USE OF NIMBUS-7 SATELLITE DATA FOR VALIDATION OF GCM GENERATED CLOUD COVER

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1. INTRODUCTION

The Nimbus-7 Satellite, launched October 24, 1978, offers a unique opportunity to conduct cloud and radiation budget related climate studies. The radiation budget observations are derived from the Earth Radiation Budget (ERB) experiment, Jacobowitz, et al. (1984). Almost three years of ERB data have been validated at this time. Concurrent cloud data are also available from the Temperature Humidity Infrared Radiometer (THIR), Clouds/ERB (CLE) tapes, Hwang (1982). However, validation studies by Stowe (1984) have shown that large uncertainties (15% to 30%) are present in the cloud amount estimates from the CLE data. This has been ascribed to the use of climatological mean monthly surface temperatures to compute the infrared thresholds separating clear and cloud surfaces and to the effects of variations in atmospheric attenuation, horizontal temperature gradients and partly cloudy fields-of-view (FOV). Subsequent studies by Stowe, et al (1983) have shown that when concurrent surface temperatures are used and the above effects are accounted for in the determination of the cloud/no cloud threshold and, in addition, reflectance measurements from the Total Ozone Mapping

Spectrometer (TOMS) are used to independently estimate total cloud amount, the accuracy of cloud estimates is greatly improved.

A Nimbus-7 Cloud Data Processing Team (CDPT) was formed by NASA in late 1982 to implement production of improved cloud products from Nimbus-7 using THIR and TOMS observations and concurrent surface temperature data from the Air Force 3-D Nephanalysis archive, Fye (1978) which begins April 1, 1979. These satellite instruments are operating normally at this writing. The CDPT began production of daily cloud products in May 1984 and monthly production is to start in January 1985. Each year of data is expected to take four months to produce.

This paper describes the cloud detection algorithms, the various products derived, and the validation of the satellite estimates of cloud amount. These validation procedures should be equally applicable to validation of GCM generated cloud cover. One could use the estimates from Nimbus-7 to replace the estimates used to validate Nimbus-7 in this paper (e.g., an analyst) and replace the Nimbus-7 estimates with the GCM estimates in the validation procedures.

2. ALGORITHM AND PRODUCT DESCRIPTION

The BCLE (Basic Clouds/ERB) algorithm is similar to the CLE algorithm in that THIR 11 μm and 6.7 μm radiances (7km and 20km resolution at nadir, respectively) are separated into clear and low, middle and high altitude cloud catagories using thresholds. The Earth is first divided into 18,630 approximately equal area ERB Sub-targets (STA), each about $(160km)^2$. Altitudes above mean sea level (MSL) of the boundaries between low and middle clouds and middle and high clouds are estimated from the International Cloud Atlas (1956). The altitude of the low/mid threshold is 2km above MSL everywhere. The mid/high cloud threshold (a step function of latitude on CLE) varies continuously from 30^o latitude to the poles according to the equation

$$Z = 7km - 1.5km \times (1 - \cos(3 \times (|Lat| - 30))) \qquad (1)$$

where |Lat| is absolute value of latitude. At latitudes less than 30^o, Z=7km.

The temperature at the Earth's surface (shelter temperature over land) within one half hour of the Nimbus-7 overpass (near local noon and midnight, except at polar latitudes) is determined from time interpolation in the Air Force three hourly Surface Temperature Analysis Archive tapes.

To determine the very important cloud/no cloud threshold, the surface temperature is first averaged for the STA and adjusted for atmospheric attenuation at 11 μm, empirically. Next, a range of temperatures with a 95% probability of being clear, i.e., temperatures within two standard deviations of the attenuated surface temperatrure, T, is computed. One standard deviation, E, is given by the equation

$$E = \sqrt{V_H + V_S} \qquad (2)$$

where $V_H = 4.0\ C^2$.

Note that V_H is the variance in attenuated temperature due to variability in humidity, computed from the differences between the empirically attenuated surface temperature and the temperature measured by THIR for selected STAs; V_S is the variance in the Air Force Surface Temperature field within the STA and accounts for geographical variation in horizontal temperature gradients, e.g., as found along coastlines. Finally, an adjustment for the effects of partly cloudy 11 µm FOVs, P, is included in the calculation of the cloud/no cloud threshold. Thus, two cloud/no cloud thresholds are specified for each orbital sighting of a STA; a cold, $T_C = T - 2E - P$, and warm, $T_W = T + 2E + P$, threshold. P has been determined empirically to be 2C.

