A STUDY OF UPPER TROPOSPHERIC CLOUDS AND HUMIDITY USING HIRS, GOES, AND NWP

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1. HIRS CIRRUS CLOUD TRENDS

Seasonal changes in semi-transparent or cirrus global cloud cover have been monitored with multispectral observations with the polar orbiting HIRS (High resolution Infrared Radiation Sounder) since June 1989. 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) and Wylie and Menzel (1999). 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 visible transmittance greater than 0.1.

Effective emissivity refers to the product of the fractional cloud cover, N, and the cloud emissivity, ε, for each HIRS observational area (roughly 20 km resolution). It has been found 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. Comparisons with 1 km resolution AVHRR data indicate that Nε represents ε entirely for optically thicker clouds (when $N\varepsilon \geq 0.5$ associated with infrared transmittance $\tau_{IR} > 0.7$, or $\tau_{vis} > 1.4$); otherwise, the contributions of N and ε are approximately equal for optically thinner clouds (when $N\varepsilon < 0.5$). Thus our estimates of cloud cover assume total FOV cloud obscuration when $N\varepsilon \geq 0.5$, and 72% cloud obscuration of the FOV when $N\varepsilon < 0.5$.

Global HIRS cloud statistics since June 1989 are shown in Table 1. They are separated by cloud type into clear sky ($\tau_{vis} < 0.1$), thin ($\tau_{vis} < 1.4$), thick ($\tau_{vis} > 1.4$), and opaque ($\tau_{vis} > 6$) clouds and separated by level in the atmosphere above 6 km, between 3 and 6 km, and below 3 km. The frequency of cloud observations in a given

