Variations in *Nimbus-7* Cloud Estimates. Part II: Regional Changes

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(Manuscript received 20 June 1991, in final form 10 April 1992)

ABSTRACT

Regional estimates of low, middle, high, and total cloud amounts derived from bispectral measurements from *Nimbus-7* have been analyzed for the six-year period April 1979 through March 1985. Fractional cloud cover for the three height categories was used to calculate a proxy mean cloud-top height. Intra- and interannual standard deviations of total cloud amount and mean cloud height show realistic patterns throughout most of the globe except at very high latitudes. Over much of the earth, intra-annual and interannual variations in total cloud amount are strongly positively correlated with variations in cloud height. Furthermore, both total cloud amount and cloud height variations are moderately correlated with sea surface temperature variations. The strongest correlations are positive in the tropics for both intra-annual and interannual variations. In middle latitudes, moderate negative correlations are associated with intra-annual variations, whereas moderate positive correlations occur on interannual time frames. In the tropics 1°C changes in temperature are statistically related to a change of total cloudiness of at least 2% and a change in cloud height of more than 0.5 km.

1. Introduction

In a companion article, Weare (1992) examines the relationships between zonal averages of cloud amounts and top heights, derived from the *Nimbus-7* analyses, for the period April 1979–March 1985. This paper analyzes the variations in regional cloud amounts and heights from the same *Nimbus-7* (500 km)^2 resolution data (Stowe et al. 1988). The current work utilizes only daytime cloud estimates based upon bispectral tests using an infrared window channel and a solar channel making measurements in the near-ultraviolet range of the spectrum. This choice was based on the fact that the bispectral algorithm gives a truer measure of low cloud behavior than the infrared-alone estimates. The general characteristics of these data are discussed in Weare (1992), Stowe et al. (1989), and Rossow and Schiffer (1991).

The available data include total cloud cover and fractions of low (f_l), middle (f_m), and high clouds (f_h). The daily values were used to calculate monthly means from which all of the following analyses were derived. The monthly means of the fractional cloud amounts for low, middle, and high clouds were used to calculate a proxy mean cloud-top height parameter. Following Weare (1992) and 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 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

$$Z_{lm} = 2\ \mathrm{km}$$
$$Z_{mh} = \begin{cases} 7\ \mathrm{km}, & \text{for latitudes} < 30° \\ 7 - 1.5(1 - \cos[3(|\mathrm{lat}| - 30]\}\ \mathrm{km}, & \text{for latitudes} > 30°. \end{cases}$$

Although a large number of alternate definitions of mean cloud height are possible, Weare (1992) shows that the one used here gives interpretable zonally averaged statistics, which are relatively insensitive to the exact choices of Z_l, Z_m, and Z_h.

The utility of this definition is further illustrated in Fig. 1, which shows the intra-annual correlations between Z_t and the fractions of low, middle, and high cloud. As shown in Weare (1992), for zonal averages, the cloud height is not only strongly correlated with the amount of high clouds but is also significantly correlated in many regions with the fractions of low and middle clouds.

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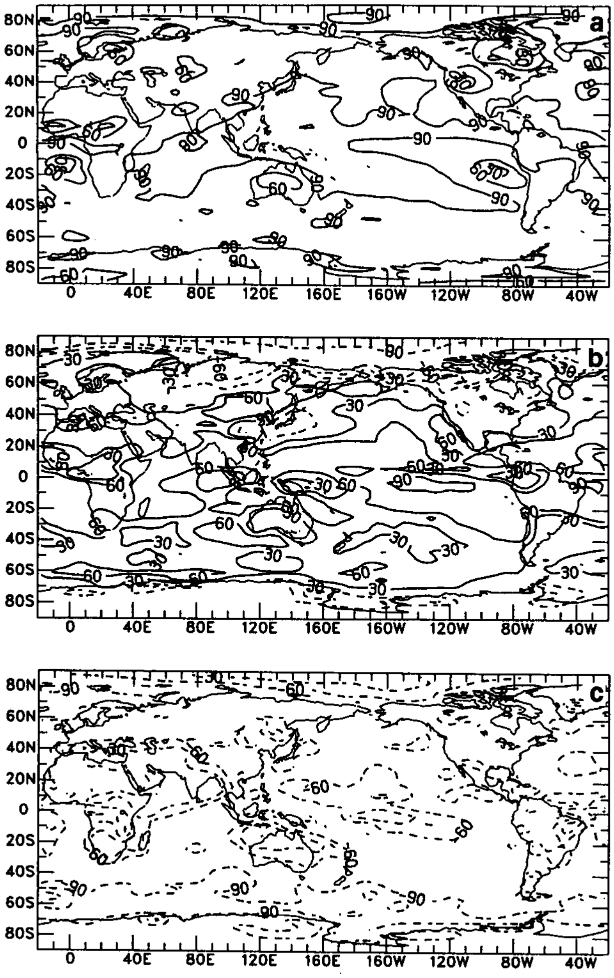

