Variations in *Nimbus-7* Cloud Estimates. Part I: Zonal Averages

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ABSTRACT

Zonal averages of low, middle, high, and total cloud amount estimates derived from measurements from *Nimbus-7* have been analyzed for the six-year period April 1979 through March 1985. The globally and zonally averaged values of six-year annual means and standard deviations of total cloud amount and a proxy of cloud-top height are illustrated. Separate means for day and night and land and sea are also shown. The globally averaged value of intra-annual variability of total cloud amount is greater than 7%, and that for cloud height is greater than 0.3 km. Those of interannual variability are more than one-third of these values. Important latitudinal differences in variability are illustrated. The dominant empirical orthogonal analyses of the intra-annual variations of total cloud amount and heights show strong annual cycles, indicating that in the tropics increases in total cloud amount of up to about 30% are often accompanied by increases in cloud height of up to 1.2 km. This positive link is also evident in the dominant empirical orthogonal function of interannual variations of a total cloud/cloud height complex. This function shows a large coherent variation in total cloud cover of about 10% coupled with changes in cloud height of about 1.1 km associated with the 1982–83 El Niño–Southern Oscillation event.

1. Introduction

Variations in the amount and properties of clouds have been hypothesized as key components of the theories of the diverse climate changes associated with El Niño–Southern Oscillation (ENSO), global warming due to increasing greenhouse gas concentrations, and nuclear winter. For instance, in a recent paper Cess et al. (1990) have shown that all 19 models that were subjected to a positive perturbation in global sea surface temperatures underwent a decrease in cloud cover.

Major efforts to derive multiyear cloud analyses from satellite data have been made by at least two groups. *Nimbus-7* cloud data have been derived for a six-year period using the methods described by Stowe et al. (1988). Members of the International Satellite Cloud Climatology Project (ISCCP) have completed several years of cloud estimates based upon a composite of operational geostationary and NOAA-N satellite observations (Rossow and Schiffer 1991). In addition, irradiance estimates for average sky and clear scenes, which have been derived from the Earth Radiation Budget Experiment (ERBE) scanner instruments aboard up to three satellites, have been completed for a number of months starting in November 1984 (Barkstrom et al. 1989; Harrison et al. 1990; Ramanathan and Collins 1991).

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This paper analyzes the variations in zonal-average cloud amounts identified in the *Nimbus-7* analysis for the full six years of available data. Those data were derived using the methods discussed in Stowe et al. (1988). There are twice-daily estimates near local noon and midnight, which run continuously from April 1979 through March 1985. This paper is meant as a supplement to the extensive summary of the first year results discussed by Stowe et al. (1989). Those authors have compared their cloud estimates to the available surface climatologies and values determined by subjective analysts and found general agreement. On the other hand, Stowe et al. (1989) and Rossow and Schiffer (1991) have found that the mean ISCCP cloud amounts are considerably larger than those derived by the *Nimbus-7* team. Unfortunately, there is at present no definitive way to distinguish which is closer to the "true" value. Part of the reason for this inability is the lack of a consistent definition of what is meant by a clouded region, especially for data analyses that sample data at intervals far greater than the size of typical clouds (Weare 1992).

2. Data

The *Nimbus-7* cloud data were obtained on magnetic tape from the National Space Science Data Center at the NASA Goddard Space Flight Center. Daily and monthly mean values for April 1979 through March 1985 were available on an equal area grid with a resolution of approximate $(500)^2$ km^2. Total cloud fractions and the fractions with tops at low (f_l), medium

(f_m), and high (f_h) levels were available for both local noon and local midnight times. The daytime (local noon) cloud estimates are based upon bispectral tests using a window infrared channel and an ultraviolet solar channel. The nighttime (local midnight) estimates necessarily rely only on the infrared information. Threshold tests to determine whether or not subregions were clouded compared satellite brightness temperatures and reflectances with those for the surface obtained from the Snow/Ice Analysis and the Surface Temperature Analysis of the U.S. Air Force 3-D Cloud Nephanalysis. The latter analyses rely upon a combination of conventional surface reports, satellite radiances, and climatology (Luces et al. 1975).

From these data monthly zonal averages were formed for 4.5° latitudinal zones. From these averages long-term monthly and annual statistics were calculated. In order to have a single index representing changes in the relative amounts of low, middle, and high cloud, a proxy mean cloud-top height was defined. Because the cloud fractions are separated into only three broad categories, and because the tops of the high clouds are not specified, various choices for this cloud height are possible. The one chosen assumes that the mean cloud heights of the low and middle clouds are the centers of their respective layers and that of high cloud is the same distance from the middle cloud as the middle is from the low. Using the definitions of the boundary between low and middle cloud (Z_{lm}) and middle and high cloud (Z_{mh}) given by Stowe et al. (1988), this proxy mean cloud height (Z_t) is defined by

$$Z_t\,(\mathrm{km}) = (Z_l f_l + Z_m f_m + Z_h f_h)/(f_l + f_m + f_h), \quad (1)$$

where

$$Z_l = (Z_{lm})/2$$
$$Z_m = (Z_{mh} - Z_{lm})/2 + Z_l$$
$$Z_h = (Z_{mh} - Z_{lm})/2 + Z_m$$

and where

$$Z_{lm} = 2.0 \text{ km}$$
$$Z_{mh} = 7.0 \text{ km} \quad \text{for latitudes} < 30°$$
$$= 7.0 - 1.5\{1 - \cos[3(|\mathrm{lat}| - 30]\} \text{ km} \quad \text{for latitudes} > 30°.$$

Since this puts the mean height of high cloud well below the tropopause height, this definition may underestimate the mean cloud-top height. This disadvantage is offset by the fact that using this definition, variations in cloud height are not dominated by changes in only the high cloud as would be the case if Z_h were made much nearer to the tropopause height. In addition, it should be noted that these heights are the estimated heights of only the highest clouds, which are the only ones visible from a satellite. Thus, for instance, if there are two cloud layers, this height corresponds only to the top of the upper layer. There is an important consequence of this distinction. If the atmosphere generally has layered clouds, then decreases in high cloud amount would necessarily be accompanied by increases in low or middle cloud cover.