FREQUENCY OF CLOUD DETECTION IN HIRS FOV OVER LAND

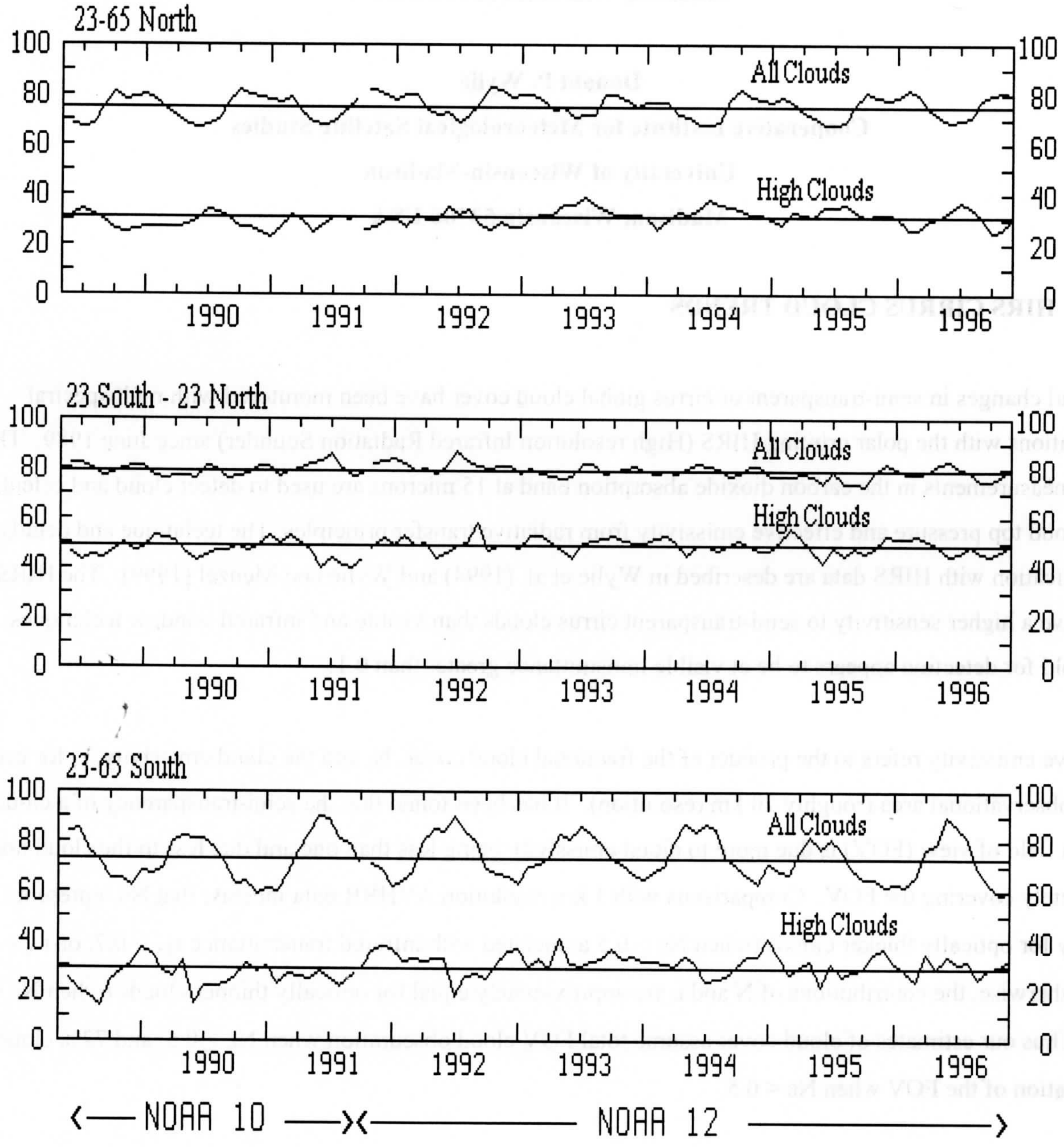

Figure 1a: The frequency of all clouds (upper line) and high clouds above 440 hPa (lower line) over land for the sunrise and sunset satellites, NOAA 10 and 12. The three panels are for latitude belts of 23°-65 ° north, 23° S-23° N, and 65°-23° south.

FREQUENCY OF CLOUD DETECTION IN HIRS FOV OVER LAND

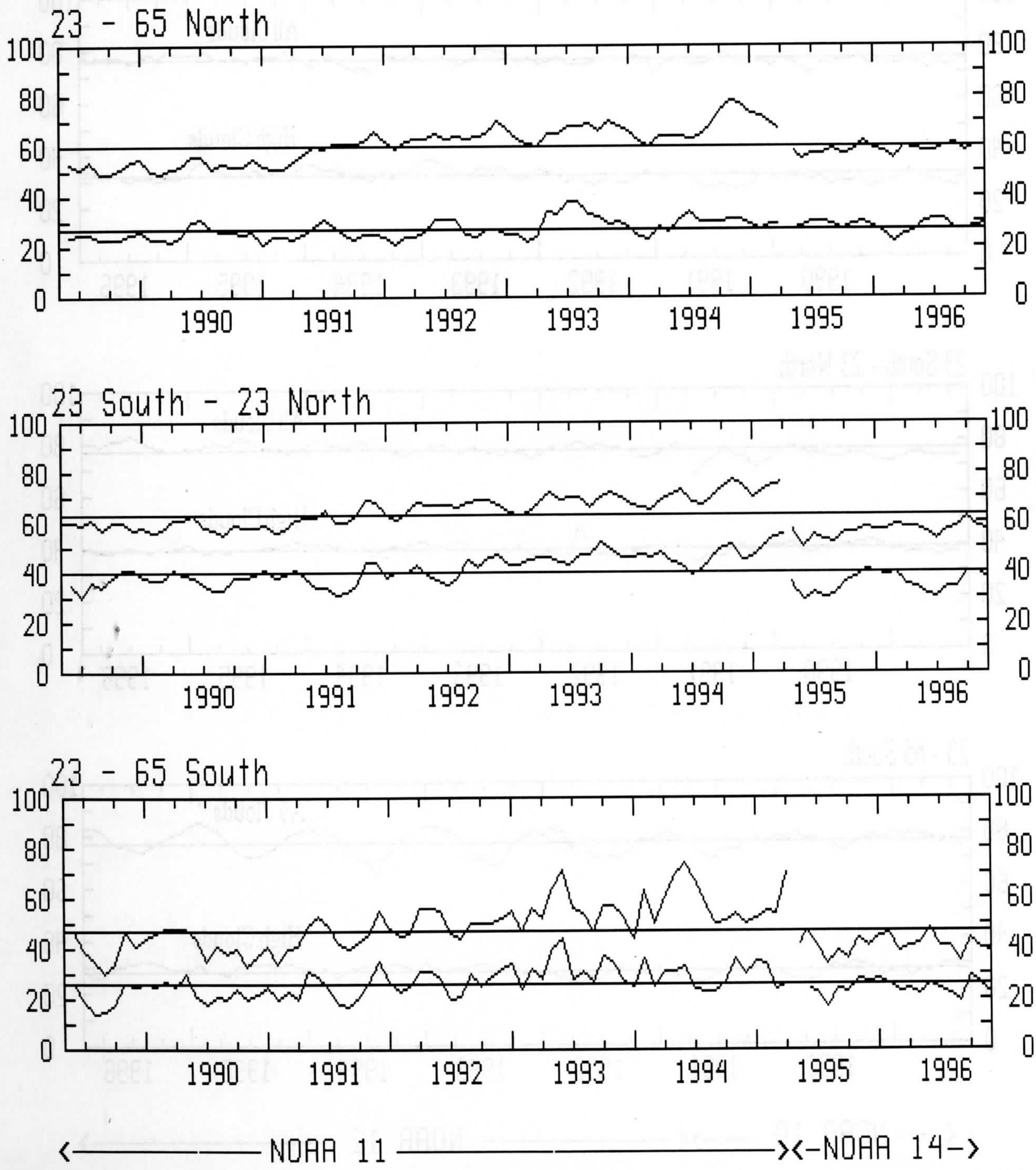

Figure 1b: The cloud frequencies over land for the midday and midnight satellites NOAA 11 and 14.