FIG. 1. Pointwise correlations (×100) of variations in the estimated mean cloud height Z_t from the six-year annual mean and variations of *Nimbus-7* estimates of (a) high, (b) middle, and (c) low-cloud fractions (percent). Only correlations approximately significant at the 95% significance ($|r| > 0.30$) level are plotted; negative values are dashed.

The calculated statistics include the six-year annual and monthly means and the intra-annual and interannual standard deviations σ given by the square roots of

$$\mathrm{var}_{\mathrm{intra}}(x_j) = \sum_{y=1}^{6}\sum_{m=1}^{12}(x_{ymj}-x_{aj})^2/71 \qquad (2)$$

$$\mathrm{var}_{\mathrm{inter}}(x_j) = \sum_{y=1}^{6}\sum_{m=1}^{12}(x_{ymj}-x_{mj})^2/71, \qquad (3)$$

where "intra" and "inter" specify the intra-annual and interannual variances; x_{ymj} is a regional estimate at location j, year y, and month m; x_{aj} is the six-year annual mean; and x_{mj} is the six-year monthly mean for the month m. Correlations of intra-annual and interannual departures were calculated for variables x and z using the formulas

$$r_{\mathrm{intra}}(x_j) = \sum_{y=1}^{6}\sum_{m=1}^{12}(x_{ymj}-x_{aj})(z_{ymj}-z_{aj})/(71\sigma_{\mathrm{intra}}(x_j)\sigma_{\mathrm{intra}}(z_j)) \qquad (4)$$

$$r_{\mathrm{inter}}(x_j) = \sum_{y=1}^{6}\sum_{m=1}^{12}(x_{ymj}-x_{mj})(z_{ymj}+z_{mj})/(71\sigma_{\mathrm{inter}}(x_j)\sigma_{\mathrm{inter}}(z_j)). \qquad (5)$$

The 95% significance levels of these correlations were derived by first estimating the approximate number of independent samples N (Leith 1973) and using a Z statistic (Brunk 1965). The number of independent samples was estimated by calculating lag correlations out to three months using formulas similar to Eqs. (4) and (5). The absolute magnitude of a correlation coefficient $|r|$ is statistically significant at approximately the 95% confidence level if

$$|r| > \frac{e^{3.92/\sqrt{N-3}}-1}{e^{3.92/\sqrt{N-3}}+1}. \qquad (6)$$

2. Variations of cloud cover and height

Figure 2 illustrates the six-year annual means and intra-annual and interannual standard deviations of the regional estimates of the local noon *Nimbus-7* total cloud amounts. The total cloud fractions are very similar to those of Stowe et al. (1989). The intra-annual standard deviations have a minimum of about 5% over the Southern Ocean and maxima of over 25% at several tropical locations. The interannual standard deviations range between 5% and 15%, with maxima and minima generally at the same locations as for the intra-annual values. Stowe et al. (1989) and Weare (1992) have suggested that the high-latitude cloud amounts are quite suspect. This is further confirmed by the large intra- and interannual standard deviations near both poles shown in Fig. 2b,c. For instance, the mean cloudiness over the eastern longitudes of Antarctica is near 40%, whereas both the intra- and interannual standard deviations often exceed 15%. Autocorrelation calculations out to three-months lag (not shown) suggest that these areas of high standard deviations have greater persistence than even the tropical Pacific, which is known to be dominated by the large interannual variations associated with El Niño–Southern Oscillation (ENSO).