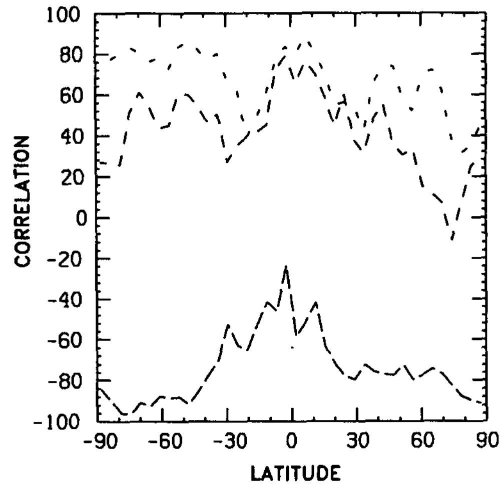

FIG. 1. Correlation coefficients (percent) between departures of cloud height and the low (long dash), middle (medium dash), and high (short dash) cloud amounts from their respective six-year monthly means.

Figure 1 illustrates one measure of the utility of this definition of the mean cloud height. This figure portrays the correlations of departures of zonally averaged cloud height and low, middle, and high cloud amounts from their respective monthly means for the entire six-year period. Correlations in this and subsequent figures with magnitudes greater than about 25% are significantly different than zero at the 95% significance level assuming that the number of independent observations is one half of the actual number of observations. The departures of the middle and high clouds show moderately large positive correlations with cloud height at most latitudes, whereas those for low cloud show moderately large negative correlations. This plot suggests that variations in the cloud height reflect variations of not a single cloud layer, but of all three layers.

An alternate definition of the mean cloud height, which puts the middle of the high cloud layer about 1.5 km higher than that used in Eq. (1), was tested. Naturally, this resulted in larger mean cloud heights. The other global statistics (to be discussed in Table 1) were, however, very similar. Although other possible definitions exist, a number of trial studies suggested that Eq. (1) defines a very useful proxy that represents well the variability of the true mean cloud-top height.

The emphasis of this paper will be on the determination of the intra- and interannual variability of total cloud amount and this mean cloud height. The calculated statistics included the six-year annual and

TABLE 1. Global-mean *Nimbus-7* day and night cloud statistics.

	Mean		$\sigma_{\text{intra-annual}}$		$\sigma_{\text{interannual}}$		$\sigma_{\text{inter}}/\sigma_{\text{intra}}$	
Variable	Day	Night	Day	Night	Day	Night	Day	Night
Total cloud (%)	50.0	53.1	7.1	8.0	2.8	3.2	.39	.40
Low cloud (%)	12.1	10.3	3.1	2.5	1.8	1.3	.57	.54
Middle cloud (%)	25.2	29.0	4.3	4.8	1.6	1.9	.37	.40
High cloud (%)	11.7	12.8	4.9	5.3	1.6	1.8	.34	.33
Cloud height (km)	4.00	4.22	0.49	0.31	0.29	0.13	.58	.43

monthly means and the intra-annual and interannual variances given by

$$\text{var}_{\text{intra}}(x_j) = \sum_{t=1}^{72} (x_{tj} - x_{aj})^2/71 \quad (2)$$

$$\text{var}_{\text{inter}}(x_j) = \sum_{t=1}^{72} (x_{tj} - x_{mj})^2/71, \quad (3)$$

where "intra" and "inter" specify the intra-annual and interannual variances, x_{tj} is a zonal average at latitude j and time t, x_{aj} is the six-year annual mean, and x_{mj} is the six-year monthly mean for the month m of the time increment t. The globally averaged means $\langle x \rangle$ and variances $\langle \text{var}(x) \rangle$ are given by

$$\langle Y \rangle = \sum_{j=1}^{40} Y_j A_j / A, \quad (4)$$

where Y is the mean or variance, A_j is the area of a given latitudinal strip, and A is the total area of the earth.

3. Globally averaged statistics

Table 1 gives a summary of the six-year global-mean statistics of cloud percentages and heights for the daytime and nighttime analyses. As shown previously (Stowe et al. 1989; Rossow and Schiffer 1991), both mean cloud amounts are smaller than those of the ISCCP analysis (Rossow and Schiffer 1991). Also as previously shown by Stowe et al. (1989), the night averages are slightly greater than the daytime observations. Using the interannual standard deviations in a t test (Brunk 1965), the day and night means are significantly different at the 95% confidence level. Since the nighttime measurements exclude the solar radiance tests, which should detect some clouds not seen by the infrared tests, the nighttime increase is not readily explained by differences in cloud identification algorithms.

Although the calculated cloud heights are conservatively estimated, the global means are about 1.0 km greater than the average estimated from the ISCCP data (Rossow and Schiffer 1991). Those authors suggest that the greater cloud amounts and lower heights of the ISCCP analysis are largely attributable to the improved detection of low clouds over oceans by the ISCCP algorithms. In addition, Table 1 shows that the average nighttime cloud heights are slightly greater than those during the day. This is due to a reduction of low clouds at night coupled with an increase of both middle and high clouds.

The intra- and interannual standard deviations of total cloud amount are similar for day and night with values of 7%–8% and 3%, respectively. The day and night intra-annual standard deviations of cloud height are nearly one-half kilometer during the day and one-third kilometer at night. The smaller nighttime value is despite the fact that the variability of high cloud amounts is slightly greater at night than during the day. This can be explained if variations in cloud amounts at different levels are correlated, as was shown in Fig. 1.

