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Improvements in High Cloud Detection Using High Scan HIRS Data

by

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1. Introduction

This is a report for work done to improve detection of high clouds using weather satellite data. The University of Wisconsin routinely collects information on the frequency of clouds and their density from the weather satellites operated by the National Ocean and Atmospheric Administration (NOAA). The High Resolution Infrared Radiometer Sounder (HIRS) on the polar orbiting NOAA series satellites provide data from which the thinner high clouds can be detected. These data are available globally and also can be acquired by line of sight ground receivers when the NOAA satellites pass over head. The University of Wisconsin has been compiling statistics of cloud frequencies for the past 16 years using the HIRS data.

The objective of this project was to improve the detection of optically thin clouds by using HIRS data from high scan angles through the atmosphere. The current statistics have been compiled only from data taken near the nadir view. The HIRS scans across the orbit tract reaching a maximum zenith angle of 59° through the atmosphere. The higher scan angles provide a longer path through the cloud making the cloud detection algorithm more sensitive to optically thin clouds. In this study we compare cloud information collected from the high scan angles to the traditional cloud data extracted from only the near nadir data. A global data set of both scan angles as been collected for one year. The increase in sensitivity of the high scan angle data is discussed.

The Wisconsin cloud statistics also have been used to verify the prediction of clouds made by one weather prediction model of the European Center for Medium Range Forecasting (ECMWF). This comparison was outside of the scan angle study. It is included here because it was included in the oral presentations to the Air Force in July, 2000. It shows the current ability cloud prediction in weather prediction models.

2. Method of Detecting Clouds from HIRS Data

HIRS has four channels in the longwave infrared spectrum from 13.3-14.7 µm. They each contain partial absorption by CO_2. Altitude sensitivity of each channel varies with the amount of CO_2 absorption. The name CO_2 Slicing implies each channel is sensitive to different levels of the atmosphere. However, the levels of sensitivity overlap each other (Figure 1).

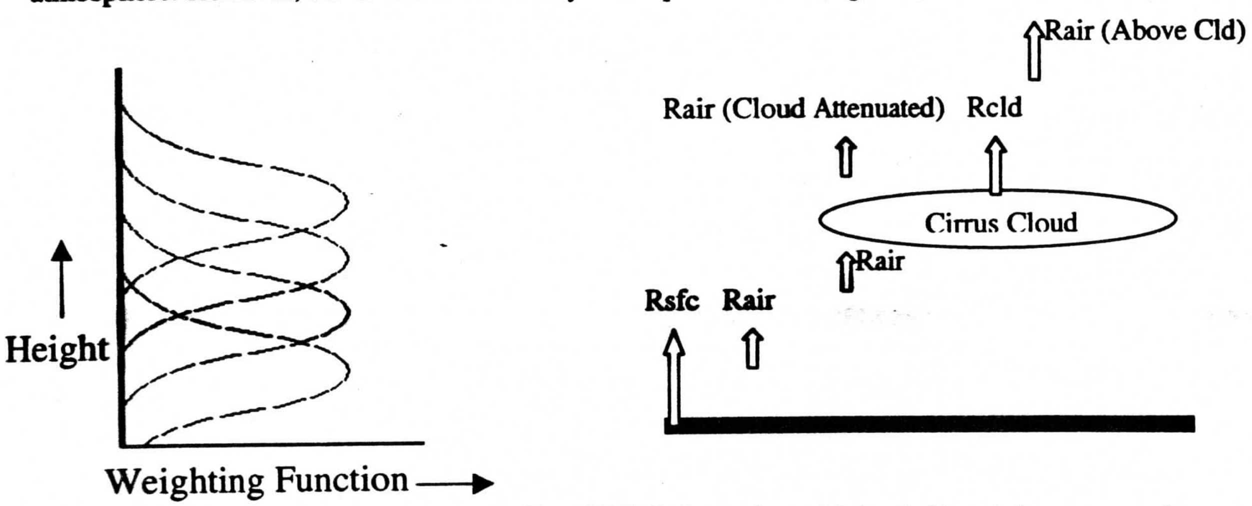

Figure 1: A schematic of the vertical profile of HIRS channel sensitivity (left) and the sources of infrared radiation passing out of the atmosphere.

The radiation reaching the satellite is assumed to come from the combination of four sources: 1) emission from the surface, Rsfc, 2) emission from air, Rair, which has been attenuated passing through the cloud, 3) emission from the cloud, Rcld, and 4) emission from air above the cloud. We assume only one level for the cloud and all radiative emission and absorption are assumed to take place at one level. Scattering in the longwave infrared is very small and not considered. Real clouds are move complex often having more than one layer and/or vertical variations in density. However, the satellite sensor sees the vertical integral of all radiation upwelling from the atmosphere. Some knowledge of the vertical profile of cloud density and layers is needed to solve the equation. Since any number of layers and any shape of the vertical profiles of cloud density are possible, the only unique solution is to assume one cloud layer.

The working equation is formed by subtracting the upwelling radiance measured at the cloudy pixel (Rcld) from an estimate of what this radiance would have been if the pixel were clear (Rclr). Using the radiative transfer terms above, the equation on the following page is derived. The full derivation of this equation is given in Wylie, Menzel, and Strabala, Journal of Climate, 1994, Vol. 7, pages 1972-1986, "Four years of global cirrus cloud statistics using HIRS."

The working equation is as follows.

$$\frac{Rclr(Ch4) - Rcld(Ch4)}{Rclr(Ch5) - Rcld(Ch5)} = \frac{N\varepsilon(Ch4) \int_{psfc}^{Pcld} \{\tau(Ch4, p) dB[Ch4, T(p)] / dp\} dp}{N\varepsilon(Ch5) \int_{psfc}^{Pcld} \{\tau(Ch5, p) dB[Ch5, T(p)] / dp\} dp}$$

Rclr – *Rcld* = Clear – Cloud radiance on the channel. *Rcld* is the measurement. *Rclr* is estimated for the location.
N = Field of view (FOV) fractional coverage.
ε = Infrared emissivity.

$$\int_{p\,sfc}^{p\,cld} \{\tau(Ch\,4, p) dB[Ch\,4, T(p)] / dp\} dp$$

is the vertical integral of atmospheric transmittance multiplied by the derivative of the Planck function. We assume $N\varepsilon(Ch4) = N\varepsilon(Ch5)$ since the channels are spectrally very close.