The mean cloud-height parameter (Fig. 3a) generally has maxima along the equator. There is also the suggestion of maxima over the higher surface altitude regions of the Rockies and Himalayas, which may be due in part to the fact that the height designations are all with respect to sea level. Comparing Figs. 2a and 3a, it may be seen that several areas of very low cloud cover are areas of cloud height maxima. These include

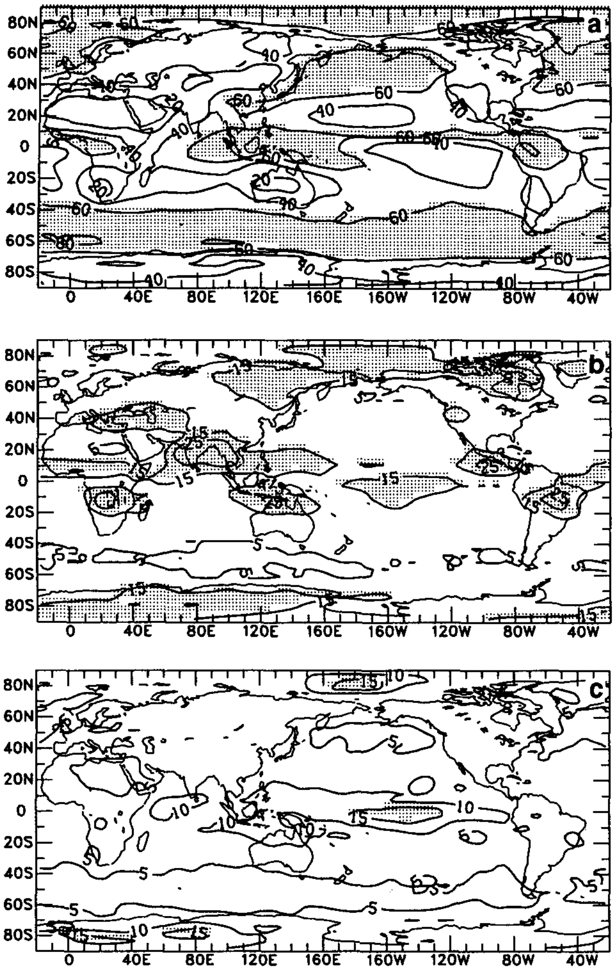

FIG. 2. *Nimbus-7* total cloud amount statistics for April 1979–March 1985. (a) Annual averages, (b) standard deviations from the annual average, and (c) standard deviations from the six-year monthly means (percent). Stippling emphasizes areas of maxima.

southern Africa, central Australia, and eastern South America. This implies that when cloud exists in these areas it tends to be convective in nature.

The intra-annual standard deviations of cloud height (Fig. 3b) exceed 1.0 km over much of the tropics and at high latitudes in both hemispheres. As discussed in Weare (1992), the values of both the means and standard deviations of cloud heights are suspect at latitudes poleward of about 70°. Areas of interest include the maximum over the eastern Sahara–Middle East zone, which must be associated with relatively deep winter systems. Also of interest are the broad bands of minima over most of the middle-latitude ocean regions, which suggests that not only are cloud amounts relatively constant in these regions (Fig. 2b) but that the clouds have heights that do not change substantially between summer and winter.

The interannual standard deviations of cloud height (Fig. 3c) are near 0.5 km over much of the globe. The maximum of over 1.5 km over the Antarctic appears to be unrealistic. The maximum over the equator near 150°W is undoubtedly attributable to the influence of the 1982–83 ENSO event that is in this data record. The maximum over the eastern Sahara suggests that the few clouds that exist in this region have very different characters in different years.

Figure 4 illustrates the intra-annual and interannual correlations of total cloud amount and cloud height. Only those correlation values that exceed the approximate 95% confidence level threshold defined by Eq. (6) are plotted. Figure 4 shows strong positive correlations for both intra-annual and interannual departures throughout most of the tropics. Weaker but still significant positive correlations are also evident for most of the middle latitudes of both hemispheres. Only the highest latitudes exhibit negative correlations. Many of these latter relations must be considered suspect be-