Table 2 illustrates for daytime *Nimbus-7* observations zonal-mean statistics of total cloud amount and cloud height calculated separately for areas dominated by either land or ocean. The mean cloud cover over sea is more than 10% greater than that over land, whereas the mean cloud height over land is more than one-half kilometer higher. These values confirm the first-year results of Stowe et al. (1989), indicating that oceanic areas have more cloud cover, which is generally at a lower altitude. In addition, the standard deviations of total cloud amounts are larger over land than over sea. Given the greater mean heights over land, this probably reflects the fact that a larger fraction of clouds

TABLE 2. Global-mean *Nimbus-7* land and ocean day cloud statistics.

	Mean		$\sigma_{\text{intra-annual}}$		$\sigma_{\text{interannual}}$		$\sigma_{\text{inter}}/\sigma_{\text{intra}}$	
Variable	Land	Ocean	Land	Ocean	Land	Ocean	Land	Ocean
Total cloud (%)	41.9	52.7	12.1	6.6	3.6	3.0	.30	.45
Cloud height (km)	4.50	3.95	0.51	0.38	0.26	0.17	.52	.44

over land are convective in nature. This is further suggested by the fact that the standard deviations of cloud height over land are considerably larger than those over ocean.

Although most of the following analyses have been calculated for both day and night observations and separately for land and sea areas using daytime observations, for simplicity the remaining discussions will concentrate on daytime observations made over both land and ocean. When, however, important differences are evident between those statistics and ones based upon nighttime observations or calculated separately for land and ocean areas, a portion of the larger analysis will be discussed.

4. Zonally averaged statistics

Figure 2 illustrates the six-year annual means and intra- and interannual standard deviations of the zonal means of local noon *Nimbus-7* total cloud amounts and heights as defined by Eq. (1). The total cloud fractions are very similar to those of Stowe et al. (1989) and other authors. The intra-annual standard deviations have a minimum of about 2% and maxima of over 14%. The minima exist in the middle latitudes of the Southern Hemisphere. The maxima exist between about 0° and 20°S and latitudes poleward of about 70°S and 60°N. These standard deviations near the poles seem exceptionally large, probably representing the difficulties in determining cloud amount in these regions. At most other latitudes, the interannual standard deviations are very roughly half of the intra-annual values. Latitudinal variations of this ratio do exist, however, with the smallest fractions near 40°N and 15°S.

The cloud height parameter (Fig. 2b) has an overall maximum just north of the equator and local maxima near 70°S, 30°S, 40°N, and 90°N. The intra-annual standard deviations of cloud height are between about 0.1 and 0.8 km. Largest values exist in the subtropics and at high latitudes. The subtropical maxima are also represented by a relatively large ratio of the interannual to intra-annual standard deviations. It should be noted that interannual variations near the South Pole are relatively large, whereas those near the North Pole are quite small. These high-latitude standard deviations suggest not only considerable uncertainty in determining the total cloud amount near the poles, but possibly even more difficulty in properly assessing cloud-top heights. This conclusion is born out by viewing the individual monthly means of cloud fractions (not shown), which show apparently artificial shifts in low, middle, and high cloud fractions. The interannual standard deviations of cloud height exceed three-fifths of the intra-annual values at many latitudes.

Figure 3 illustrates the annual mean zonal averages of total cloud amount and cloud height for day and night observations. Although the global averages

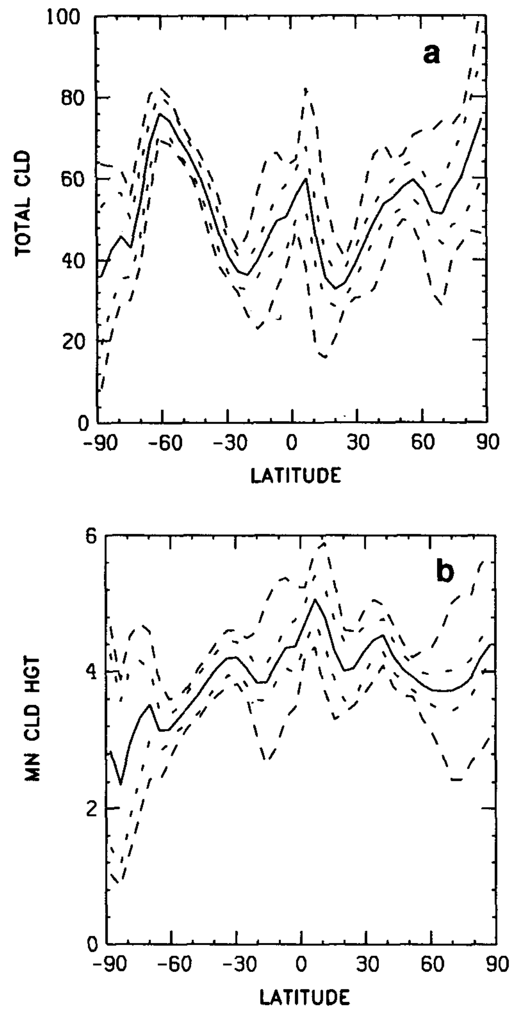

FIG. 2. Six-year zonal means (solid lines) of (a) total cloud amounts (percent), and (b) cloud heights (kilometers) derived from the *Nimbus-7* cloud analysis. Long and short dashed curves are the zonal means plus and minus two times the values of the intra-annual and interannual standard deviations, respectively.

showed that about 3% more cloud is observed at night, Fig. 3a confirms the Stowe et al. (1989) result that this difference is confined to the tropics where the night values exceed those of the day by up to about 8%. At higher latitudes, the daytime cloud percentages are near or slightly greater than those at night. Figure 3b, illustrating the day and night cloud heights, shows nearly the opposite situation. Although globally, nighttime heights are greater, this is true only poleward of about 15°, where differences greater than 0.15 km exist.

