A 3-Year Climatology of Cloud and Radiative Properties Derived from GOES-8 Data Over the Southern Great Plains

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Introduction

While the various instruments maintained at the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains (SGP) Central Facility (CF) provide detailed cloud and radiation measurements for a small area, satellite cloud property retrievals provide a means of examining the large-scale properties of the surrounding region over an extended period of time. Seasonal and inter-annual climatological trends can be analyzed with such a dataset. For this purpose, monthly datasets of cloud and radiative properties from December 1996 through November 1999 over the SGP region have been derived using the layered bispectral threshold method (LBTM). The properties derived include cloud optical depths (ODs), temperatures and albedos, and are produced on two grids of lower (0.5°) and higher resolution (0.3°) centered on the ARM SGP CF. The extensive time period and high-resolution of the inner grid of this dataset allows for comparison with the suite of instruments located at the ARM CF. In particular, Whole-Sky Imager (WSI) and the Active Remote Sensing of Clouds (ARSCL) cloud products can be compared to the cloud amounts and heights of the LBTM 0.3° grid box encompassing the CF site. The WSI provides cloud fraction and the ARSCL computes cloud fraction, base, and top heights using the algorithms by Clothiaux et al. (2001) with a combination of Belfort Laser Ceilometer (BLC), Millimeter Wave Cloud Radar (MMCR), and Micropulse Lidar (MPL) data. This paper summarizes the results of the LBTM analysis for 3 years of GOES-8 data over the SGP and examines the differences between surface and satellite-based estimates of cloud fraction.

Methodology

GOES-8 provides continuous coverage of the SGP region and thus is used to derive cloud properties via the LBTM (Minnis et al. 1995). This algorithm uses pre-designated clear-sky visible and infrared (IR) thresholds to select pixels as clear or cloudy, using 0.65 μm visible (VIS) radiances and 11 μm IR temperatures. The GOES-8 VIS radiances were calibrated against Visible and Infrared Scanner (VIRS) as described by Minnis et al. (2001). Broadband longwave (LW) 5 - 50 μm fluxes and shortwave (SW) 0.2 - 5 μm are estimated using narrowband to broadband correlations (Minnis and Smith 1998) between

GOES-6 and data from the Earth Radiation Budget Experiment (ERBE). Using gridded synoptic sounding profiles, clouds are classified into three height bins: low (0 - 2 km), middle (2 - 6 km), and high (6 km - tropopause). Optical depths are estimated by comparing the VIS reflectances to values from a parameterization of radiative transfer model calculations (Minnis et al. 1993). Infrared emissivity is then derived from OD to adjust cloud top temperatures. Cloud products derived with the LBTM include OD, cloud thickness, cloud top height and temperatures, and cloud center heights, and temperatures. Radiative parameters include the clear and total VIS albedos and clear and total SW albedos as well as the corresponding IR brightness temperatures and outgoing LW radiation. Values for selected parameters are presented here for daytime solar zenith angles (SZA) less than 80° only. The remaining parameters are available in the online datasets.

The 0.5° grid overlays a domain extending from 32°N - 42°N and 91°W - 105°W, while the 0.3° grid covers 36.16°N - 37.06°N, 97.04°W - 97.94°W. The central box of the inner grid facilitates comparison with the instruments at the CF. Cloud amounts derived from GOES-8 data for this central box, covering an area of approximately 1600 km^2, are compared with cloud amounts derived from the WSI (Johnson et al. 1989) and ARSCL data (Clothiaux et al. 2001).

The ARSCL cloud amounts are based on cloud occurrence for each 10-second interval during a half hour period (corresponding to the GOES-8 image temporal resolution). Thus, if half of the 10-second measurements within that half hour record a cloud occurrence, the cloud amount is defined as 50 percent. The GOES-8 cloud amounts are based on a spatial average, while the ARSCL cloudiness is a temporal mean. The WSI can view the entire sky, which can vary in horizontal extent depending on the amount of foreshortening by low- and middle-level clouds. In general, the WSI views a different areal extent than either ARSCL or the LBTM grid box. Differences in the methodologies and spatial mismatch will cause significant discrepancies in one-to-one cloud amount comparisons. In an attempt to smooth some of these instantaneous uncertainties, only monthly average cloud amounts from each source are compared.