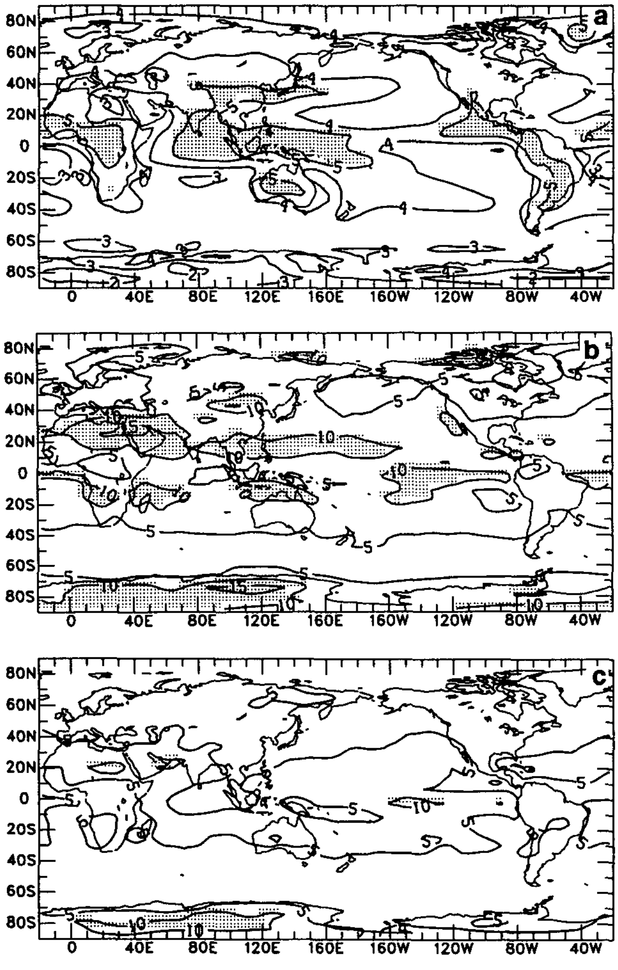

FIG. 3. *Nimbus-7* cloud height [Eq. (1)] statistics for April 1979–March 1985: (a) annual averages (km), (b) standard deviations from the annual average (km × 10), and (c) standard deviations from the six-year monthly means (km × 10). Stippling emphasizes areas of maxima.

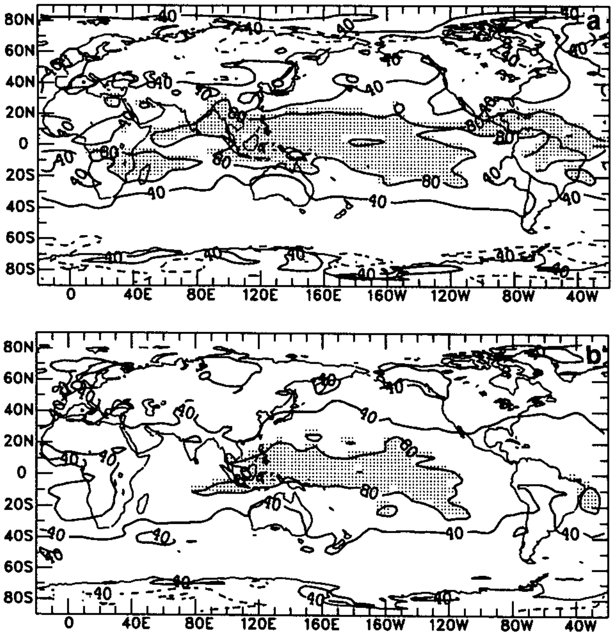

FIG. 4. Pointwise correlations (×100) of variations of *Nimbus-7* total cloud amounts and cloud heights (percent) (a) including the annual cycle and (b) excluding the mean annual cycle. Only correlations that are significant at approximately the 95% confidence level are plotted; negative values are dashed. Stippling emphasizes areas of maxima.

cause of the larger uncertainties in the total cloud and, especially, cloud height estimates in these regions. Some of the negative correlations, however, might represent true variations in which extensive summer stratus is replaced in winter by less extensive deeper frontal clouds.

One might hypothesize that much of the observed relationship between total cloud amount and cloud height is due to the fact that satellites can only observe the uppermost layer of a possibly multilayer cloud system. If one assumes that high clouds always have low or middle clouds below them, then decreases (increases) in high clouds would always be accompanied by increases (decreases) in low or middle cloud amounts. This would result in negative correlations between the amounts of clouds at different levels. Figure 5 shows the intra-annual correlations between the three possible combinations of high, middle, and low cloud amounts. From this figure it can be seen that this assumption cannot explain the relationships between high and middle clouds; however, over much of the oceans it may partially explain some of the relations between high and low and middle and low cloud changes. On the other hand, even for low clouds, Figs. 5b and 5c show that over well-defined continental regions increases (decreases) in high or middle cloud are often associated with no change or even increases (decreases) in low cloud amounts. Thus, the observed correlations between cloud amount and height in Fig. 4 cannot merely be attributed to the covering and uncovering of lower clouds by higher ones.