FREQUENCY OF CLOUD DETECTION IN HIRS FOV OVER OCEANS

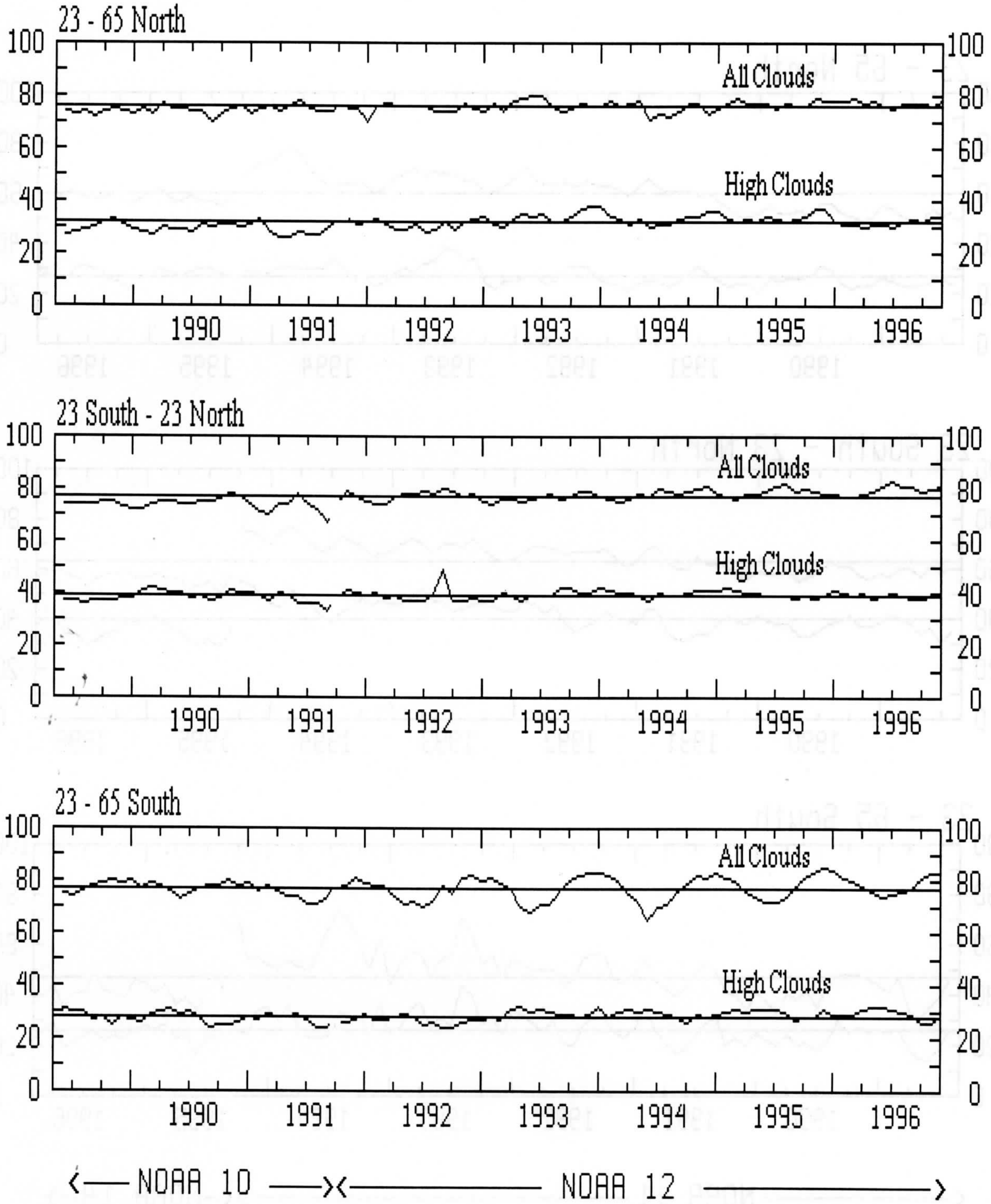

Figure 1c: The cloud frequencies over water for sunrise and sunset satellites NOAA 10 and 12.