Additionally, seasonal and annual averages of LBTM-derived parameters will be presented, in an attempt to begin recording climatological trends of cloud and radiative properties over the SGP area. Seasonal averages are computed for winter (January, February, March), spring (April, May, June), summer (July, August, September), and autumn (October, November, December). All of the designated months from December 1996 through November 1999 are included.

Results

Figure 1 shows the time series of monthly mean total and layer cloud amounts for the entire 10° x 14° domain. Low cloud cover varies between 4.7 and 13.5 percent with a maximum during March 1998. Variations in the mid-level and high cloud amounts drive most of the changes in total cloudiness over the area. Maximum total cloudiness generally occurs during winter with minima during the late summer and early autumn. This seasonal pattern is reflected in the spatial distributions of total cloudiness in Figure 2. For the entire domain, winter cloud amounts exhibited the greatest average, 58.4 percent, followed by a mean total cloud cover of 54.3 percent during spring. Minimum mean cloud amounts

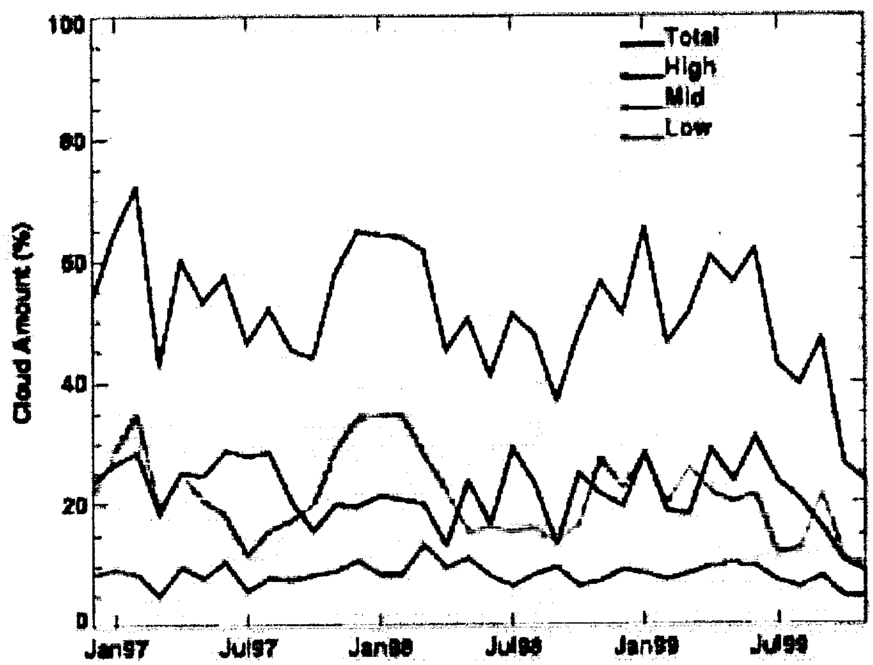

Figure 1. Time series of monthly mean cloud amounts from GOES-8 over the SGP domain.