The cloud amounts and heights for land and sea areas are illustrated in Fig. 4. As may be seen from Fig. 4a, total cloud amounts over sea away from the equator and the poles typically are greater than those over land by 10%–15%. Analysis of the separate low, middle, and high cloud amounts (not shown) suggest that the greater oceanic values are usually due to larger amounts

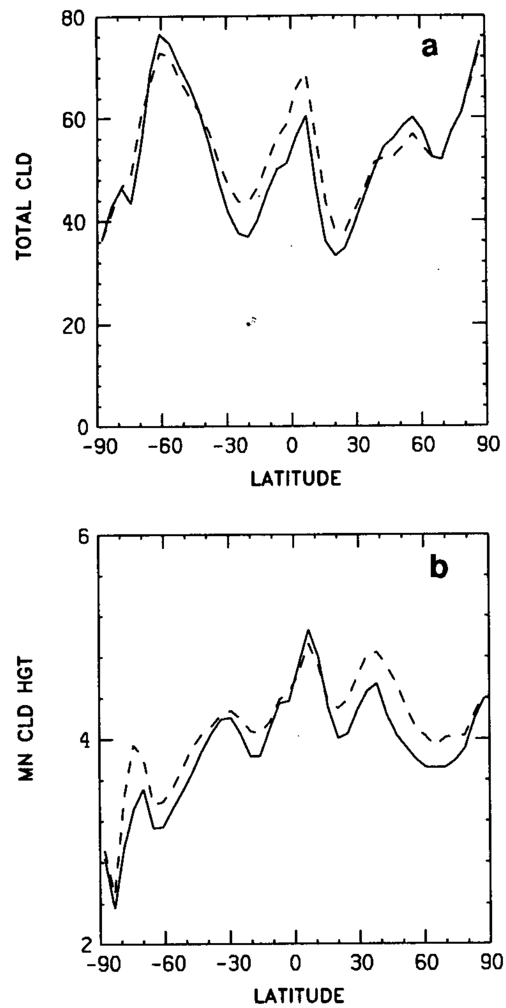

FIG. 3. Six-year zonal means of (a) total cloud amount (percent), and (b) mean cloud height (kilometers) for daytime (solid lines) and nighttime (dashed lines) observations.

of low-level clouds. This is partially confirmed in Fig. 4b, showing the land and sea zonal means of cloud height. Generally, the mean oceanic heights are a fraction of a kilometer less than the land values. The primary exception is again near the equator where land and sea cloud heights are nearly identical. In addition, the tropical peak of mean cloud height, corresponding to the position of the intertropical convergence zone, is more distinctive over the sea, whereas the land values show a broad zone of relatively high clouds south of the equator in the annual average. This pattern of total cloud amount and cloud height variations is consistent with the hypothesis that low clouds are generally underestimated over land.

5. Annual cycle

An efficient way to show the seasonal variations of the *Nimbus-7* cloud amounts and heights is to use empirical orthogonal functions (EOF) (Kutzbach 1967). It can be expected that monthly departures of the zonal averages from the corresponding annual mean will give rise to a dominant EOF, explaining more than half of the variance, whose time coefficients strongly reflect the annual cycle. The daytime zonally averaged *Nimbus-7* total cloud amounts and heights for the entire six-year period were used to calculate departures from the annual means illustrated in Fig. 2. These were then subjected to an empirical orthogonal analysis in which calculations of the functions were limited to data equatorward of 67.5°, since EOF analyses (not shown) including higher-latitude data gave dominant EOFs, which had strong high-latitude features apparently related to the spuriously large standard deviations in these regions shown in Fig. 2.

Figure 5 illustrates the most important functions and associated time coefficients for total cloud cover and

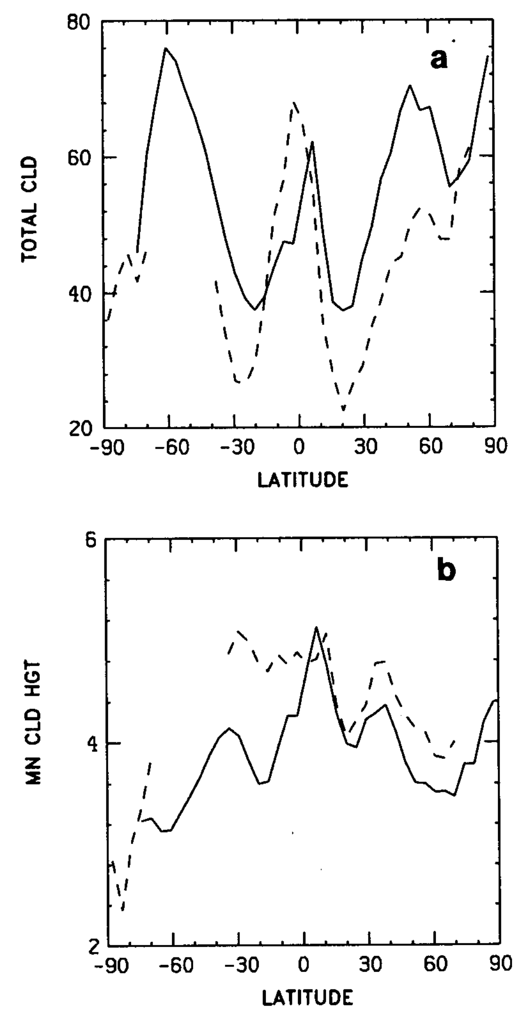

FIG. 4. Six-year zonal means of (a) total cloud cover (percent), and (b) cloud heights (kilometers) for only grids dominated by ocean (solid lines) or land (dashed lines) surfaces.