The only unknown is *Pcld*, the cloud top pressure. The left side of the equation contains measurements whereas the right side has only calculations of the integrated upwelling radiation. From two HIRS channels from 13.3 to 15 μm, one cloud height can be derived.

The emittance of the cloud can be solved for by

$$N\varepsilon = \frac{Rclr - Rcld}{Rclr - B(Tc)}$$

where *Tc* is the temperature of the atmosphere at level *Pcld* and *B(Tc)* is the Planck function calculation of the radiance that would have been emitted from level *Pcld* if the cloud would have been radiatively opaque. $N\varepsilon$ is effectively the infrared signal of the cloud divided by what the signal would have been if the cloud were radiatively opaque. It is also 1.0 – IR transmission.

With $N\varepsilon$ the optical depth of the cloud can be calculated.

$\tau vis = -2 \ln(1.0 - N\varepsilon)$

Using the ratio of two channels not only removes the problem of cloud transmission and emissivity ($N\varepsilon$), it also minimizes errors in radiative transfer calculations that come from inaccurate atmospheric temperature and moisture soundings. The largest problem in the calculation is estimating the clear radiance term, Rclr. This will be discussed later.

3. Cloud Frequency Statistics

The mean cloud frequency statistics from 6 years of HIRS data are shown in Figures 2-5. These images were taken from the author's web page, http://www.ssec.wisc.edu/~donw. The monthly summary statistics also are available at the Hanscom AFB PDAC and the Photon Research Inc. Tool Kit.

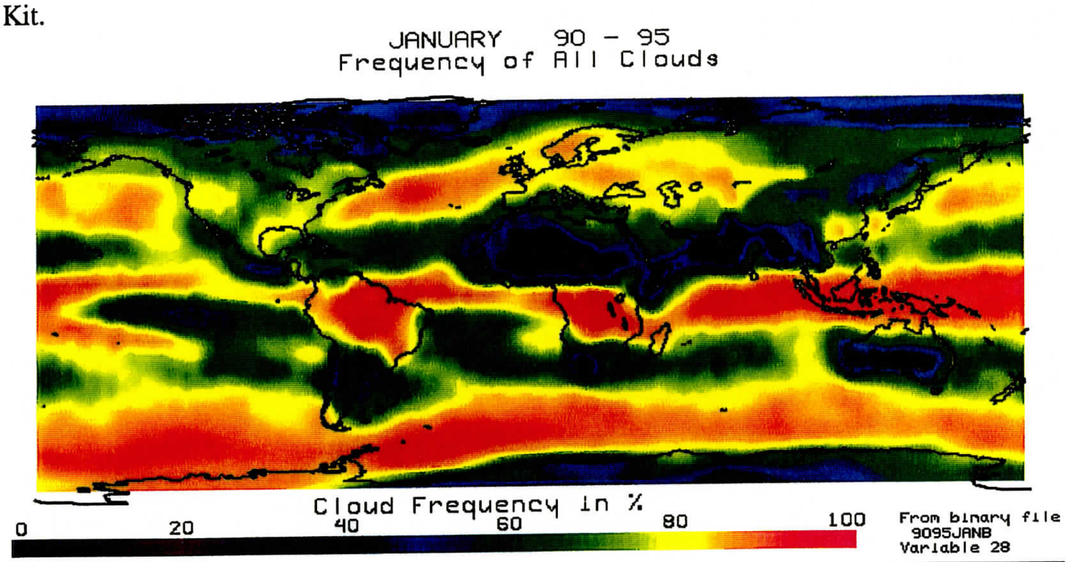

Figure 2: The mean frequency of clouds in January from the HIRS nadir data.

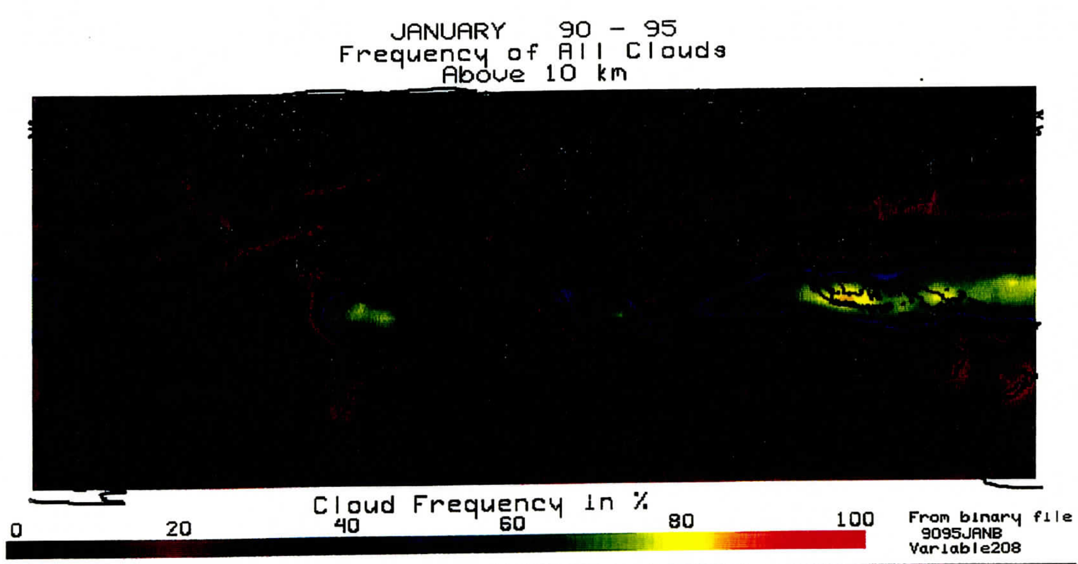

Figure 3: The mean frequency of clouds above 10 km in January from HIRS.