FREQUENCY OF CLOUD DETECTION IN HIRS FOV OVER OCEANS

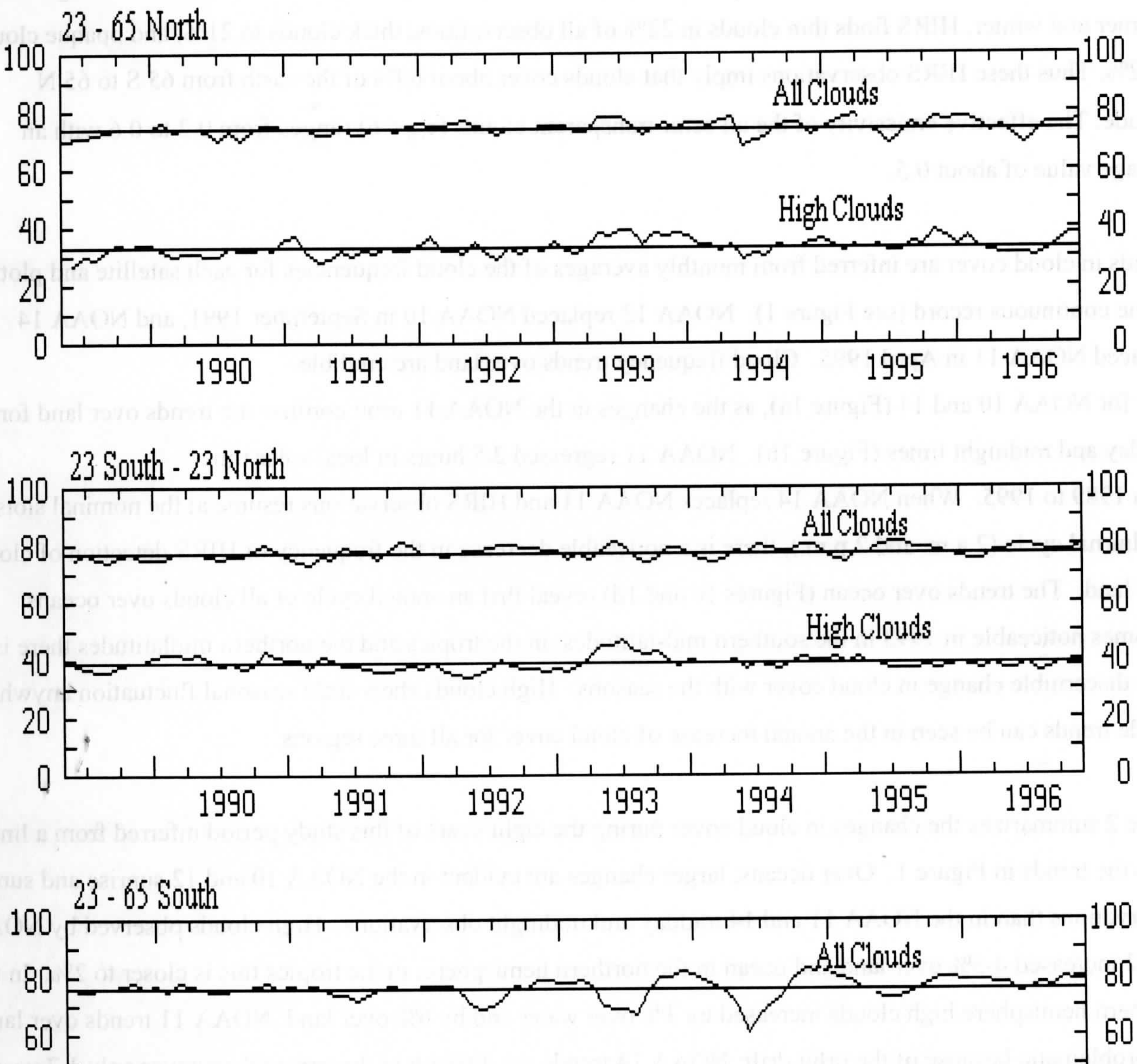

Figure 1d: The cloud frequencies over water for the midday and midnight satellites NOAA 11 and 14.

level of the atmosphere in Table 1 are the percentages of only observations to that level. On the average for summer and winter, HIRS finds thin clouds in 22% of all observations, thick clouds in 21%, and opaque clouds in 32%. Thus these HIRS observations imply that clouds cover about 69% of the earth from 65 S to 65 N latitude. The effective emissivity of the all semi-transparent clouds ($\tau_{vis} < 6$) ranges from 0.2 to 0.6 with an average value of about 0.5.

Trends in cloud cover are inferred from monthly averages of the cloud frequencies for each satellite and plotted as one continuous record (see Figure 1). NOAA 12 replaced NOAA 10 in September 1991, and NOAA 14 replaced NOAA 11 in April 1995. Cloud frequency trends over land are credible only for NOAA 10 and 14 (Figure 1a), as the changes in the NOAA 11 orbit confuse the trends over land for the midday and midnight times (Figure 1b). NOAA 11 regressed 2.5 hours in local solar time from 1989 to 1995. When NOAA 14 replaces NOAA 11 and HIRS observations resume at the nominal slots in the diurnal cycle (2 a.m. and 2 p.m.), there is a noticeable decrease in the frequency of HIRS detection of cloud over land. The trends over ocean (Figures 1c and 1d) reveal that an annual cycle of all clouds over oceans becomes noticeable in 1993 in the southern mid-latitudes; in the tropics and the northern midlatitudes there is little discernible change in cloud cover with the seasons. High clouds show little seasonal fluctuation anywhere. Subtle trends can be seen in the annual increase of cloud cover for all three regions.