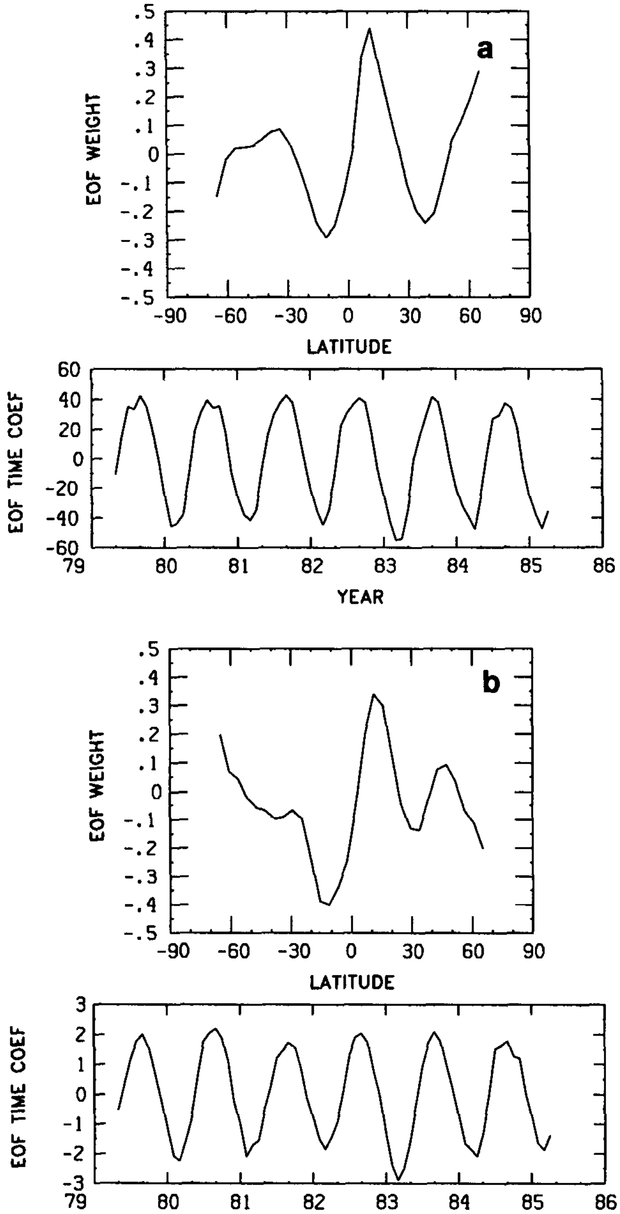

FIG. 5. Empirical orthogonal functions (upper) and time coefficients (lower) of the dominant function of monthly zonally averaged departures of (a) total cloud amount and (b) cloud height from the six-year annual mean values.

cloud height. These functions represent about 76% and 64% of the total variance, respectively. The dominant function of total cloud amount (Fig. 5a) shows a strong spatial maxima near 10°N with minima near 15°S and 40°N. The associated time coefficients have a very regular annual cycle with maxima in the Northern Hemisphere summer. This mode is clearly associated with the seasonal migration of the intertropical convergence zone (ITCZ) and the subtropical high pressure zones. A possibly important downward trend of about 2% over the six-year period is also evident in the time series in Fig. 5a.

The dominant EOF of departures from the annual mean of zonally averaged cloud height is similar to that for cloud fraction. Inspection of the respective total cloud amount and cloud height empirical orthogonal functions and time coefficients suggests that a 30% increase in total cloud amount is associated with approximately a 1.2-km increase in mean cloud height in the tropics. This strong relation in the tropics between cloud amount and height is further illustrated in Fig. 6, which shows the correlations between the zonal average values of total cloud cover and mean cloud height. The correlations between about 20°N and 20°S exceed 0.80, which are significant at greater than the 99% confidence level. Other latitudes show smaller and less-consistent values.

In order to more clearly highlight the seasonal interactions between total cloud amount and height, an EOF analysis of a total cloud–cloud height complex (Kutzbach 1967) was calculated. In this analysis, the EOF is composed of the best linear combination of both the total cloud and cloud height departures. The calculation of this EOF involves the diagonalization of a mixed cloud amount–cloud height correlation matrix in which the departures of the variables are normalized by their respective intra-annual standard deviations. The dominant function of this complex, together with its time coefficient in units of standard deviations, are illustrated in Fig. 7. This dominant EOF complex, which explains nearly 58% of the coupled variance, has spatial patterns of total cloud amount and cloud height, which are very similar to those of the separate EOF analyses. This confirms that seasonal variations of these two variables are tightly related. The exact

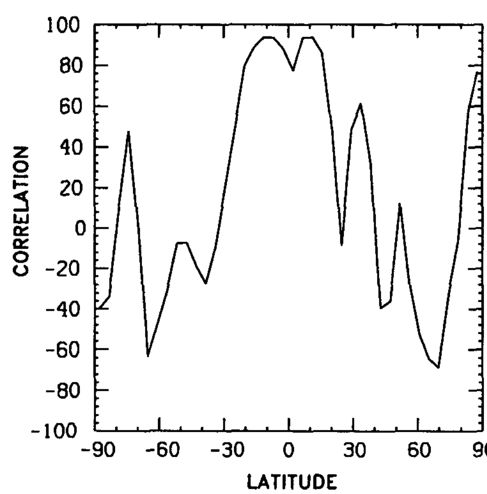

FIG. 6. Correlation coefficients (percent) between departures of zonally averaged total cloud amount and cloud heights from their respective annual means for six years.