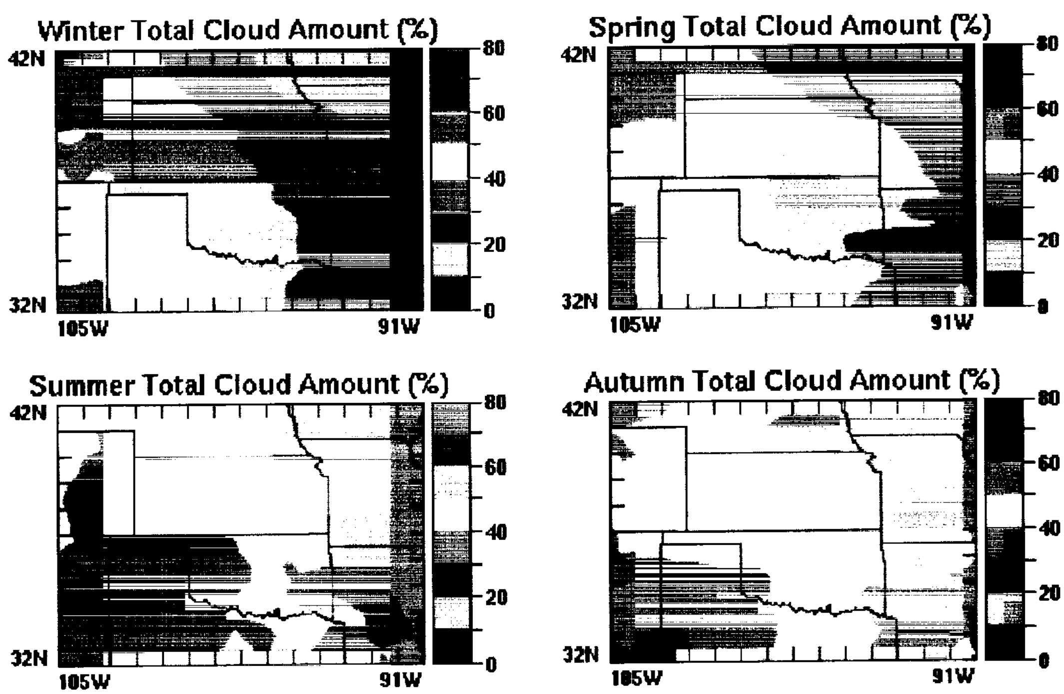

Figure 2. Mean seasonal total cloud amount from GOES-8.

occurred during summer and autumn with values of 44.9 and 45.8 percent, respectively. Cloud amounts are typically smallest in the southwestern portion of the domain and greatest in the eastern third of the domain during all seasons.

Other LBTM-derived parameters also have notable seasonal variations. Mean heights were fairly constant throughout the year for low and middle clouds (1.3 - 1.5 km for low; 3.6 - 3.8 km for mid-level), but high-cloud center heights, shown in Figure 3, varied significantly with season. Summertime average high cloud-center heights were greatest at 10.4 km compared to spring, autumn, and winter with 9.1, 8.5, and 8.1 km, respectively. During winter, the tropopause is lowest thus constraining the maximum altitude of the cloud tops. Mean cloud altitude generally increases from north to south. Winter produced the greatest mean cloud OD (Figure 4) with an average of 20.7, while summer yields the smallest values averaging 11.7. The mean optical depths during spring and fall were 15.0 and 21.7, respectively. The greatest mean cloud optical depths occur in the eastern third of the domain with the largest mean cloud fractions. The smallest domain-averaged total SW albedos (Figure 5) occurred during summer (25.1 percent), while winter had the largest values at 36.8%. Autumn and spring average albedos are 33.2 and 29.4 percent, respectively. Some variation in mean albedo is expected due to changing SZAs during the year with the lowest albedos corresponding to the lowest SZA. However, the 12 percent difference between winter and summer is mostly due to seasonal variations in cloud amount (Figure 2) and OD (Figure 4). The spatial variation of SW albedo is primarily due to the distributions of these same parameters.