3. Variations of cloudiness and sea surface temperatures

The *Nimbus-7* cloud fractions and proxy heights have been related to variations in sea surface temperatures (SST) derived by the Climate Analysis Center (CAC) of the U.S. Weather Service (Reynolds 1988). The CAC SST analyses were available on a 2.5° × 2.5° grid for the period April 1979–December 1984 for the earth north of 40° S. In order to carry out point-by-point comparisons, the CAC SSTs were transformed to the *Nimbus-7* equal-area grid using bidirectional cubic spline interpolation (Press et al. 1986).

Figure 6 shows the intra-annual and interannual cor-

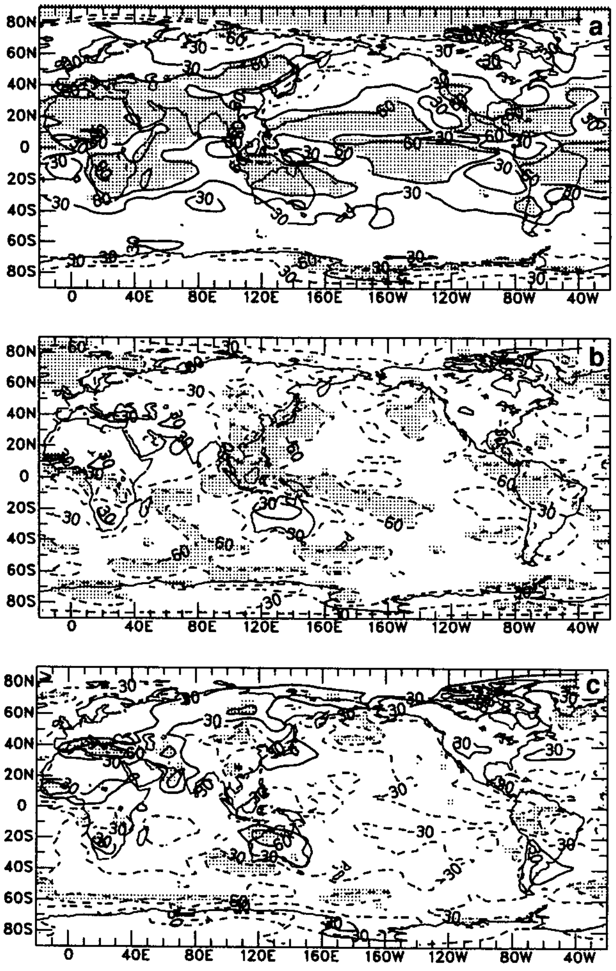

FIG. 5. Pointwise intra-annual correlations of variations of *Nimbus-7* high cloud amounts with (a) middle and (b) low cloud amounts and (c) middle and low cloud amounts. As in Fig. 4 except stippling indicates regions of correlations with magnitudes greater than 0.6.

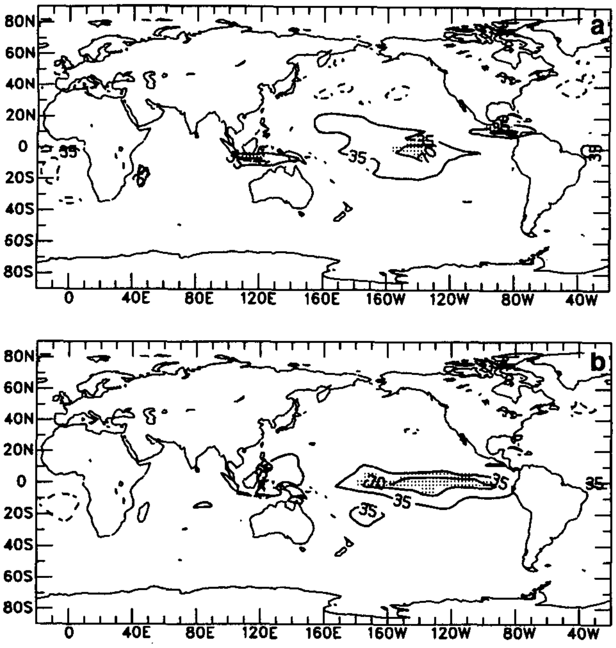

FIG. 6. Pointwise correlations of variations of *Nimbus-7* total cloud amounts and CAC sea surface temperatures (a) including the annual cycle and (b) excluding the mean annual cycle. As in Fig. 4.