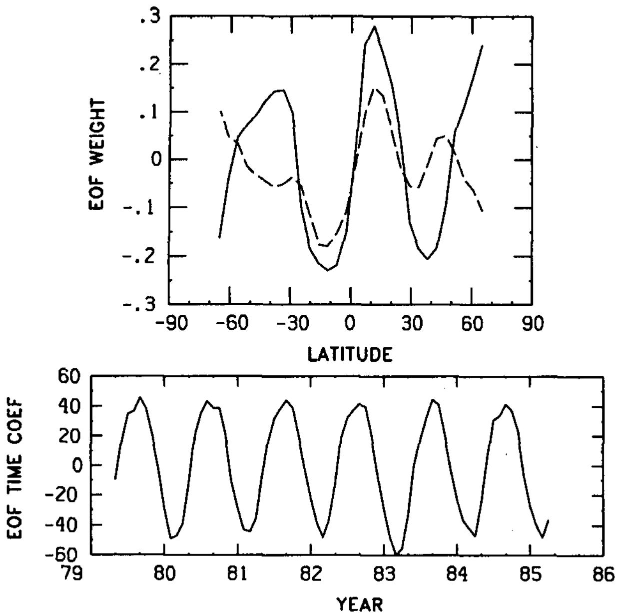

FIG. 7. Dominant empirical orthogonal function of a complex of intra-annual departures of zonally averaged total cloud amount (solid line) and cloud height (dashed line) and associated time coefficients as in Fig. 5.

nature of the relations, however, differs by latitude. In the tropic and subtropic latitudes, positive (negative) changes in cloud cover are related to increases (decreases) in cloud height as was shown in Fig. 6. In middle latitudes, however, increases (decreases) in cloud cover are either only weakly related to changes in height or are associated with decreases (increases).

6. Interannual variations

Although the period of cloud data is only six years, it is possible to illustrate some aspects of interannual changes, especially those associated with the large 1982–83 ENSO event. Empirical orthogonal functions of both total cloud cover and mean cloud height were calculated from zonal-average departures from the six-year monthly means. Figure 8 illustrates the most important functions and time coefficients for total cloud amount (explaining 26% of the variance) and cloud height (explaining 31% of the variance). The most important mode of total cloud is clearly dominated by changes in the tropics associated with the 1982–83 ENSO event. Very small changes outside of the tropics or in other time periods are illustrated. This mode suggests that toward the latter stages of the ENSO event, early in 1983, total cloud amount just south of the equator increased, while that just north of the equator decreased by a similar amount. The magnitude of the maximum changes was about 10%. Although the intra-annual analysis described in Fig. 5a showed a slight downward trend, none is evident in this ENSO mode of interannual variations.

The dominant EOF of cloud height does not indicate a distinct ENSO signal. Instead, the time coefficients suggest a weak downward trend. The EOF weights suggest that although this trend occurs at nearly all latitudes, it is most important near 25°N. Figure 9, showing the low, middle, and high cloud departures for a region centered near 25°N, illustrates an erratic downward trend in middle and high cloud amounts together with an upward trend in low cloud amounts. Although these trends may have some physical significance, they

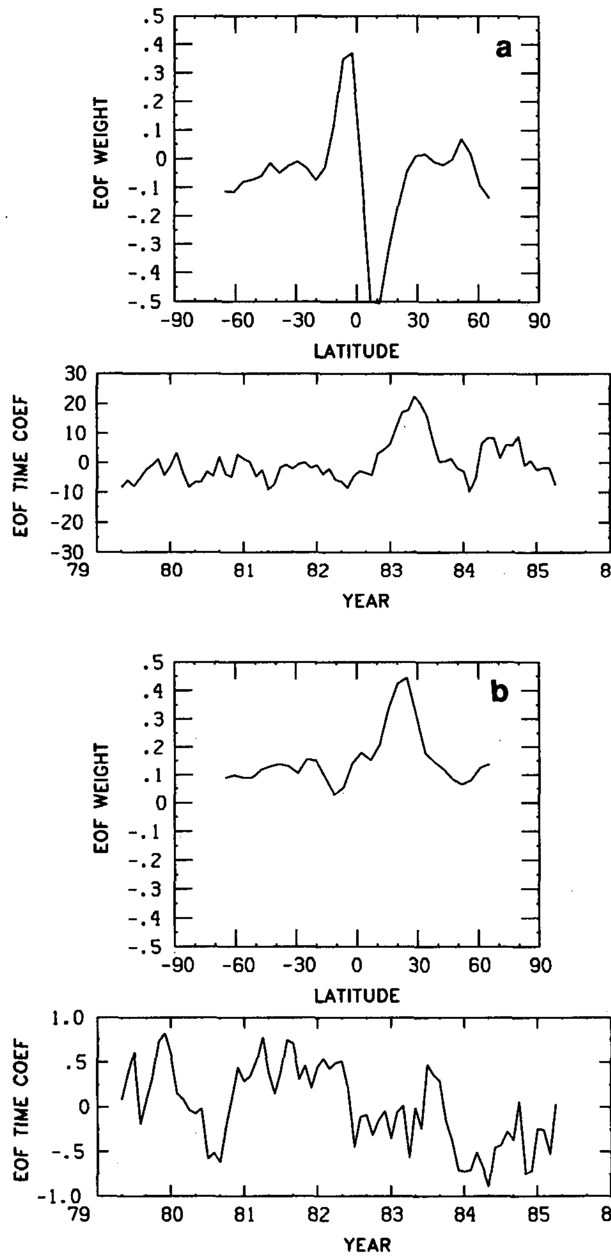

FIG. 8. Most important empirical orthogonal functions and associated time coefficients of interannual variations in zonally averaged (a) total cloud cover and (b) cloud height.