Table 2 summarizes the changes in cloud cover during the eight years of this study period inferred from a linear fit to the trends in Figure 1. Over oceans, larger changes are evident in the NOAA 10 and 12 sunrise and sunset observations than in the NOAA 11 and 14 midday and midnight observations. High clouds observed by NOAA 10-12 increased 4-5% over land and ocean in the northern hemisphere; in the tropics this is closer to 2%. In the southern hemisphere high clouds increased by 3% over water and by 6% over land. NOAA 11 trends over land are problematic because of the orbit drift; NOAA 14 trends are difficult to discern as they cover only 1.7 years to date.

2. HIRS AND NWP TEMPERATURE AND MOISTURE IN CLEAR AND CLOUDY SKIES

A comparison has been made between the National Centers for Environmental Prediction global model and NOAA 11 HIRS measurements with data from 1 to 8 November 1998 (Table 3). The HIRS measured 6.7, 11.1, and 13.9 micron blackbody temperatures in cloud free skies are compared to calculations from the NCEP Final Analysis temperature and moisture soundings. The NCEP model 6.7 micron brightness temperatures (sensitive

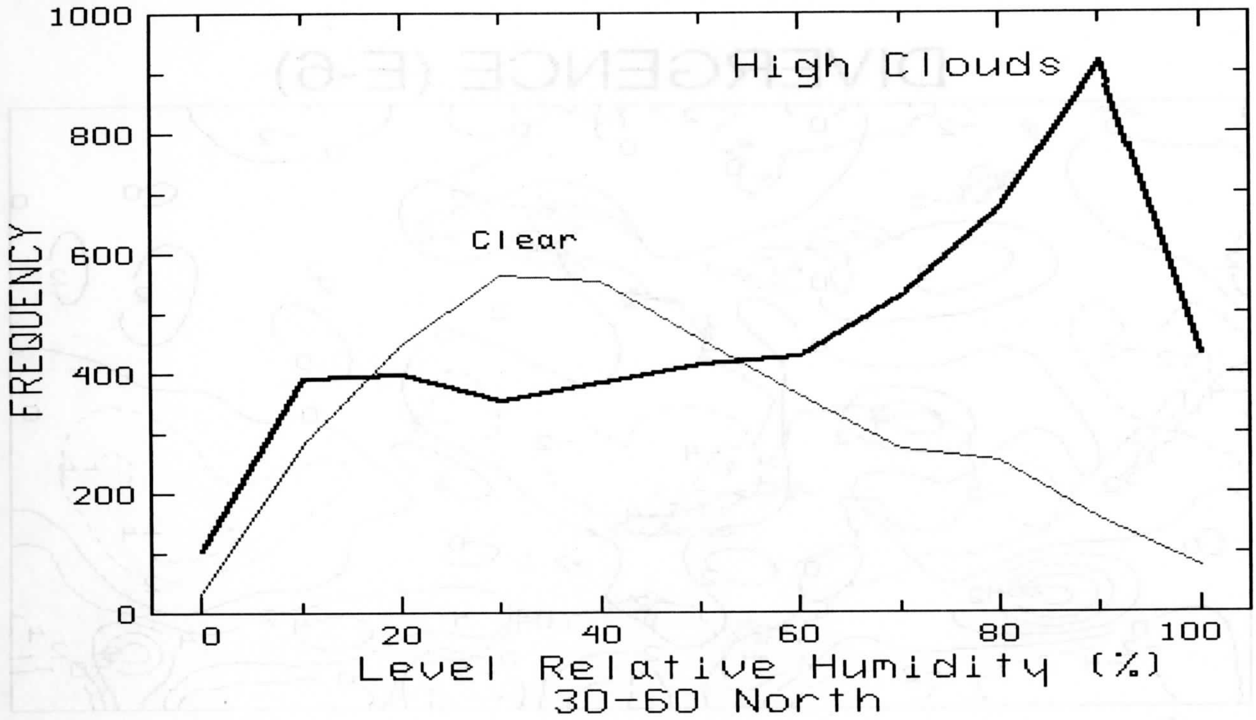

Figure 2a: Relative Humidity from the NCEP Final Analysis at the level of the NOAA 11 HIRS cloud reports. The 300 mb level was used in the clear areas.