relations of the monthly average CAC SST variations with those of *Nimbus-7* total cloudiness. Moderately large positive correlations are evident along a broad tropical band. A likely explanation is that higher SSTs lead to greater convective cloud cover in this region. Since the largest positive correlations are in the central and eastern equatorial Pacific, the 1982–83 ENSO event undoubtedly has contributed substantially to the interannual correlations in this area. Thus, a longer length of observational record would be required to assess the universality of the positive interannual correlations between SST and cloudiness. Relatively weak negative correlations are illustrated for the intra-annual variations over the middle-latitude oceans and for both intra-annual and interannual variations over the Atlantic near 15°S. This might be interpreted to imply that at these locations greater cloud cover leads to less surface heating and reduced SSTs.

Figure 7 illustrates the correlations between the intra-annual and interannual variations in SST and the *Nimbus-7* cloud height parameter. There is a broad band of the tropics with significant moderate positive correlations. Since all three ocean basins exhibit similar relationships for both intra-annual and interannual variations, this result seems not to be wholly related to the changes associated with the 1982–83 ENSO. This has been partially confirmed by the fact that the correlations calculated excluding data for July 1982–June 1983 (not shown) have similar features of somewhat smaller magnitudes compared to those shown in Fig. 7. No large areas of significant negative correlations are evident for either intra-annual or interannual variations. Thus, in the tropics increased SSTs are associated with increases in both total cloud and high cloud amounts.

In order to help clarify the relationships between SST and cloudiness, correlations were calculated separately between variations of SST and low, middle, and high cloud amounts. Figure 8 shows the correlations for each associated with intra-annual variations. The maps for interannual variations (not shown) look very similar in the tropics but show only small areas of significant patterns at latitudes poleward of 30°. Figure 8a shows that the correlations with high cloud amount have patterns similar to those for cloud height. The correlations for middle clouds (Fig. 8b) show moderate positive correlations in the tropics and negative correlations in the middle latitudes. Those for low clouds (Fig. 8c) show moderate negative correlations at nearly all latitudes. Taken together, Figs. 6–8 indicate that in the tropics higher SSTs are associated with greater total, high, and middle cloud cover and average cloud height, and smaller low cloud amounts. Thus, during ENSO it is expected that over the tropical Pacific low cloudiness would be reduced and high cloudiness would be enhanced. Other observational studies based upon marine surface reports (Weare 1983) and earlier satellite analyses (e.g., Ramage and Hori 1981) tend to confirm this conclusion. On the other hand, those earlier studies also tend to show that

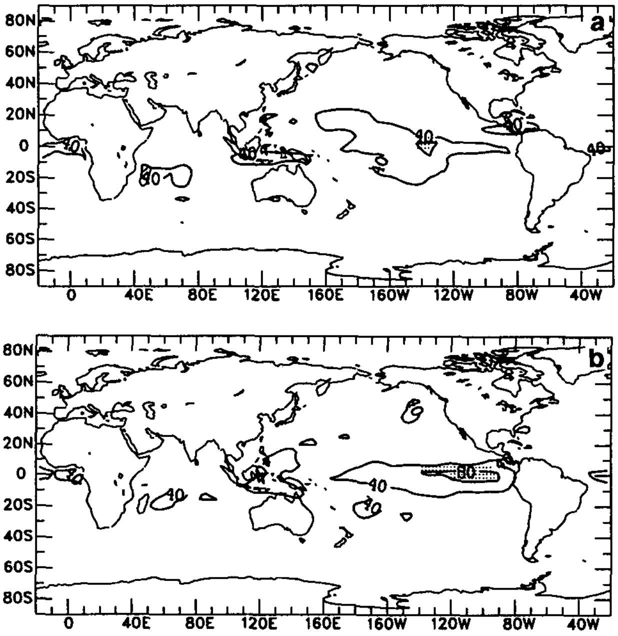

FIG. 7. Pointwise correlations of variations of *Nimbus-7* cloud height and CAC sea surface temperatures (a) including the annual cycle and (b) excluding the mean annual cycle. As in Fig. 4.