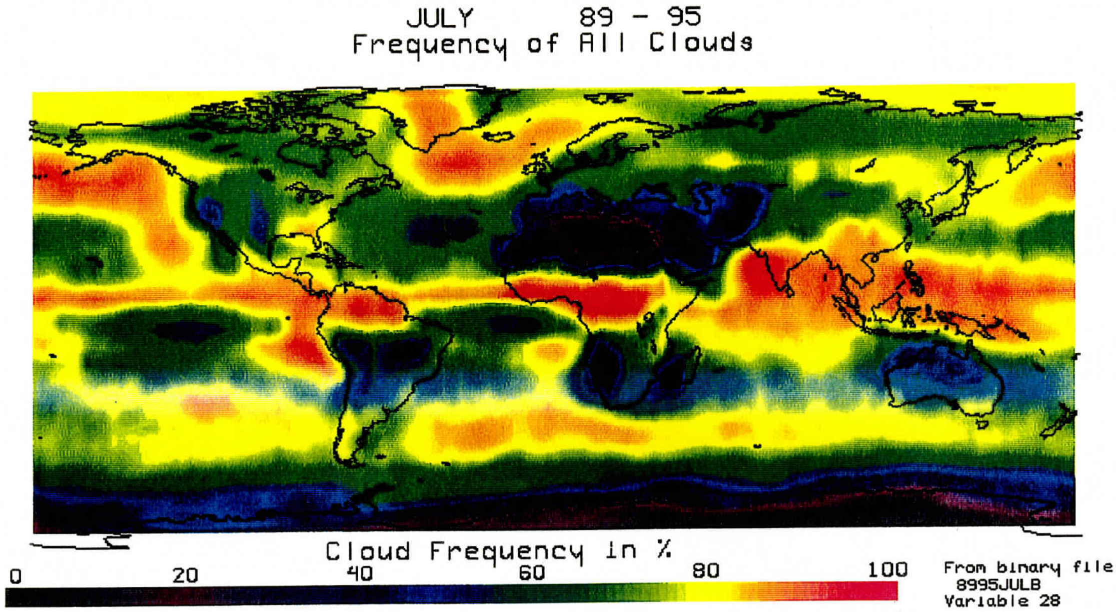

Figure 4: The mean frequency of clouds in July.

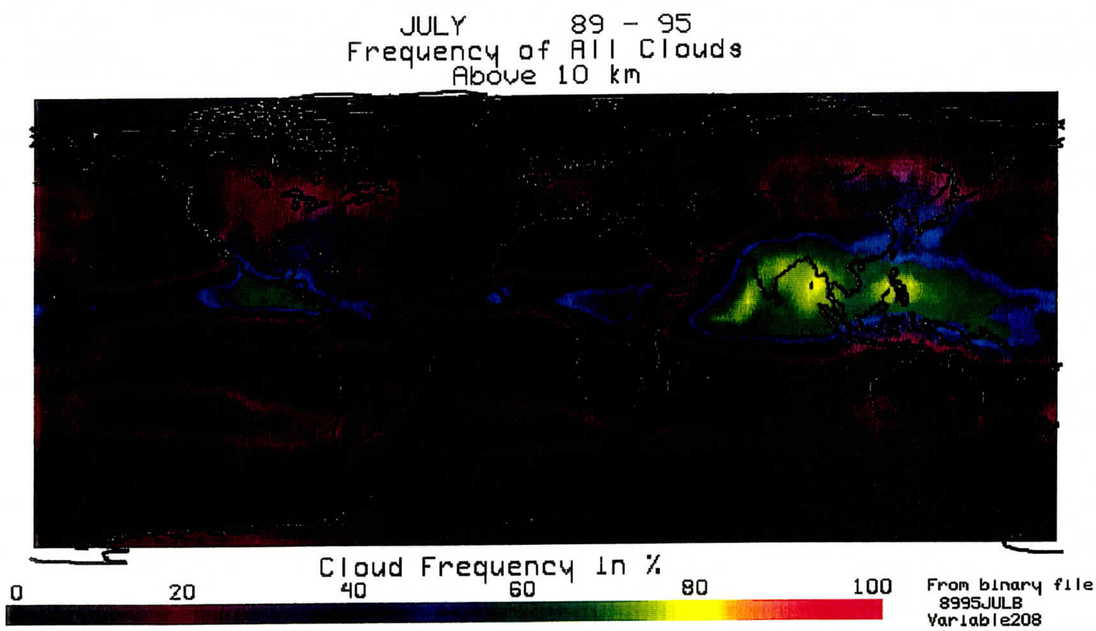

Figure 5: The mean frequency of clouds above 10 km in July. Available at http://www.ssec.wisc.edu/~donw and the Hanscom AFB PDAC.

The mean statistics show that clouds are most frequently found in the tropics. Most of the high clouds above 10 km are produced by the deep convective anvils. Poleward of the convective zone are the subtropical deserts over land and the subtropical high pressure areas over oceans where cloud frequencies are low. In the temperate latitudes cloud frequencies increase because of fronts and low pressure systems.

Cloud frequencies also decrease in the upper troposphere (the same color scale is used on all images). Cloud frequencies vary greatly between sites of interest. Kwajalein Island which is the right side of all images (8.7 N, 167 E, right boundary is 180 longitude), has some of the highest cloud frequencies. The Korean Peninsula has a large latitude difference in cloud frequency in July – higher frequencies in the south and lesser frequencies in the north. The Middle East has moderately low cloud frequencies.

4. Comparison to Other Satellite Data

The Stratospheric Aerosol and Gas Experiment (SAGE) sensor is more sensitive to high clouds than most current HIRS cloud detection systems. The SAGE gains sensitivity from its scanning geometry. SAGE looks at the sun as it appears and disappears over the horizon on each orbit. This is nearly a 90° nadir viewing angle. It would be horizontal except for the curvature of the earth. Thin clouds easier to detect in SAGE data because of the long path length through them. Two comparison have been made between the Wisconsin HIRS data and SAGE. They are

Wylie and Wang, J. Geophysical Research, 1997, Vol. 102, pages 29,893-29,900, "Comparison of cloud frequency data from the high-resolution infrared radiometer sounder and the Stratospheric Aerosol and Gas Experiment II", and

Wylie and Wang, J. Geophysical Research Letters, 1999, Vol. 26, pages 3373-3375, "Comparison of SAGE-II and HIRS co-located cloud height measurements."

In the 2nd paper, the height difference between the HIRS *Pcld* measurement and the cloud top detected by SAGE were compared. The HIRS *Pcld* represents the mean height where the cloud absorption and re-emission take place. It theoretically should be the middle of diffuse clouds. For dense clouds and radiatively opaque clouds, *Pcld* should be the cloud top. The difference between the SAGE and *Pcld* is the error of *Pcld* from the "true " cloud top. The following scatter diagram shows the measurements of 71 clouds by both systems.