The low/middle cloud threshold is determined from first using the climatological temperature lapse rate between the surface and the 2km level and extrapolating from the unadjusted, concurrent surface temperature. An empirical adjustment for attenuation at the 2km level is then computed and subtracted from the 2km temperature. The middle/high cloud threshold is determined by extrapolation from the unadjusted 2km temperature to the altitude defined by (1) using the climatological lapse rate above 2km for that STA and month of year.

Each THIR 11 µm FOV is placed into one of four clear/cloud histogram bins (temperature thresholds are converted to radiance units) for the STA being viewed. When a climatological inversion is present and the surface temperature is less than 280K, any FOV with a radiative temperature greater than T_W is classified warm cloud and replaces the low category in the four-level histogram. At night, this is perhaps the only way of detecting the presence of clouds which are warmer than the Earth's surface (so-called black clouds). After all FOVs for one orbital pass of a STA have been processed, the population of FOVs in each histogram bin and the mean and RMS (root-mean-squared) statistics for the 11 μm and co-located 6.7 μm radiances are computed. The ratios of populations in the histogram bins to the total STA population gives the fractional amount of that category covering the STA. After seven days of data have been processed, (THIR operates continuously) all data are recorded onto one magnetic tape (BCLE) in chronological order for subsequent processing. Other STA information saved on the BCLE include satellite zenith angle, histogram boundary radiances, fraction of land, minimum and maximum 11 μm radiances and the average terrain altitude.

It has been found, empirically, that when low clouds fill the entire TOMS FOV (approximately $(50km)^2$ at nadir) the TOMS reflectivity at 0.38 μm is greater than 35% and for reflectivities below 8% there is rarely any cloud in the FOV. At this wavelength, snow-free land and ocean have about the same reflectivity. Also, the ocean exhibits negligible specular reflection. This unique behavior has been utilized in a cloud detection algorithm which computes the amount of cloud cover in a TOMS FOV by linear interpolation between the clear and overcast reflectivities. All snow-free FOVs located within a sunlit STA are averaged to give the TOMS total cloud amount. Snow coverage is provided by Air Foce Snow Analysis Archive tapes.

The THIR infrared algorithm (BCLE) is most prone to error from low altitude clouds that are at a temperature near that of the surface. Conversely, the TOMS algorithm is most prone to error from high altitude, cumulo-form clouds, which partially fill the relatively large TOMS FOV and are sufficiently reflective (60% or more) to cause the TOMS algorithm to overestimate amount. Thus, the best daytime estimate of total cloud amount is obtained by merging the two independent estimates with an algorithm that gives the most weight to the most accurate estimate, new-CLE (NCLE) algorithm. The NCLE algorithm merges the two estimates with the following equation,

$$NCLE = BCLE \times (1 - W) + TOMS \times W \quad (3)$$

where $W = W1 \times W2$,

$W1 = N/(N+1)$,

and $W2 = |BCLE - TOMS|/(BCLE + TOMS)$.

When W= 0, BCLE gives the best estimate and as W approaches 1, TOMS gives the best estimate. W consists of two factors: W1 depends on the number of TOMS samples, N, in a STA such that, for oblique views, the TOMS estimates will be given less weight than for nadir views; W2 varies in such a way that, when BCLE and TOMS are in good agreement, TOMS will be given less weight, but when in poor agreement, particularly when BCLE indicates less cloud than TOMS (which is typical of low cloud errors in BCLE), more weight is given to TOMS.

When NCLE total cloud amount is less than BCLE, the BCLE low, then mid and then high cloud amounts, in that order, are decreased so as to agree with the NCLE amount. These become the NCLE estimates for these cloud types. Also, a test for thin cirrus is performed. If total cloud amount from NCLE is more than 25% greater than the TOMS estimate, the NCLE amounts of middle and high cloud are added to give an estimate of thin cirrus. Thin cirrus typically is low in reflectivity but appears as a middle or high cloud in the infrared. When NCLE total cloud amount is greater than BCLE, the difference is added to the low cloud amount. The increased low cloud amount and the BCLE estimates of mid and high cloud become the NCLE estimates. The NCLE clear and cloud radiances are unchanged from the BCLE values except when the TOMS algorithm detects clouds when BCLE detects none. In this case, the BCLE clear radiance is assigned to the radiance of the NCLE low cloud amount. At night and also when snow completely covers a STA, no adjustments are made to any of the THIR cloud estimates, i.e., the BCLE results are used.