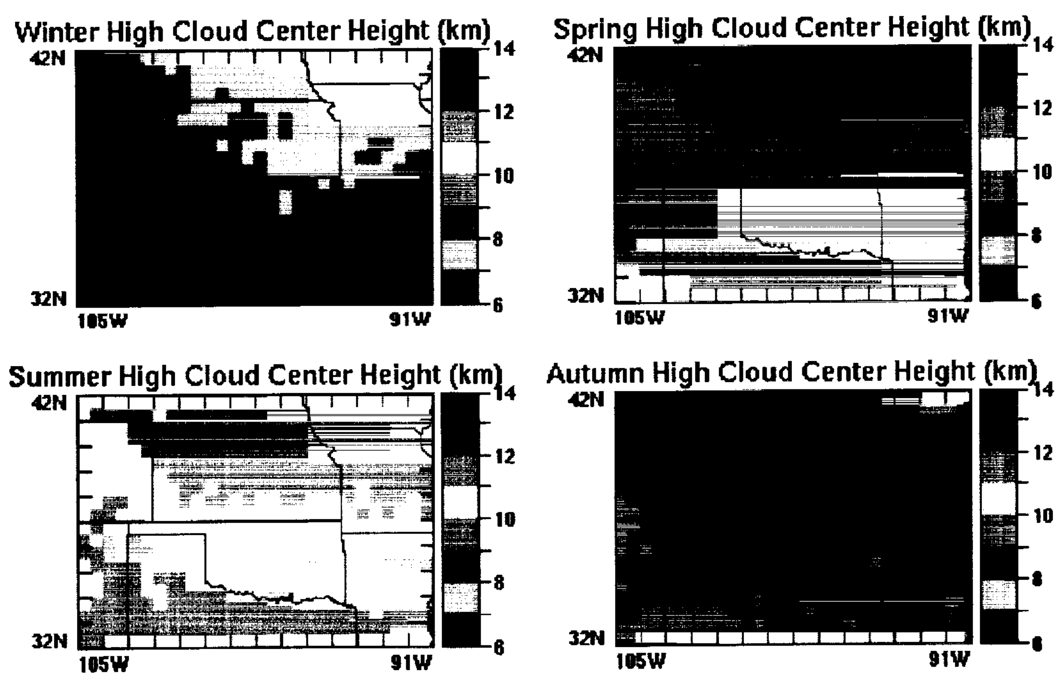

Figure 3. Same as Figure 2, except for cloud effective center height.

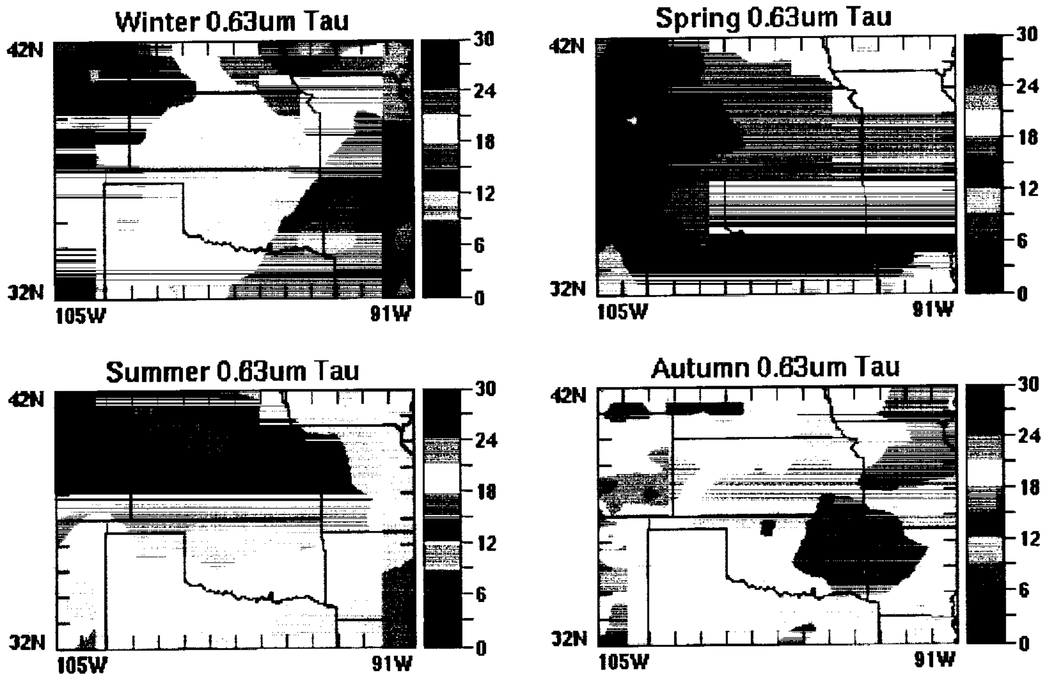

Figure 4. Same as Figure 2, except for cloud OD.