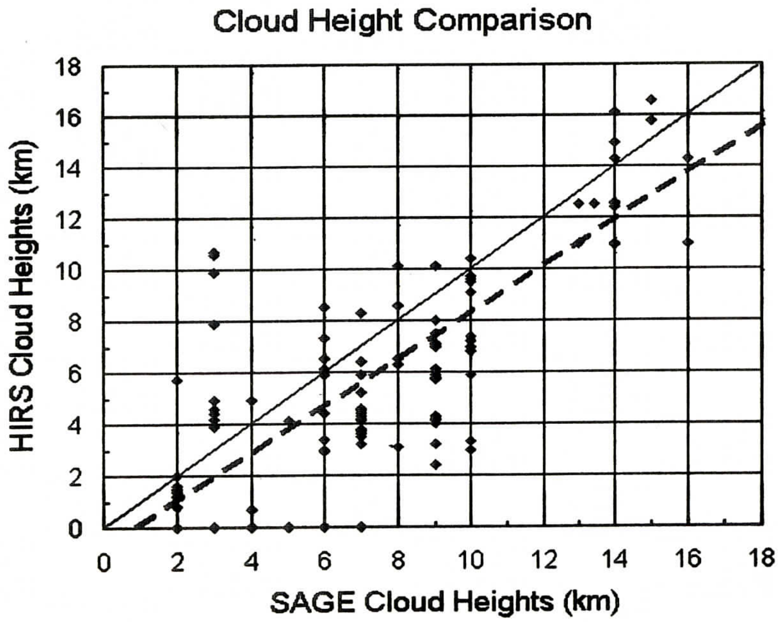

Figure 6: Scatter plot of height measurements from SAGE and HIRS data.

The HIRS retrieved cloud height averaged 1.6 km below the SAGE cloud top. For high clouds the difference was 2.0 km. This confirms the adjustment in cloud heights made to HIRS the data shown on the web page http://www.ssec.wisc.edu/~donw .
Comparisons of HIRS derived cloud heights also were made to lidar measurements of cloud tops using University of Wisconsin Lidar data collected in Everglades City, FL during September 1996. The HIRS measurements are the red numbers in Figure 7. The red square is the location of the lidar. The yellow numbers are also satellite derived cloud heights from the Geostationary Sounder instrument on GOES-8. Both HIRS and Sounder derived cloud heights are in meters/100 (i.e 15=1,500 m and 167=16,700 m).

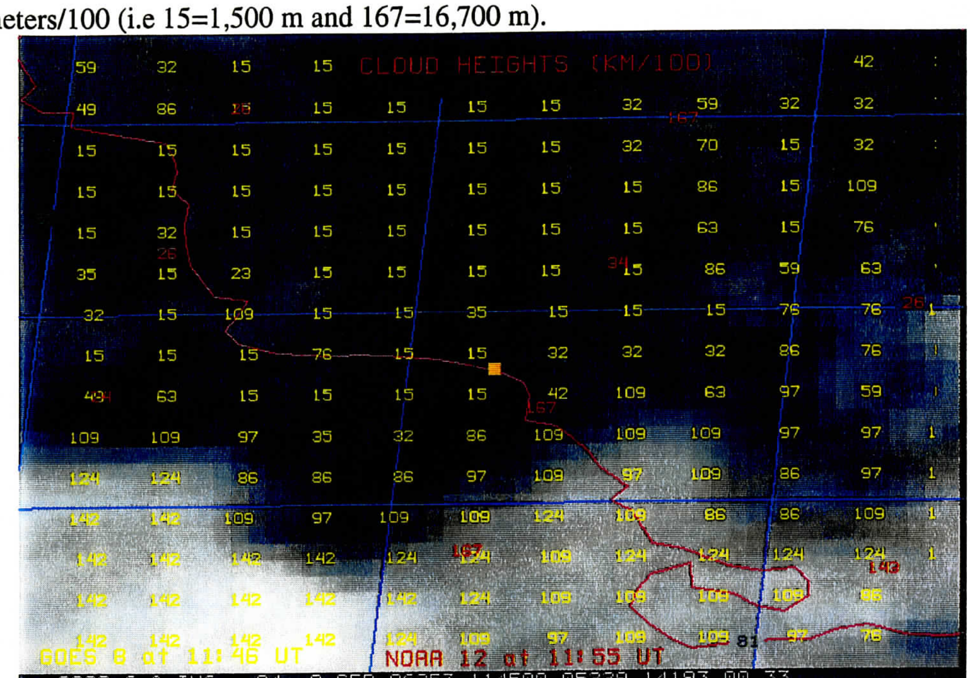

Figure 7: HIRS derived clouds heights in 100's meters in red. Cloud heights in yellow are from a similar sensor on the geostationary satellite GOES-8.

The HIRS data are more widely spaced because Everglades City was on the far reach of the sensors scan. This is also a reason for the HIRS derived cloud heights being higher than the Geostationary Sounder.

The Volume Imaging Lidar (VIL, see Figure 8) scanned from northwest to southeast. The vertical cross section is shown in the next Figure. The VIL scan covered only about one Sounder Pixel in each direction from Everglades City (red square).

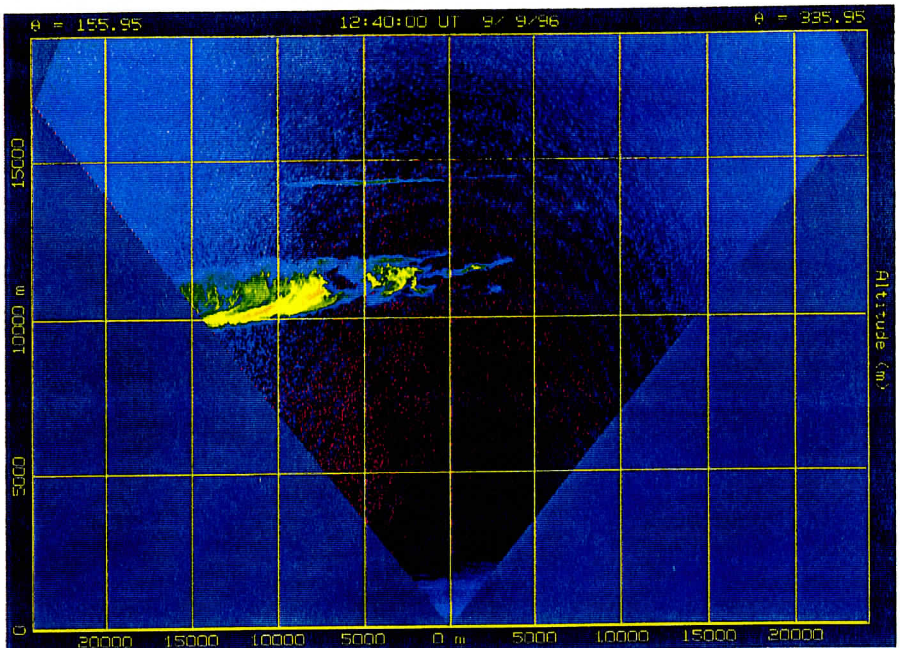

Figure 8: A cross section of backscatter return from the Volume Imaging Lidar in Everglades City Florida.