The results of the TOMS adjusted THIR cloud estimates and other ancillary data from the BCLE tape are written to a weekly archived data tape referred to as the NCLE tape. Its format is identical to the BCLE except for the addition of eight parameters: TOMS reflectivity; TOMS total cloud amount; thin cirrus amount; solar zenith angle; and the NCLE estimates of amount of clear, low, middle and high cloud.

As each month of NCLE tapes is produced, they are processed into Nimbus-7 CLOUD-MATRIX (CMATRIX) tapes. Each tape will contain one calendar year of cloud amount and radiance statistics. The STA information is averaged into ERB target areas, approximately $(500km)^2$, latitudinal zones, hemispheric and global resolution. Tape files will contain daily and monthly average daytime and nighttime values of cloud amount and radiance as well as values related to the variance in space and time of these quantities. Altogether there will be about 130 parameters on the CMATRIX tape.

In addition, all algorithms except CMATRIX can be used to estimate cloud amount within TOMS FOVs resulting in CLT, BCLT and NCLT cloud products at

$(50km)^2$ resolution. Currently, only CLT and BCLT are being produced routinely.

3. VALIDATION METHODS, RESULTS AND CONCLUSIONS

There are three techniques that are being used to validate Nimbus-7 satellite estimates of cloud amount: 1) a statistical intercomparison with analyst estimates derived from independent, concurrent satellite images and conventional meteorological reports; 2) qualitative intercomparisons of independent, concurrent satellite images with computer simulated matching images derived from the satellite cloud estimates; and 3) quantitative intercomparison with other satellite and/or surface derived cloud climatologies.

Statistical intercomparisons have been used by Stowe (1984) to estimate the systematic and random errors of the Nimbus-7 CLE cloud product. The slope and intercept of the linear regression line with analyst as dependent variable and satellite as independent variable is used together with the mean difference to infer systematic error of the satellite values relative to the analyst. The standard deviation of the random error of the satellite derived cloud amount is assumed to lie between a lower limit given by (standard error/ $\sqrt{2}$) and an upper limit given by the RMS difference between analyst and satellite. These error estimates are probably overestimates because they are computed relative to an analyst, who contributes some systematic and random error to the intercomparison results. Tables 1-3 give the results of this type of validation for daytime and nighttime selected STAs, for water, land and coastal areas, respectively.

TABLE 1. Errors in Nimbus-7 Cloud Amounts Relative to an Analyst for Water Areas. Plus (Minus) Means Satellite Estimate Greater (Less) than Analyst.

ALGORITHM	Correlation Coefficient	Systematic Error (%)			Random Error (%)	
		Mostly Clear	Mean	Mostly Cloudy	S. E./$\sqrt{2}$	RMS
			Daytime (230 Cases)			
CLE	0.74	-5	+11	+22	15	29
BCLE	0.95	-5	0	+3	8	12
TOMS	0.92	+3	+5	+6	10	15
NCLE	0.96	+3	+2	-1	7	11
			Nighttime (143 Cases)			
CLE	0.86	-2	+6	+9	12	18
BCLE	0.95	+1	+4	+5	7	11

TABLE 2. Same as Table 1 but for Land Areas.

ALGORITHM	Correlation Coefficient	Systematic Error (%)			Random Error (%)	
		Mostly Clear	Mean	Mostly Cloudy	S. E./$\sqrt{2}$	RMS
			Daytime (127 Cases)			
CLE	0.80	-13	-3	+11	16	29
BCLE	0.81	-19	-14	-5	17	28
TOMS	0.90	-6	-2	+3	13	19
NCLE	0.82	-17	-13	-3	17	27
NCLE (85 Snow-Free Cases)	0.95	-5	-5	-6	10	14
			Nighttime (38 Cases)			
CLE	0.04	-45	+39	+55	32	83
BCLE	0.97	-1	0	+2	8	11

TABLE 3. Same as Table 1 but for Coastal Areas.