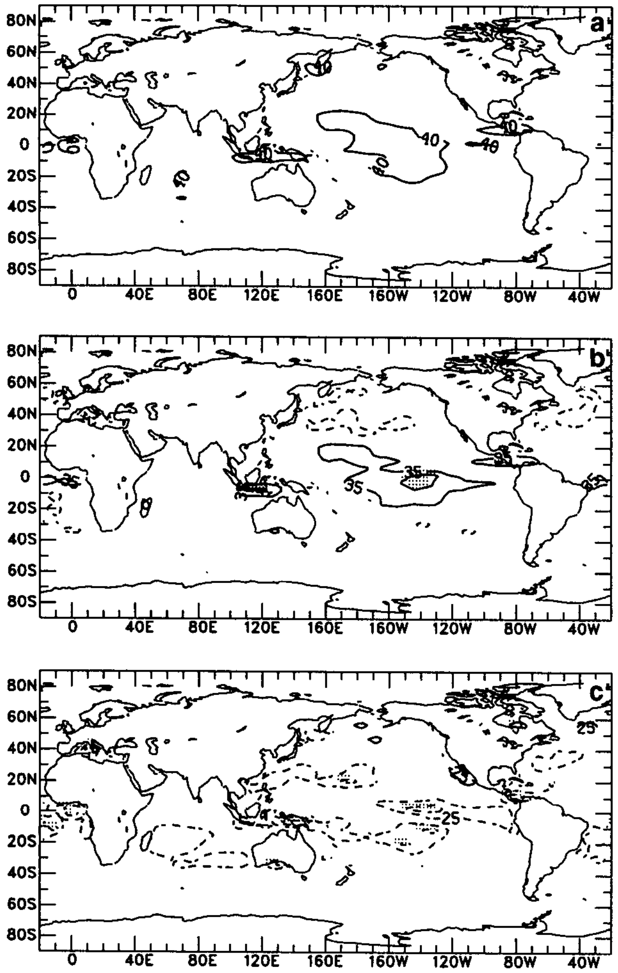

FIG. 8. Pointwise correlations of variations of CAC sea surface temperatures from the long-term annual mean and variations from a six-year annual mean of *Nimbus-7* estimates of (a) high, (b) middle, and (c) low cloud fractions (percent). As in Fig. 4.

during ENSO the higher SSTs in the eastern equatorial Pacific are associated with less, not more, total cloudiness. The situation at higher latitudes differs considerably from that of the tropics. In this case there are no large regions of significant correlations of high cloud with the surface temperature, and variations in both middle and low clouds are usually negatively correlated with SST. Thus, as is evident from Fig. 6, total cloud amount must be negatively correlated with SST.

In order to assess the magnitudes of changes in cloud amounts or height for a given change in SSTs, the linear regression coefficients relating SST as independent variables and coincident cloud cover as dependent variables were calculated for both intra-annual and interannual variations. Figure 9 illustrates the slopes associated with intra-annual variations in total cloud amounts and cloud top heights. Although the slopes between SST and total cloud cover are quite variable in space, they imply that a 1°C increase (decrease) in tropical SSTs is associated with at least a 2% increase (decrease) in total cloud cover and at least a 0.2 km increase (decrease) in the cloud height. Although the implied changes are larger in the central Pacific area most influenced by the 1982–83 ENSO, they are of similar magnitudes at other tropical locations and for either intra-annual or interannual variations (not shown). Thus, realistic changes in SST may be associated with sizeable modifications of both cloud amount and the vertical distribution of those clouds.

4. Discussion

Nimbus-7 estimates of cloud amount and height changes exhibit substantial variations nearly everywhere. Intra-annual and interannual variations of cloud cover exceed 5% over nearly all of the globe with the largest changes generally over the tropics and the smallest changes over the middle-latitude oceans. Variations in proxy cloud heights generally exceed 0.3 km with the largest changes in the lower latitudes and smallest changes over the middle latitudes. Precise quantitative assessments of the accuracies of the illustrated standard deviations are difficult, if not impossible, to make at this time. The analysis of the *Nimbus-7* data by Stowe et al. (1988) and others imply that strong confidence may be placed in these assessments of variability over the oceans, especially outside of the