The VIL picked up a thin cloud layer around 14.5 km with a thicker layer from 9.8-12.5 km. The Geostationary Sounder shows cloud heights in the thicker layer, 10.9 km (109 on the image) while the HIRS shows higher heights of 16.7 km. The HIRS cloud height retrevials are above the highest clouds seen by the VIL. The reason for discrepancy is the error in the clear radiance estimate (*Rclr*) used in the calculation. It came from spatial interpolation of data measured closer to the nadir view (directly under the satellite). The data at Everglades City were from scan paths of >50° from zenith through the atmosphere. The large scan path increased the sensitivity of the HIRS cloud retrieval algorithm but the error of not accounting for increased scan path in the *Rclr* term caused the *Pcld* calculation to be above the cloud. A comparison of 28 HIRS measurements with lidars data at Everglades City is shown in Figure 9.

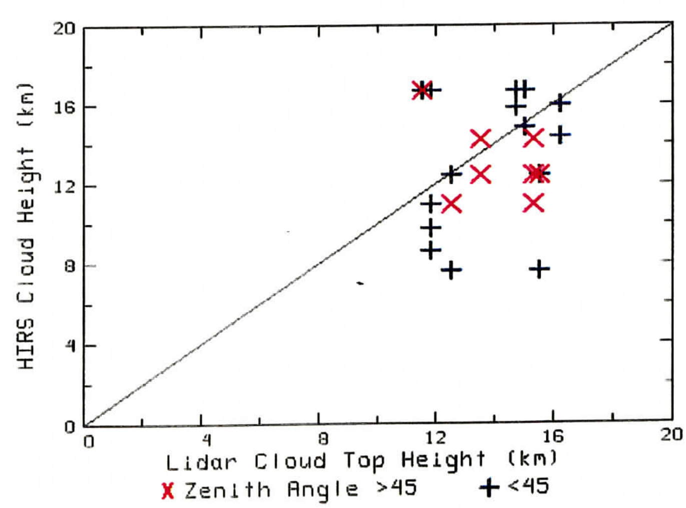

Figure 9: Cloud heights form HIRS compared to lidar data.

Zenith angle scans > 45° (X) average higher than the lower scan angles (+). The average differences are shown in the Table 1.

The cloud height bias, HIRS-Lidar. Number of points compared are in parenthesis.

	Light Clouds Optical Depth <1.4 IR Emissivity <50%	Dense Clouds Optical Depth >1.4 IR Emissivity >50%	All Optical Depths
High Scan Angle >45°	+1.5 km (11)	+0.9 km (3)	+1.4 km (14)
Scan Angles <45°	-2.1 km (10)	-3.3 km (4)	-2.5 km (14)
All Scan Angles	-0.2 km (21)	-1.5 km (7)	-0.5 km (28)
HIRS-SAGE (Mostly Nadir Scan Angles)			-1.6 km (71)
GOES/VAS-Lidar in Wisconsin (1986)			-1.3 km

The Florida comparison with lidar shows an average difference of 0.5 km between HIRS cloud height retrievals and the cloud top. The low zenith scan angle data averaged 2.5 km below cloud top while the high scan data averaged 1.4 km above the cloud top. Dense clouds (emissivity >50%) also had lower heights than optically thin clouds. The SAGE vs. HIRS comparison average of 1.6 km also is shown in the Table 1. On the bottom row is an older comparison the GOES Atmospheric Sounder on GOES-6. It had a mean difference of 1.3 km. The Florida 1996 data show less difference of the HIRS retrievals from the other cloud top measurements than in other experiments. The unique feature of Florida 1996 is that its tropical data while most of the other data is from mid-latitudes.

5. High Scan Angle Cloud Data

The Wisconsin HIRS cloud analysis currently uses only data zenith scan angles < 10° through the atmosphere. A parallel run was made using the opposite condition of zenith scan angles >45° ignoring the other data. The parallel run was made for one year starting in April 1999. Figure 10 depicts the scan range of the HIRS sensor.

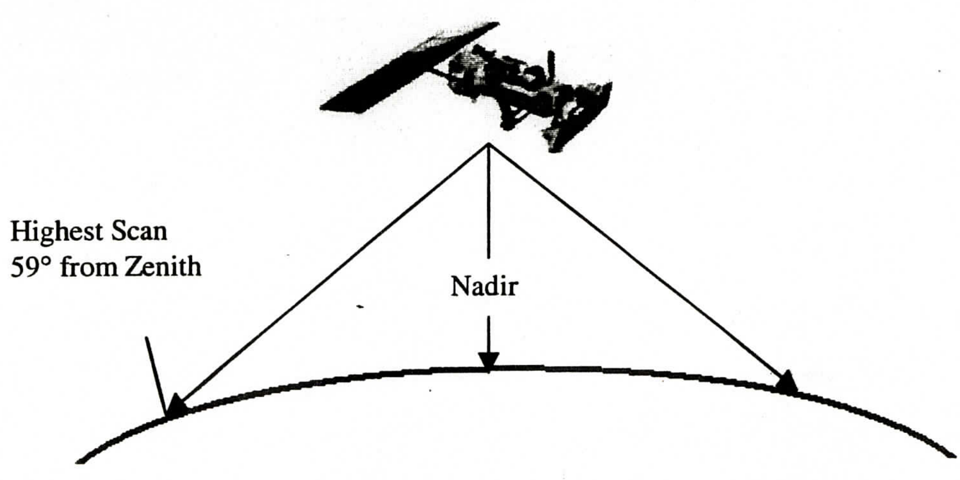

Figure 10: A schematic of the HIRS scan angle range on the surface of the earth.