ALGORITHM	Correlation Coefficient	Systematic Error (%)			Random Error (%)	
		Mostly Clear	Mean	Mostly Cloudy	S. E./$\sqrt{2}$	RMS
		Daytime (183 Cases)				
CLE	0.61	-19	+2	+21	20	34
BCLE	0.72	-26	-13	+6	18	31
TOMS	0.91	-6	0	+6	11	16
NCLE	0.82	-14	-7	+1	15	22
NCLE (148 Snow-Free Cases)	0.92	-4	-1	+2	10	14
		Nighttime (93 Cases)				
CLE	0.71	+10	+25	+31	21	39
BCLE	0.94	-1	+4	+9	10	14

A substantial reduction is evident in both systematic and random error as the algorithms become more complex from CLE to NCLE. Daytime land and coastal STAs show the least improvement. For these cases, the TOMS algorithm seems to be in better agreement with the analyst, but because some of the TOMS FOVs are snow covered, the TOMS results are given very little weight in determining NCLE amount. It is possible that the analyst is confusing some of the snow covered areas with cloud, which would cause the apparent systematic errors in BCLE and NCLE. For snow-free cases, NCLE systematic errors are less than 10%, the random errors range between 7% and 14%, and the correlation coefficient exceeds 0.9, day or night. The BCLE cloud estimates for land at night are much improved over CLE, due primarily to the use of concurrent surface temperature in specifying the cloud/no cloud threshold.

Qualitative intercomparison has been useful, particularly in illustrating the differences between BCLE and NCLE results. GOES (Geosynchronous Observational Environmental Satellite) images have been simulated with a computer graphics device at NASA/GSFC using BCLE and NCLE cloud estimates. Comparison of these images with the actual GOES images has led to the following conclusions: 1) NCLE estimates of total cloud amount usually agree with BCLE estimates to within 5%; 2) only rarely do they disagree by more than 15%; these two results indicate that nighttime estimates from BCLE are probably only slightly less accurate than daytime NCLE estimates; 3) thin cirrus is detected in regions where they appear in the GOES images. Warm cloud estimates have been validated by qualitative intercomparison with concurrent surface observations and RAOB data. Although difficult to validate on a case by case basis because of the localized nature of warm clouds, the satellite estimates occur in geographical regions where warm clouds often form, e.g., Siberia in winter.

As an example of the third technique, Figure 1 shows comparisons between zonal mean cloud amount estimates from Nimbus-7 CMATRIX results for 28 days in June 1979 and two frequently referenced cloud climatologies, London (1957) and Berlyand, et al. (1980) for summer and June periods, respectively. The CMATRIX results are in good agreement with the climatologies in location of the relative maxima and minima but have larger peak to peak variability. This is particularly evident in the tropics. It is apparent that total cloud cover is greater near local midnight than near local noon, as observed from Nimbus-7, by about 4%, globally. The hemispheric and global averages from Nimbus-7 are closer to

London's climatology near local noon and closer to Berlyand's near local midnight. Local noon cloud cover is slightly greater than local midnight between the latitudes of 45^0 and 60^0 in both hemispheres. The agreement between the two observation times south of 60^0 S is an artifact of having used climatological monthly mean surface temperatures to replace Air Force Surface Temperatures over Antarctica, which are systematically too warm, and also because only BCLE estimates are used over snow covered areas. These cloud amount estimates are, as a consequence, of questionable accuracy, although the zonal averages don't disagree markedly from the two climatologies.

Figure 2 shows a comparison between the zonal mean values of low, middle and high cloud amount of London and CMATRIX local noon and local midnight estimates. It is apparent that the surface based estimates of London are biased towards low clouds and the satellite estimates are biased towards middle clouds. This occurs because middle and high clouds are obscurred from the surface observer by low clouds and conversely, low clouds will be obscurred from the satellite view by middle and high clouds. Most of the difference between Nimbus-7 local noon and midnight cloud amount is caused by increased middle cloud amount at night. This is physically plausible since most convective activity occurs in afternoon and evening hours and usually produces cloud tops in excess of the 2km low/mid threshold. It is doubtful that this is an effect of not having TOMS data at night because; 1) low cloud would most likely be the cloud type affected and 2) June 1979 CMATRIX results show that the global mean local noon cloud amount with the infrared only algorithm (BCLE) is 2% lower than when the NCLE algorithm is used. If the nighttime increase were due to a systematic error in the