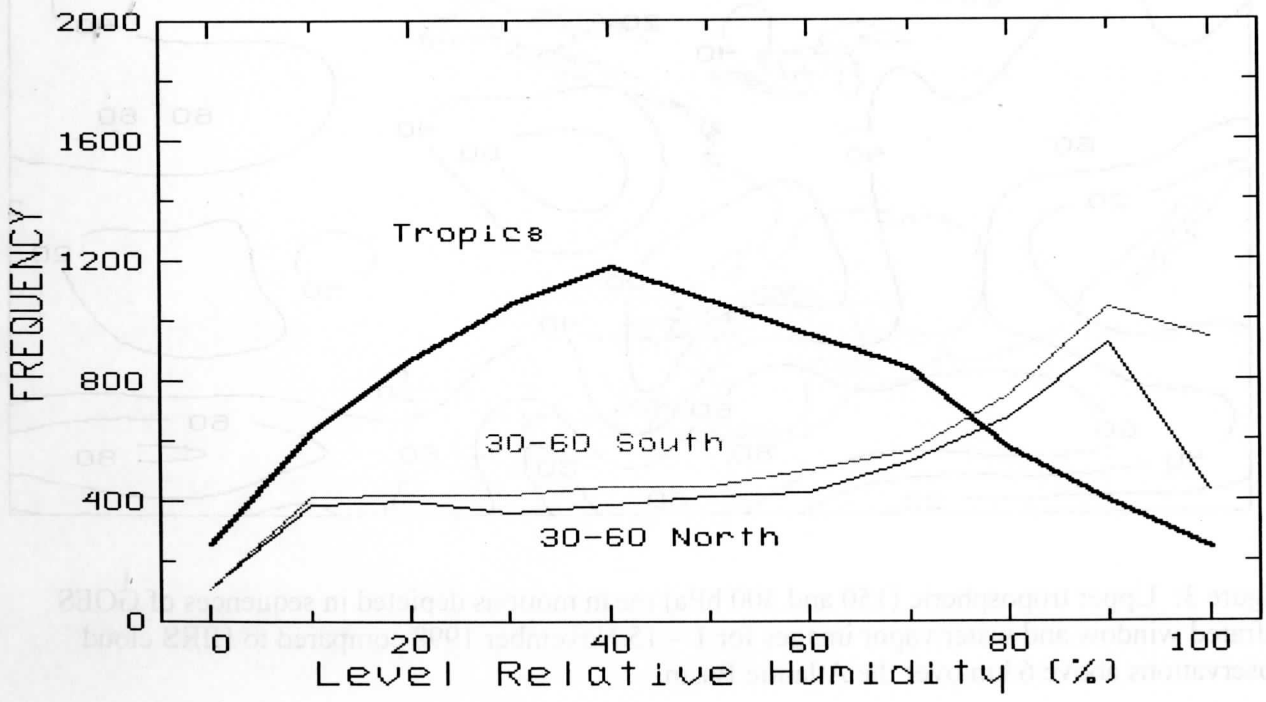

Figure 2b: The frequency of Relative Humidity values for the high clouds in the three latitude belts