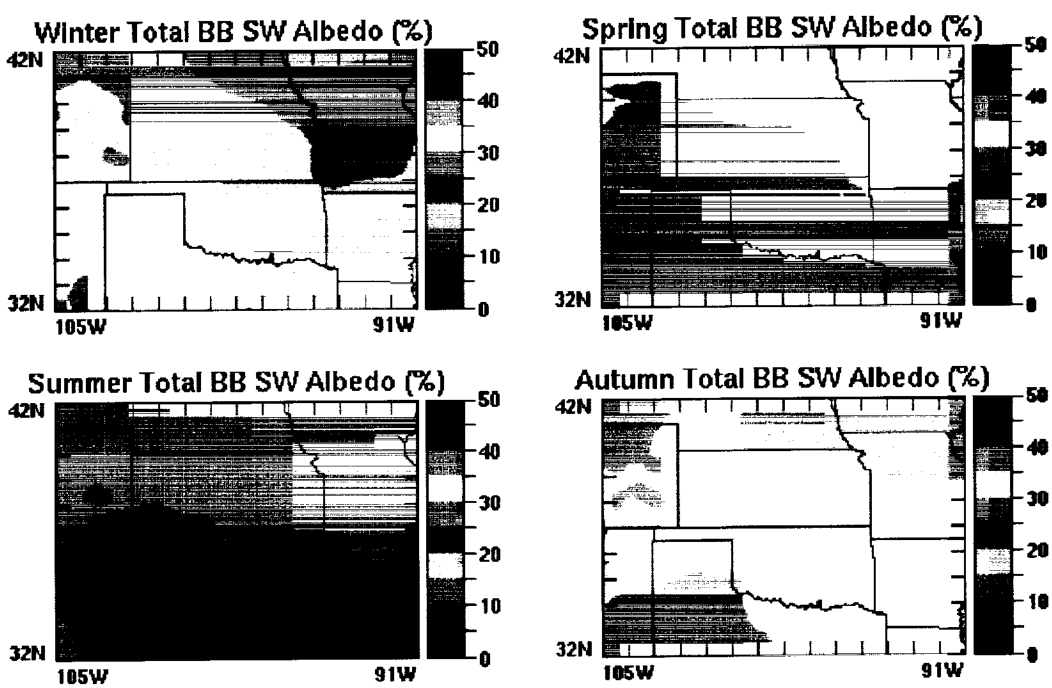

Figure 5. Same as Figure 2, except for SW albedo.

The average values of several cloud parameters for 1997 and 1998, shown in Figures 6 and 7, respectively, revealed similar patterns although the gradients in 1998 were more regular than in 1997. Mean total cloud amount was slightly greater during 1997 (53.4 percent) than during 1998 (50.3 percent). Average high-cloud center height was ~9.2 km during both years. There was little difference in the mean total SW albedos: 30.6 and 30.0 percent during 1997 and 1998, respectively. The 3-year average total cloud amounts, high-cloud center heights, ODs, and SW albedos are shown in Figure 8. The average total cloud amount and OD for this period were 50.7 and 16.7 percent, respectively. Total broadband SW albedo was 29.9 percent, while average high cloud height was 9.3 km.