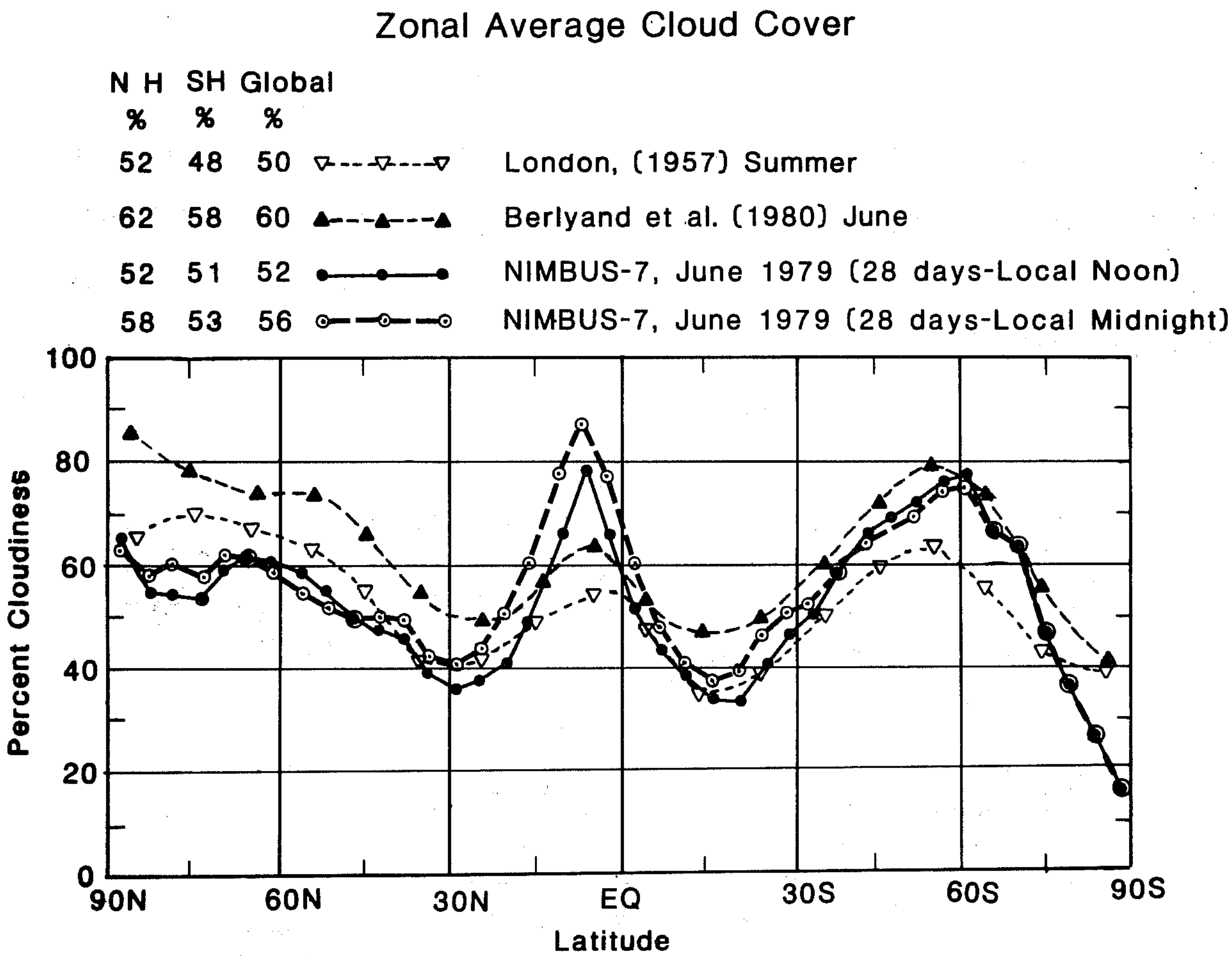

Figure 1. Intercomparison of Zonal Average Total Cloud Amount

BCLE algorithm, the daytime BCLE results would also be systematically higher, not lower, than NCLE.