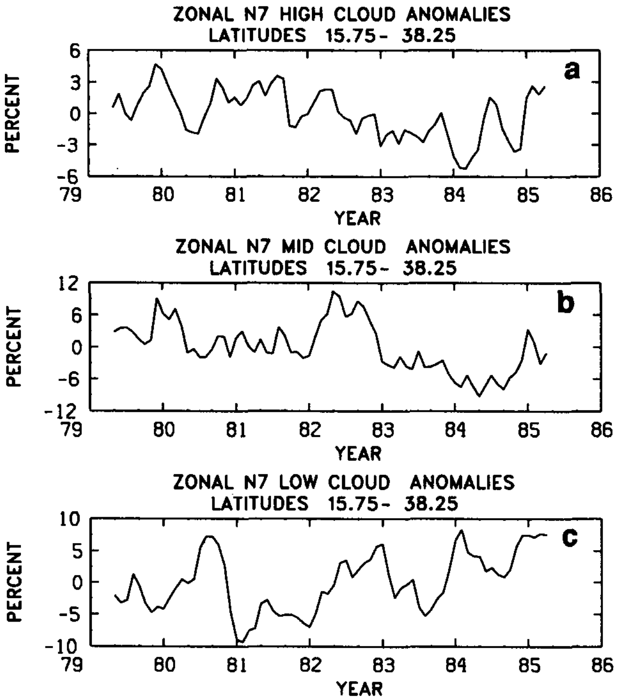

FIG. 9. Variations in the percent of (a) high, (b) middle, and (c) low cloud amounts for the zones between 15.7° and 38.25°N.

also may be due to slow changes in the satellite radiances or surface datasets used in the threshold tests to estimate fractional cover of the three cloud-height categories over the six-year period.

The EOFs of interannual departures of combined total cloud amount and cloud height were also calculated. Although the dominant function, shown in Fig. 10, explains only about 17% of the combined variance, the spatial patterns and time coefficients show a strong coherent signal in the mature phase of the 1982–83 ENSO. In this case within the tropics both cloud amounts and heights increased south of the equator and decreased a similar magnitude to the north. In April of 1983 near 10°N and 10°S, there are departures of more than 10% in total cloud amount and 1.1 km in average cloud height. The magnitudes of these changes have been confirmed by looking at time series plots of anomalies of cloud amount and height for these two regions. Poleward of about 20°, the pattern is less distinct. In southern latitudes, there is the strong indication that late in the 1982–83 ENSO the total cloud amount decreased over a broad range of latitudes at the same time that cloud heights remained nearly constant. At the same time, in northern latitudes there is an indication of an increase in cloud height near 30°N and a decrease in cloud amount north of 50°N.

These relationships are clarified by looking at correlations of interannual perturbations of cloud amounts and heights. Figure 11 shows that the departures of total cloudiness from the six-year monthly means are quite strongly related to departures of cloud height in the equatorial region. Correlations at other latitudes are not significant at the 95% confidence level, except possibly near the South Pole where uncertainties in the data suggest possibly spurious negative correlations. On the other hand, Fig. 11 shows that the correlations of interannual departures of middle amounts with high cloud amounts have moderate positive values at most latitudes south of about 50°N. This is in contrast with the moderate and weak negative correlations at most latitudes between departures of low and high cloud.

Figure 11 also has implications for the assumptions concerning the nature of the overlapping of cloud layers in an atmospheric column. If high clouds always had lower clouds below, from the point of view of a satellite decreases in high cloud amount would always be accompanied by increases in either low or middle cloud amounts. The correlations in Fig. 11 show this to be very approximately true for zonal averages of low clouds, but untrue for middle clouds. On the other hand, if high clouds were accompanied by no lower-level clouds, decreases in high cloud amount would tend to be uncorrelated with middle or low cloud amounts. This is apparently only rarely the case. On the contrary, changes in the processes that lead to increases (decreases) in high clouds seem to result in increases (decreases) in middle clouds in nearby areas. It is also possible that those same processes lead to changes in low cloud amounts even after the effects of obscuration of low clouds by high and middle clouds are accounted for.

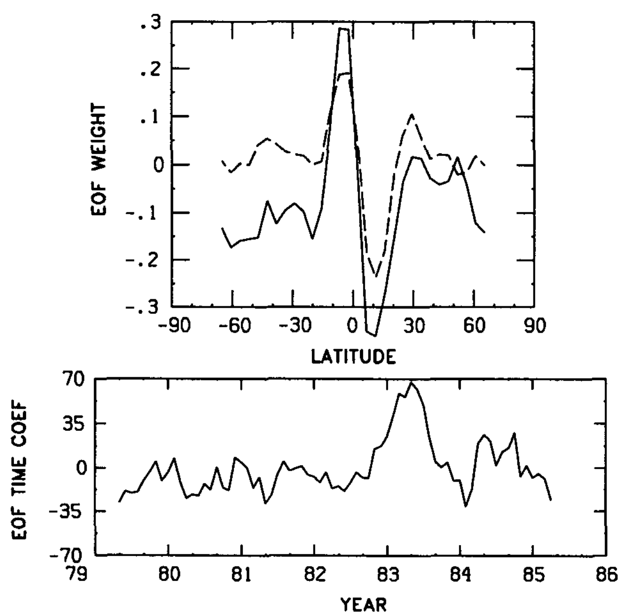

FIG. 10. Dominant empirical orthogonal function of a complex of interannual departures of zonally averaged total cloud amount (solid line) and cloud height (dashed line) and associated time coefficients as in Fig. 7.

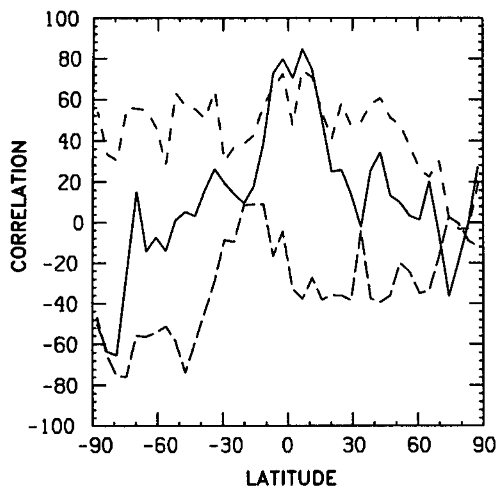

FIG. 11. Correlation coefficients (percent) between departures of zonally averaged cloud values from their six-year monthly means: Total cloud amount versus cloud height (solid line); middle cloud amount versus high cloud amount (short dash); low cloud amount versus high cloud amount (long dash).