The daytime cloud amounts derived from LBTM over the CF are compared with ARSCL-derived cloud amounts and selected WSI data in Figure 9. Agreement between LBTM- and ARSCL-derived cloud amounts for daytime cloud only is reasonably close. The ARSCL cloud fraction is 4.1 percent greater than GOES, on average, with a root means square (rms) monthly difference of 8.2 percent. The WSI mean cloud amounts are generally lower than either the ARSCL or GOES values although there is good agreement for a few months. However, due to the sparse sampling of WSI data at the time of the comparison, the results are not an accurate reflection of the overall differences in WSI-derived and LBTM-derived cloud amounts. If nighttime data are included, the average difference between the ARSCL and GOES increases to 10.7 percent with an rms difference of 13.3 percent. This difference highlights the errors in the nighttime satellite results based on the LBTM, which uses IR data only at night. The method typically misses many of the low-level clouds because the surface skin temperature and the cloud-top temperatures are very close. Thus, the nocturnal cloud fractions are too low by ~18 percent.

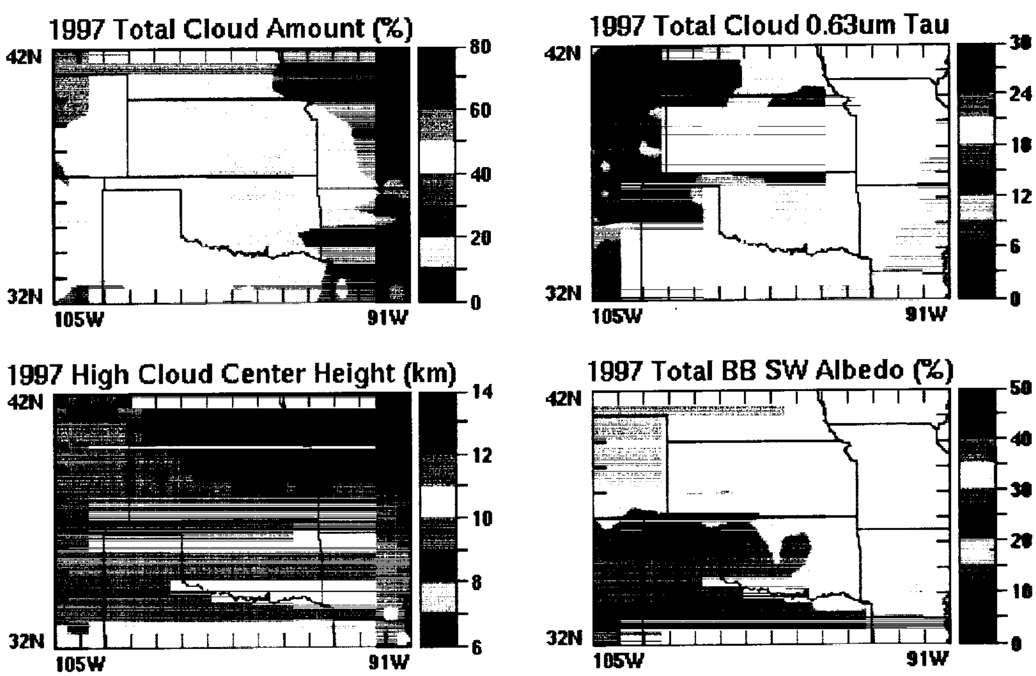

Figure 6. Mean daytime cloud parameters from GOES-8 for 1997.