The validation of BCLT and NCLT products has not been presented explicitly in this paper. However, since the algorithms are identical to BCLE and NCLE, respectively, the validation results presented should apply to the BCLT and NCLT as well.

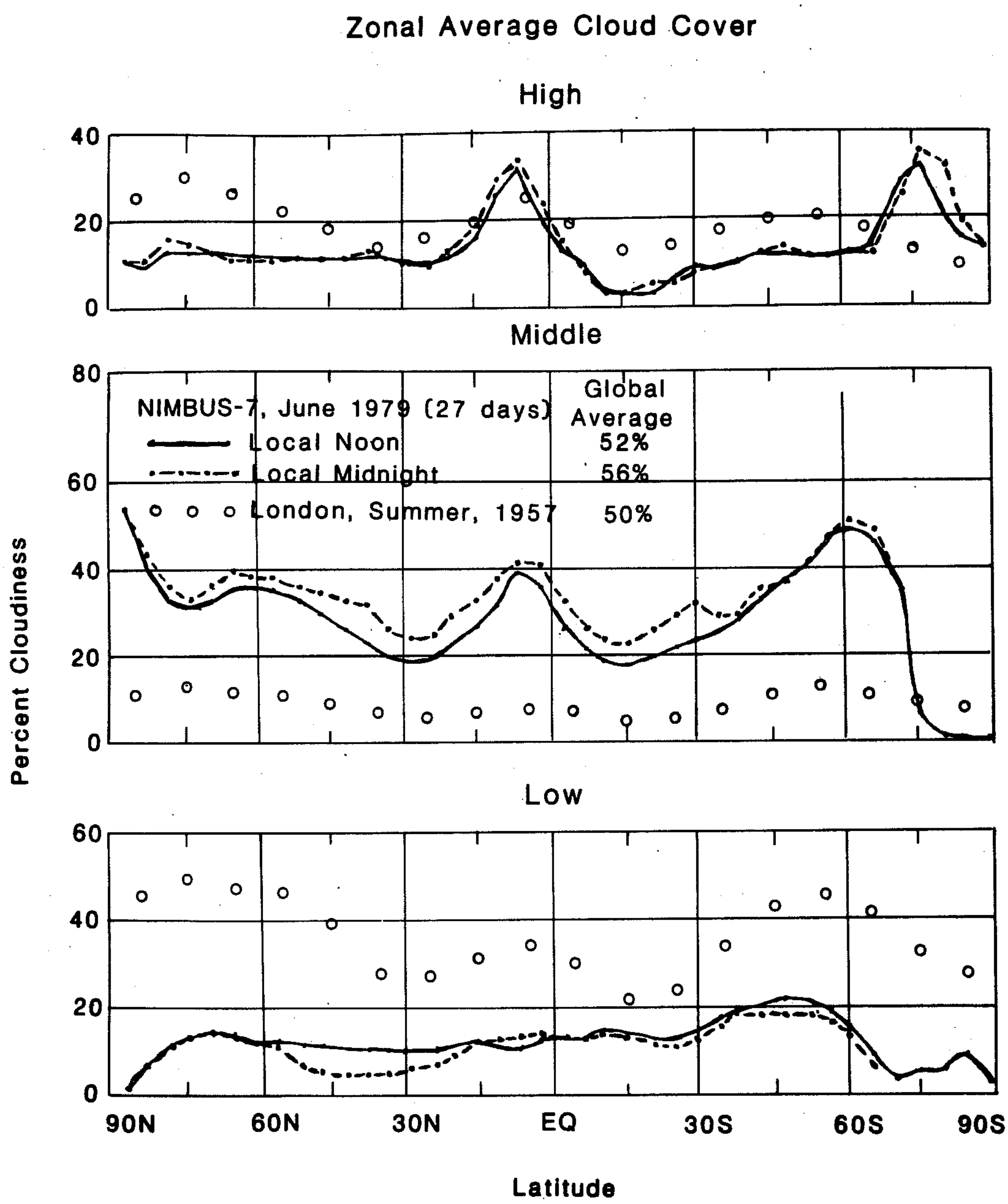

Figure 2. Same as Figure 1 but for Low, Middle and High Cloud

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