The problem in the Florida 1996 HIRS data is that the *Rclr* term in the working equation has not been corrected for the path through the atmosphere. *Rclr* will decrease in the high angle scans because of absorption by atmospheric gasses is higher due to the longer path through the atmosphere. The theoretical calculations on the right side of the working equation consider the path length. The current method of deriving *Rclr* does not. The Wisconsin global HIRS analysis uses data with only one path length, the nadir views. For the Florida data set, all scan angles were used to give more days where the HIRS took common data with the lidars. This produced unrealistically warmer *Rclr* values for the high scan data since most *Rclr* measurements were made at lower scan angles. This is why the HIRS *Pcld* solution was often above any cloud detected on the lidar.

The parallel high scan angle run used only *Rclr* data from the same high scan angles. This prevented mixing of the scan data as done for the Florida experiment. The difference between one year of nadir vs. high scan data is shown in Figure 11. This is one year of data divided into three regions by latitude. The mean cloud frequencies are from the nadir data – the operational standard. The dashed lines are the differences in cloud frequencies of the high scan analysis from the nadir analysis.

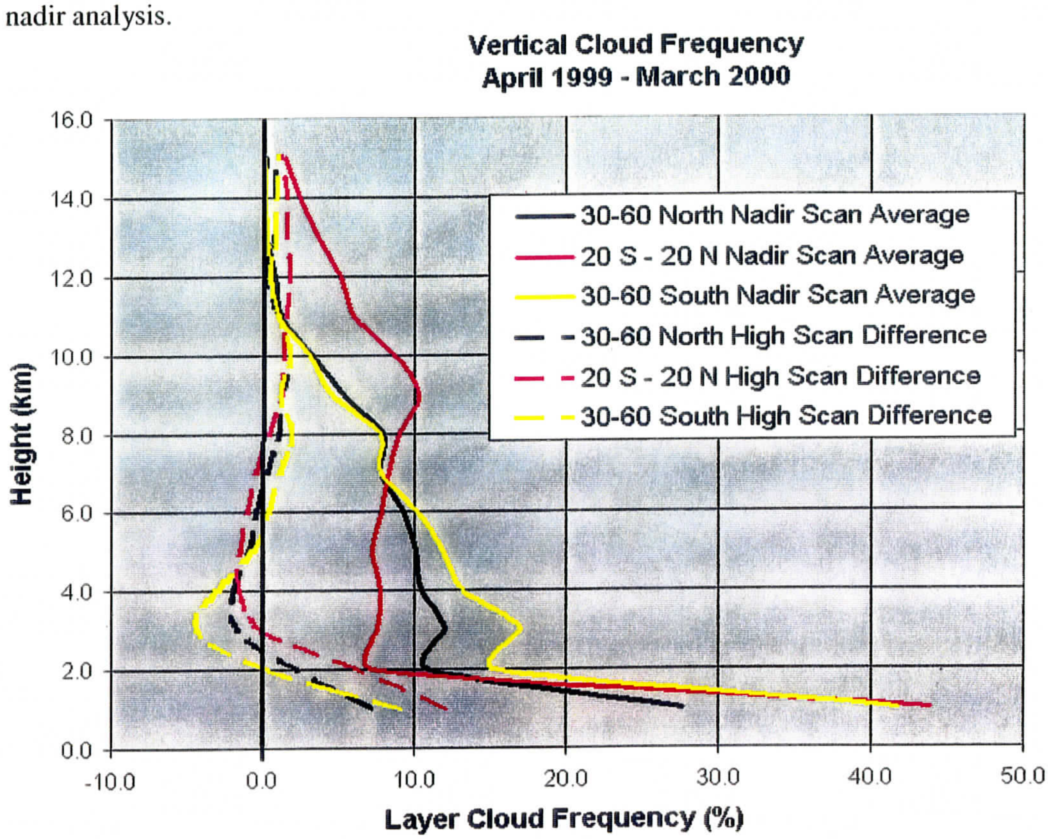

Figure 11: The frequency of clouds with height and the change in frequency found by using the high scan angle data (dashed lines).

The high scan analysis found more clouds mainly in the lowest 1 km. The reason for increased cloud detection is that the HIRS Field of View (FOV) is twice as large at the high scan angles than nadir. More partly cloudy FOVs are counted as clouds. Correction for the cloud and clear fractions inside the FOV are not possible since the CO_2 absorbing channels do not see the lowest km.

The other major difference of the high scan angle analysis from the nadir analysis is the reduction in cloud detection from 3-6 km and the increase in detection above 8 km. The increased detection comes from the longer path through the atmosphere increasing the optical depths of the clouds. In the high scan angle run, some clouds now passed the CO2 equation that failed in the nadir analysis. They moved from altitudes of 3-6 km to above 8 km. The change is 5-10 % (percentage of all HIRS clear and cloudy observations). These changes are summarized in Table 2.

Table 2: Summary of the differences between the nadir and high scan HIRS cloud data.

	>6 Km	>6 Km, O.D.<1.3	T(clear)
30-60 North	5 %	3%	-0.7 K
Tropics (20 S - 20 N)	10 %	4 %	-0.4 K
30-60 South	7 %	4 %	0.0 K

The blackbody clear radiance temperatures (b.b temp of *Rclr*) also decreased in the northern hemisphere and the tropics. The southern hemisphere is surprising because the average Tclr remained constant.

The HIRS cloud analysis has recently been modified for the version used on Kwajalein Island by the Aeromet Corp. This version only considers HIRS data near Kwajalein which simplifies the problem because horizontal gradients in temperature are very small in this region. The method of deriving *Rclr* has been modified. It is now calculated from the temperature and moisture sounding. Calculated clear radiances (*Rclr*) will differ from satellite measurements because the soundings and the satellite calibrations have errors. To remove these errors, a data set of clear FOVs is made by comparing the HIRS 11 μm measurements to the Sea Surface Temperature (SST) analysis provided by NOAA. Corrections are made for water vapor attenuation in this channel. Then FOVs with the blackbody radiance temperatures close to the SST are selected as mostly probably clear. *Rclr* is calculated for these FOVs and statistically compared to the HIRS measurements. A mean bias statistic is determined for each channel and scan angle. Then the *Rclr* for the cloud height equation is calculated from the sounding and the statistical bias is removed. This procedure removes the problem found in the Florida 1996 analysis. An example of two HIRS passes over Kwajalein Island is shown in Figure 12. Kawaklein is located at the red box near the outer limit of the scan. The cloud heights are in km. Notice that few high clouds were found along the outer scan row. The technique used in Florida 1996 found mostly high clouds at the scan limit.