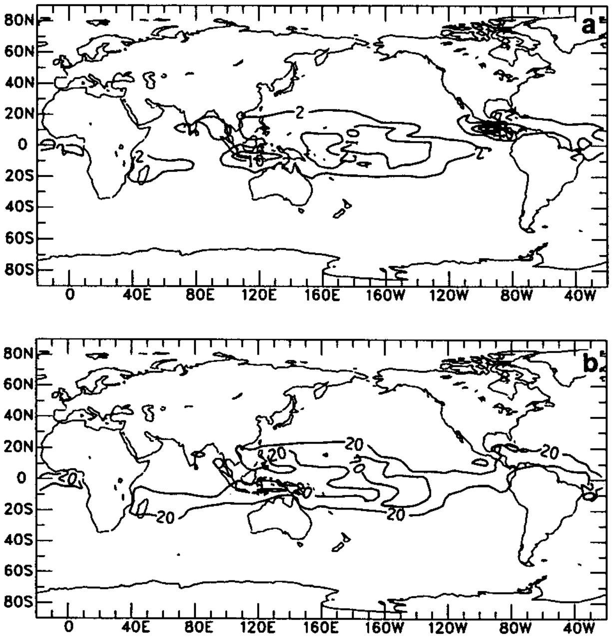

FIG. 9. Estimated intra-annual change in (a) total cloud percent and (b) cloud height (km × 100) for a 1°C change in sea surface temperature corresponding to the correlations illustrated in Figs. 6a and 7a.

permanent stratus regions of the eastern oceans. The current analysis and that of Weare (1992), however, strongly suggests that extreme care must be used when interpreting the high-latitude results.

Both intra-annual and interannual variations in total cloud amount and cloud height are strongly positively correlated over large parts of the tropics and subtropics. Analysis of the fractions of low, middle, and high cloud show that this is generally the result of the fact that high and middle cloud amounts are generally strongly positively correlated, whereas high and low amounts are moderately negatively correlated. This conclusion has strong implications for the cloud changes and their consequences that might be expected during climatic change (Schneider 1972).

Perhaps even more important for climate change theories is the fact that this analysis shows that both intra-annual and interannual variations in sea surface temperatures are moderately positively correlated with both total cloud amount and height over much of the tropics. Weaker negative correlations are evident over parts of the middle latitudes. The positive correlations with cloud height over the central and eastern Pacific have been previously suggested in reference to ENSO events (Ardanuy et al. 1987). In these cases higher SST are associated with more deep convection. These earlier studies, however, did not suggest that total cloudiness is also positively correlated with SST. Furthermore, the current analysis suggests that the positive correlations are true not only over the central Pacific but also elsewhere in the tropics and that they exist even when the influence of the July 1982–June 1983 ENSO period is removed from the calculations.

These results can be compared to a recent summary of modeling studies (Cess et al. 1990), which investigated the influence of altering the SST boundary conditions of a group of sophisticated atmospheric climate models. In each case, higher SSTs were associated with global cloudiness decreases. This is in contrast to the results of Fig. 6 for the tropics indicating that higher SSTs for intra- and interannual variations are associated with cloudiness increases. Only at higher latitudes are small areas of negative correlations evident. Since in all of these models reduced cloud amounts tend to lead to surface heating, these model changes induce a strong positive feedback mechanism. On the other hand, it would be expected that the positive correlations indicated by the observations would result in a negative feedback in the tropics. It is difficult with the available data to discern the global effect.

Changes in model cloud heights associated with the increased SST differ for the various models analyzed in Cess et al. (1990). In many cases higher SSTs give rise to higher clouds, as is found for the tropics in the present results. In these cases higher clouds induce a positive feedback that when coupled with the positive feedback associated with amount decreases makes these models especially sensitive to SST changes. On the other hand, in some models changes in cloud heights and optical depths result in a negative feedback, which partially balances the positive feedback due to cloud amount changes. The observational results shown in Figs. 6 and 7 imply a relatively weak feedback, which may be either positive or negative, due to the partial cancellation of the negative feedback due to cloud amount changes and the positive feedback due to cloud height variations. Overall, for the tropics, at least, the present results are in apparent disagreement with all of the model results.

Finally, total cloud amount and mean cloud-top height are not the only parameters that influence the nature of the feedback between clouds and climatic changes. Other factors include cloud thickness, condensed water content, cloud particle size, and whether condensate is liquid or ice. Furthermore, sea surface temperature changes are clearly not the only, nor perhaps the primary, climate variable that influences cloud formation. Other important variables include relative humidity departures at various elevations, low-level moisture convergence, and boundary-layer heating. Therefore, there is a great deal more research that must be carried out in order to unambiguously decipher the relationships between climate change and changes in global cloudiness.

Acknowledgments. This work was supported by the Department of Energy through a contract with the Western Regional Center of the National Institute of Global Environmental Change. The *Nimbus-7* data were provided by the National Space Science Data Center with the cooperation of Drs. H. Lee Kyle and Larry Stowe.

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