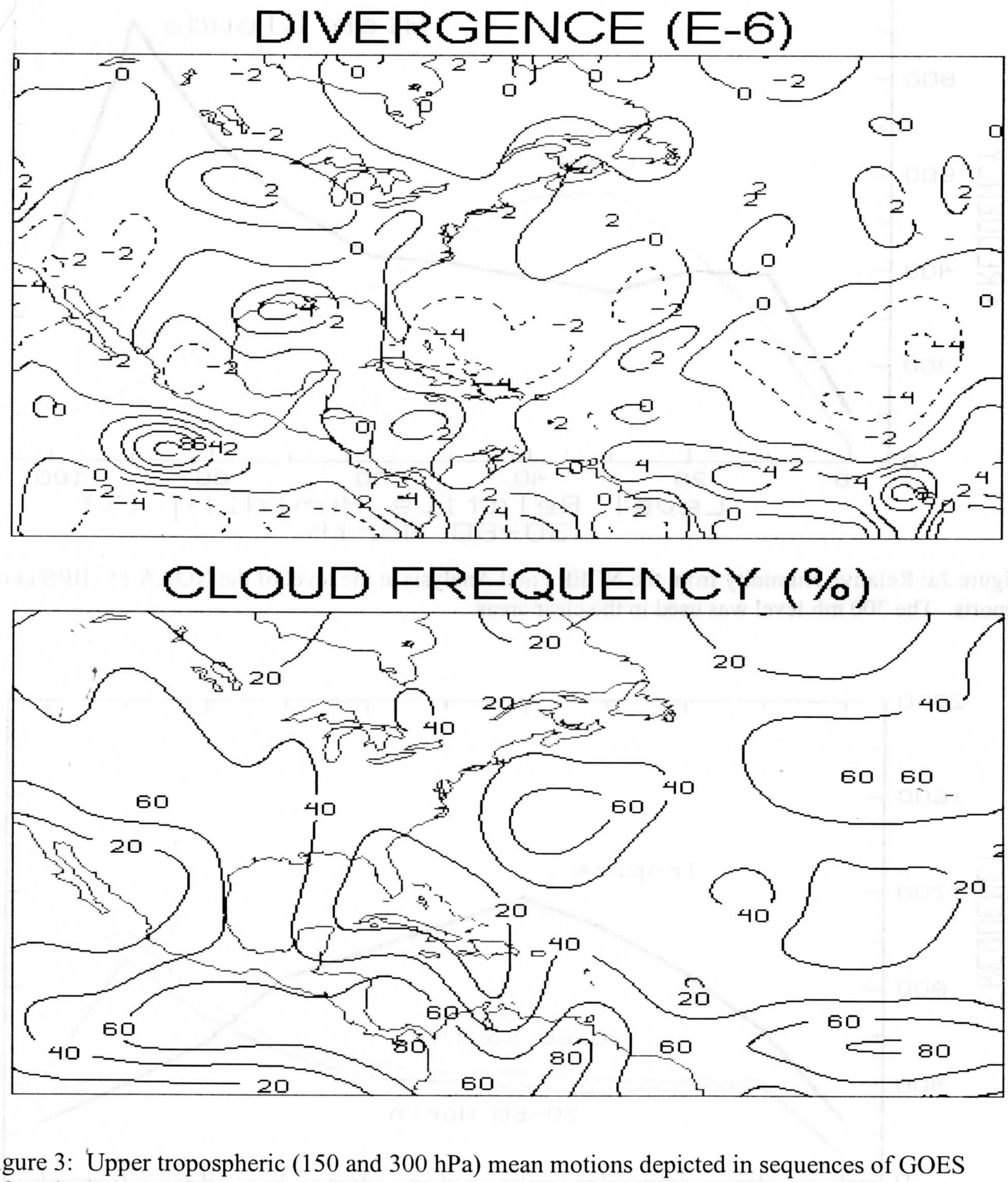

Figure 3: Upper tropospheric (150 and 300 hPa) mean motions depicted in sequences of GOES infrared window and water vapor images for 1 – 15 November 1998 compared to HIRS cloud observations above 6 km over the Atlantic Basin.

to moisture) are 1.5 to 1.9 K warmer than those measured by HIRS. Using the Soden and Bretherton (1996) weighted average of relative humidity from 500 to 200 hPa for estimating Upper Tropospheric Humidity (UTH), these temperature differences indicate relative humidity differences of 3 to 6%. The 11.1 micron window brightness temperatures (sensitive to surface conditions) show NCEP to be biased slightly warm by 0.4 to 0.9 K; these comparisons are only over oceans and possibly indicate some residual cloud effects in the HIRS measurements. This would mitigate some of the dry bias (reducing it to 0.6 to 1.2 K or 2 to 4%). The model 13.9 micron brightness temperatures (sensitive to temperature) are 0.7 to 1.9 K colder than those measured by HIRS; the possible residual cloud effects enhance this cold bias (increasing the differences to 1.6 to 2.3 K). This comparison suggests that the NCEP global model Final Analysis model is too cold (by roughly 2 K) and dry (by roughly 3 %) in the upper troposphere. These differences interfere with the model 's ability to generate and sustain clouds appropriately.

NCEP determinations of UTH in cloudy and clear areas have also been compared (Table 4). Cloudy areas are defined as those FOVs where the HIRS cloud retrievals are 500 hPa or higher; FOVs with lower clouds are not used in the comparison. The UTH differences between high clouds and clear areas range between 17 to 19%; the largest contrast occurs in the tropics. Clear versus cloudy sky relative humidities (RH), inferred with respect to liquid water at 300 hPa in clear conditions or at cloud level in clouds, show differences of 14 to 22%. The distribution of RH values in clear and cloudy skies are very different (Figure 2a). Clouds are found in a wide range of RH values, but appear most often at 90% RH. Clear areas also exhibit a range of RH values, but most are under 50% RH. Values of RH are smaller in the tropics than in the mid-latitudes (Figure 2b). The lower RH values in the tropics are believed to be due to computation with respect to water rather than ice (for example, the water RH 46% in the tropics translates into ice RH 63%); the upper troposphere is colder in the tropics than in the mid-latitudes so these clouds should mostly be ice.

3. COMPARISONS OF HIRS CLOUDS AND GOES/GMS UPPER TROPOSPHERIC FLOW

As found in Schmetz et al (1995), it is believed that large scale dynamics are the governing factor for cloud formation processes associated with humidity fields, especially in the tropics. To illustrate this further, the upper tropospheric motions depicted in sequences of GOES and GMS infrared window and water vapor images have been collected for 1 – 15 November 1998. The mean motion between 150 and 300 hPa for these two weeks are compared to the UW HIRS cloud observations above 6 km. Figure 3 shows comparison in the Atlantic Basin (covered by GOES East). There is some correlation in the tropics; areas of high divergence greater than 6 x 10^{-6} sec^{-1} (high UTH) in the tropical convection areas have a mean cloud amount above 6 km of more than 60% and subsidence areas of high convergence less than –4 x 10^{-6} sec^{-1} (low UTH) are associated with cloud amounts less than 20%. This correlation is less obvious in the mid-latitudes. The similar results (not shown) are found in the Pacific regions (covered by GOES West and GMS). Upper tropospheric cloudiness is increased in regions of upper level motion divergence, and decreased in regions of convergence. The large scale dynamics associated with tropical divergences (and hence areas of high UTH respectively) are likely forcing the generation and sustaining the presence of clouds. This suggests that numerical models will improve their representation of clouds in the tropics when improved data on upper tropospheric winds and moisture are assimilated.