7. Conclusions and discussion

This analysis of the *Nimbus-7* satellite cloud data has supplemented the work of Stowe et al. (1989), providing new insights into the changes in cloudiness associated with seasonal and interannual variations of weather and climate. Based upon the six-year annual mean statistics:

1) Interannual standard deviations are often greater than 5% of the total cloud cover and are typically between two-fifths and three-fifths of the intra-annual values. No comparable estimates of variability have been published for the ISCCP analysis.

2) The interannual standard deviations of the mean cloud height exceed 0.3 km in subtropical latitudes.

3) Comparisons of day and night observations suggest that in the tropics there is greater nighttime total cloud cover with little difference in height. On the other hand, at higher latitudes the nighttime total cloud amounts differ little from those during the day, while cloud heights are larger by up to about 0.3 km.

4) Except in the equatorial zone and at very high latitudes, total cloud cover over oceans is usually much greater than over land, whereas cloud heights over land are up to about 0.6 km greater. These differences are mainly due to the larger amount of low cloud detected over oceans relative to land areas.

Based upon empirical orthogonal and correlation analyses of departures of total cloud cover and height from their respective annual means, it is concluded that:

1) The dominant mode of variation is such that increases (decreases) in cloudiness of up to about 30% near 10°N are accompanied by decreases (increases) near 10°S and 40°N and increases poleward of 50°N. This mode clearly represents movements of the ITCZ and the subtropical high pressure zones. The temporal variations have a strong annual cycle, with maxima in the Northern Hemisphere autumn.

2) The dominate mode of total cloudiness is accompanied by a comparable dominant mode of cloud height changes such that within the tropics and subtropics increasing (decreasing) cloud amounts of about 30% tend to be accompanied by increasing (decreasing) cloud heights of more than 1.2 km. This is consistent with the general observations that the mostly clouded ITCZ is mainly made up of deep convective clouds, whereas the relatively cloudless subtropical high regions are populated mainly with low-level trade cumuli.

3) The positive relationship between cloud amount and heights in the tropics is confirmed by EOF analysis of a complex of these two fields and correlations of greater than 80% in the tropics.

4) A weak downward trend in total cloudiness of about 2% over the six-year record is apparent.

Analyses of departures of total cloud cover and height from their respective six-year monthly means illustrates an important interannual mode in both associated with the ENSO phenomenon. In this case:

1) The dominant EOF of total cloud amount shows that during the mature phase of the 1982–1983 ENSO, total cloud cover just south of the equator increased by about 10% at the same time that it decreased just to the north.

2) The dominant EOF of cloud height does not show a clear relation with the 1982–83 ENSO, but suggests a rather erratic decline in cloud height, which is most pronounced near 25°N.

3) On the other hand, the dominant EOF of a complex of total cloud amount and cloud height shows variations in cloud amount and height that are clearly related to the 1982–83 ENSO. In this case, as for seasonal variations, in the tropics changes in cloud amount and height tend to be closely interrelated.

The positive correlations in the tropics between intra- and interannual variations of cloud height and amount have possible implications for climate change theories (Hartmann et al. 1986). Schneider (1972) has estimated how much the radiation balance at the top of the atmosphere is altered by changes in both cloud-top height or cloud amount. Using the results summarized in his Fig. 3 and our conclusion that cloud height increases of 1.0 km are accompanied by approximately a 10% increase in the total cloud amount, then the equilibrium temperature of the earth would increase by about 1 K. On the other hand, if the 1.0 km increase were accompanied by a 20% increase in cloud cover, then the equilibrium surface temperature would decrease about 1 K. Thus, the net result is very sensitive

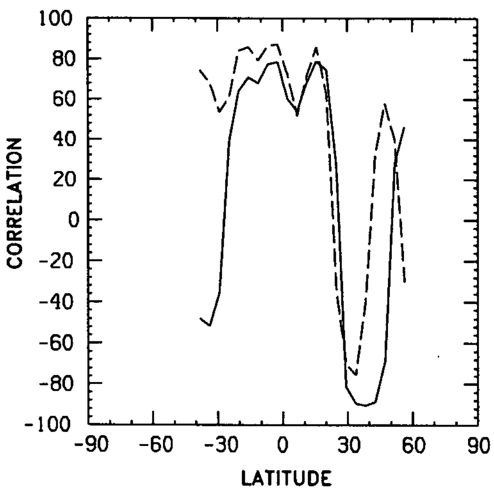

FIG. 12. Correlation coefficients (percent) between departures of zonally averaged sea surface temperatures from the 1980–84 annual means and total cloud amounts (solid line) and cloud height (dashed line) from their respective annual means for the period 1980–84.

to the exact magnitudes of the observed changes, which are presently quite uncertain. In addition, one must always remain aware that the correlations associated with intra- and interannual variations may not represent those of climate changes such as might accompany a global warming.

Another way to approach the question of the link between cloudiness and surface temperature is to look at the direct correlations between cloud amounts and surface temperatures. Figure 12, which shows the intraannual correlations between Climate Analysis Center sea surface temperatures (Reynolds 1988) and total cloud amounts and cloud-top heights, indicates that in the tropics there is a strong link for both variables over the seasonal cycle. Correlations associated with interannual changes (not shown), however, show significant values only in the region near 5°S, where ENSO-related changes are greatest. It is difficult to speculate on whether such results are applicable to climatic changes. Nevertheless, they are sufficiently intriguing as to warrant further research with longer and different cloud datasets and with climate models with realistic cloud and radiation physics.

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