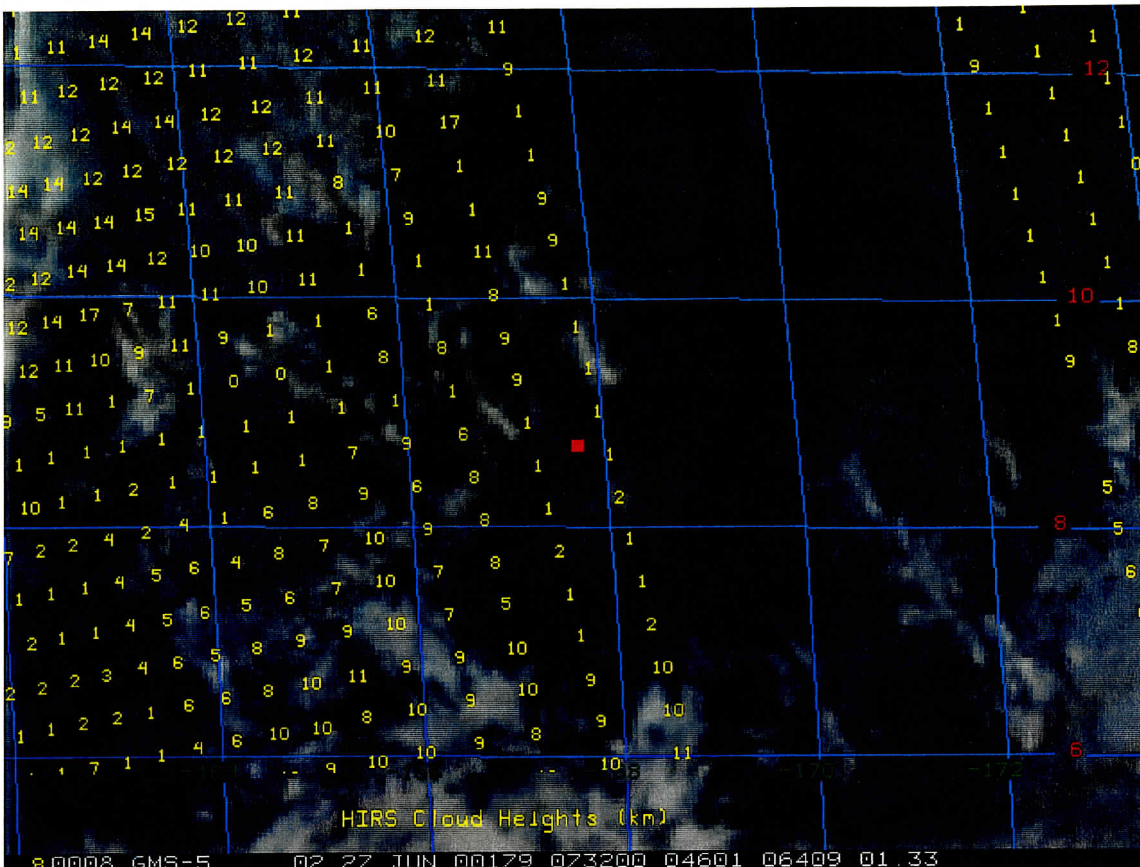

Figure 12: HIRS derived cloud heights plotted on a geostationary infrared image of clouds in the western Pacific Ocean. The square marks Kwajalein Island.

The revised technique for Kwajalein appears to have solved the scan angle problem. Global use of this technique is being investigated.

6. Verification of Weather Forecast Model Cloud Predictions

A comparison of cloud forecasts from the European Center for Medium Range Forecasting model (ECMWF) was made to Wisconsin HIRS cloud observations. This comparison was made to evaluate the skill of the ECMWF model. This is a global model operationally used for general weather forecasting by most European countries. It is considered to be the best global model in operation. The ECMWF cloud probability forecast is compared to the HIRS observations in Figure 13. These are monthly averages. For the ECMWF it is the average of high cloud (< 400 mb) forecasts for 6 hours, made every 6 hours over one month.

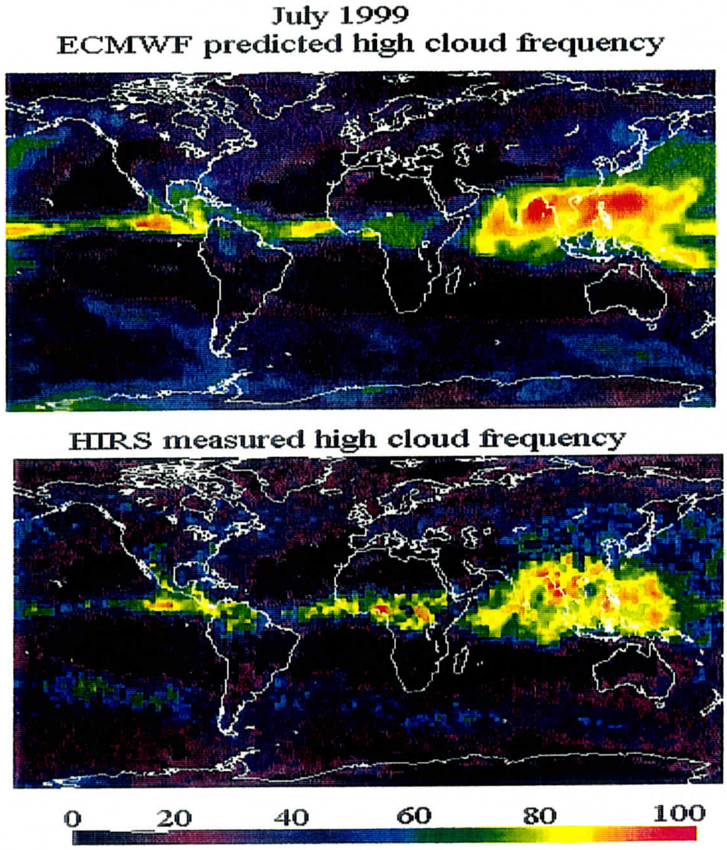

Figure 13: The frequency of cloud forecast by the ECMWF model averaged for the month of July 1999 (top panel) compared to the measurement of cloud frequency from HIRS data (bottom panel).

The ECMWF forecasts agree very well with the HIRS observations. Similarly good agreement also was found for January 1999 in addition to the July 1999 data shown here.