4. CONCLUSIONS

Global upper tropospheric transmissive cirrus cloud cover has been charted since June 1989 using NOAA polar orbiting HIRS multispectral infrared data. HIRS finds thin clouds in 22% of all observations, thick clouds in 21%, and opaque clouds in 32%. The average cloud cover is found to be about 69% from 65 S to 65 N latitude. Time trends were re-examined in detail; the ten year record has indications of an increase of high clouds in the northern mid-latitudes (0.5% per year) but little change elsewhere. The seasonal cycle of cloud cover in the southern hemisphere became very noticeable in 1993.

Comparison of NCEP global model Final Analysis and HIRS measurements suggest that the model is too cold (by roughly 2 K) and dry (by roughly 3 %) in the upper troposphere. These differences interfere with the ability of the model to generate and sustain clouds appropriately. The differences of NCEP UTH determinations in cloudy minus clear skies range from 17 to 19%; the largest contrast occurs in the tropics.

In addition the divergence of the upper tropospheric motions are derived from sequences of geostationary water vapor images. These divergence fields have been shown to be highly correlated with upper tropospheric humidity. The GOES and GMS divergence of upper tropospheric motions for the first two weeks of November 1998 are compared with the global cirrus coverage. There is some similarity in the tropics; areas of high divergence (high UTH) in the tropical convection areas exhibit considerably more cloudiness in the upper troposphere than subsidence areas of high convergence. This similarity is less obvious in the mid-latitudes. Nevertheless, a relationship between clouds, ambient relative humidity fields, and large scale dynamics begins to emerge.

5. REFERENCES

Schmetz, J., C. Geijo, W. P. Menzel, K. Strabala, L. Van de Berg, K. Holmlund, and S. Tjemkes, 1995: Satellite Observations of Upper Tropospheric Relative Humidity, Clouds, and Wind Field Divergence. *Beitr. Phys. Atmosph.*, **68**, 345 - 357.

Soden, B., and F. B. Bretherton, 1996: Interpretation of TOVS water vapor radiances in terms of layer average relative humidities: Method and climatology for the upper, middle, and lower troposphere. *J. Geo. Res.*, **101**, 9333-9343.

Wylie, D. P., W. P. Menzel, H. M. Woolf, and K. I. Strabala, 1994: Four Years of Global Cirrus Cloud Statistics using HIRS. *Jour. Clim.*, **7**, 1972-1986.

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

Table 1: Cloud Types found at each level in the troposphere summer and winter from Jun 1989 to Feb 1997 between 65 N and 65 S latitude

Summer (Jun, Jul, Aug)

	all	thn	thck	opq
hi	34	15	14	5
mid	26	11	9	6
low	45	0	0	45
all	73	22	20	31

Winter (Dec, Jan, Feb)

	all	thn	thck	opq
hi	34	15	15	4
mid	32	11	11	10
low	47	0	0	47
all	76	23	21	32

hi	> 6 km	thn	NE<.5
mid	3-6 km	thck	NE<.95
lo	< 3 km	opq	NE>.95

Table 2: The change in the frequency of cloud detection (all clouds and high clouds above 440 hPa) from Jun 1989 to Feb 1997. The change is percentage of observations that found cloud at the end minus the beginning of the study period.

OVER WATER

	All Clouds				High Clouds			
Latitude belt	10/12		11/14		10/12		11/14	
	mean	inc	mean	inc	mean	inc	mean	inc
23°-65° north	75.7	+3.1	74.3	+1.7	31.6	+4.9	33.1	+3.3
Tropics	76.8	+6.6	77.5	+2.1	39.0	+1.6	38.7	-0.4
23°-65° south	77.1	+1.7	76.1	+1.5	28.4	+2.7	29.7	+1.3

OVER LAND

	All Clouds		High Clouds	
Latitude belt	10/12		10/12	
	mean	inc	mean	inc
23°-65° north	75.4	+1.1	30.6	+4.2
Tropics	79.3	-2.1	48.5	+2.0
23°-65° south	73.5	-2.0	29.4	+6.2

Table 3: Comparison of the 6.7, 13.9, and 11.1 micron blackbody temperatures measured by HIRS on NOAA 11 and calculated using the NCEP Global Data Assimilation System Final Analysis. Numbers are NCEP - HIRS blackbody radiance temperatures (in degrees Kelvin).

	6.7μ		13.9μ		11.1μ	
	T	ΔT	T	ΔT	T	ΔT
30 - 60 N	243.5	+1.9	244.9	-1.0	288.7	+0.9
20 S - 20 N	249.2	+1.6	250.5	-1.9	295.7	+0.4
30 - 60 S	243.3	+1.5	243.7	-0.7	282.1	+0.9

Table 4: UTH and RH averages inferred from the NCEP Final Analysis for cloudy and clear areas inferred from the HIRS data. RH values are with respect to water.

	UTH		RH	
	Cloudy	Clear	Cloudy	Clear
30-60 N	61%	43%	59%	45%
20 S - 20 N (Tropics)	43%	26%	46%	24%
30-60 S	64%	45%	63%	45%

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