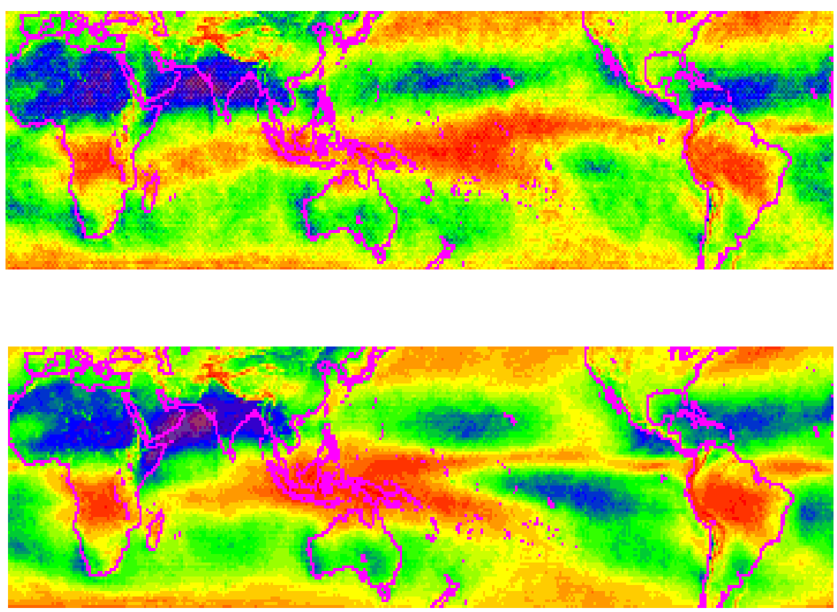

**Figure 4:** High cloud (above 6 km) frequency of occurrence during El Nino years (top) compared with all the other years (bottom) during northern hemisphere winters (December, January, and February) in the 1980s and 1990s.