A second comparison was made where the ECMWF 6 hour forecast cloud probably was summed for two categories: 1) when HIRS also found a cloud at the same location, and 2) when HIRS did not find a high cloud. This test was done to see how much the ECMWF cloud forecast changed between clear and cloudy observations. The results are shown in Figure 14. The upper panel is the average of all ECMWF forecasts only when high clouds were found while the lower panel is the average of the ECMWF forecasts when HIRS did not detect high clouds. Ideally the top panel should be red implying a 100% forecast when clouds were found and the bottom panel should be black implying a 0% forecast when clouds were not found. The reality is that the ECMWF had its highest probabilities when clouds were found and lower probabilities when they were not. The ECMWF probabilities differed between top and bottom panels. This still indicates skill in the ECMWF forecasts even though they aren't perfect. For most of the mid-latitudes, the ECMWF shows considerably good skill. However, in the deep tropics, the ECMWF forecast high cloud probabilities even when HIRS did not find clouds. These areas also have the highest occurrences of clouds (see the previous Figure). My conclusion is that ECMWF has considerable skill in forecasting clouds except for the regions in the bottom panel where yellow and red colors appear.

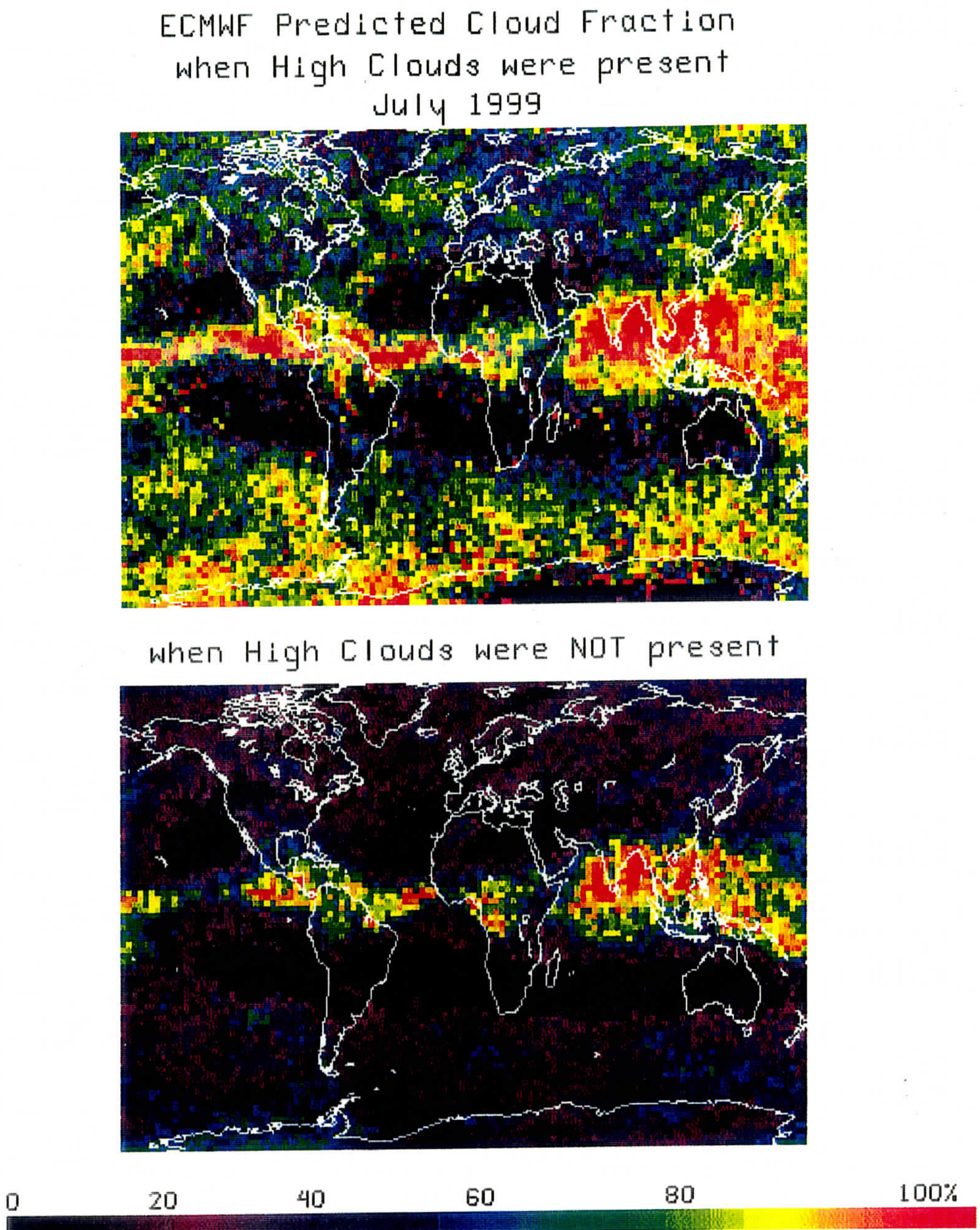

Figure 14: The top panel is the probability of a high cloud forecast by the ECMWF model averaged for the month of July 1999 for only the cases where HIRS verified a true high cloud was present. The bottom panel is the average ECMWF forecast cloud probability when HIRS indicated no high cloud was present.

6. Summary and Conclusions:

6.1) The cloud heights from the Wisconsin HIRS analysis are about 1.6-2.0 km below true cloud top from the comparisons with SAGE and lidars. This bias occurs mostly for optically thin clouds. For optically dense clouds it is less. It also validates the cloud height correction applied to the statistics on high cloud probability shown in the web page http://www.ssec.wisc.edu/~donw

6.2) To calculate cloud heights from HIRS data over all of the HIRS scan swath, the clear radiance term, *Rclr*, in the equation has to be calculated from the temperature and moisture sounding and adjusted for biases. The method used to analyze the Florida 1996 over estimates cloud heights (biased high) at the high scan angles.

6.3) The use of HIRS high scan data will increase detection of high clouds by 5-10%. Most of this increase comes from detection of optically thin clouds. Reports of low clouds also will increase which may be a bias from the inability of the sensor to detect some of the smaller holes in the low cloud field.

6.4) The ECMWF model shows good skill in forecasting high clouds (< 400 mb, or >7 km) in most areas of the world. Problems occur in the regions of most frequent cloud cover in the convective areas of Indonesia, Africa, and South America.