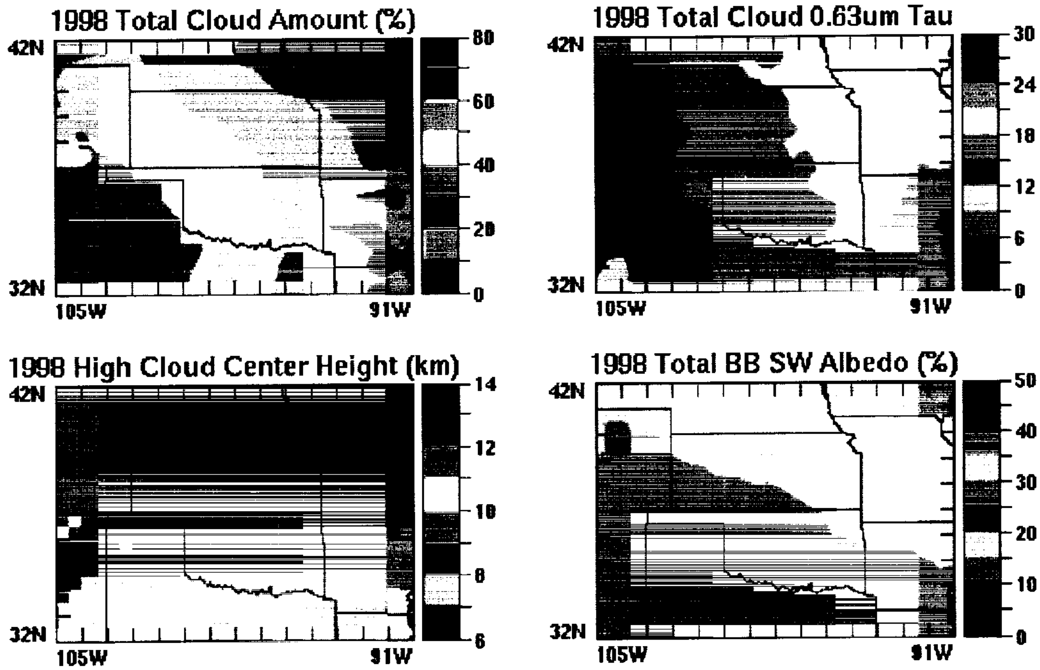

Figure 7. Mean daytime cloud parameters from GOES-8 for 1998.

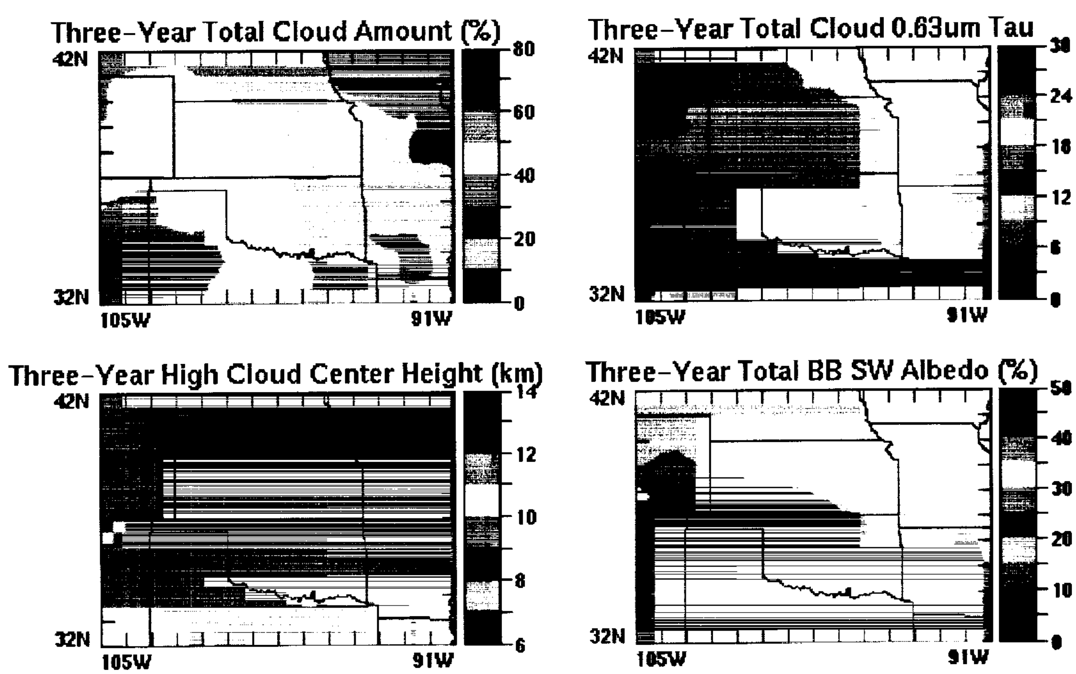

Figure 8. Mean daytime cloud parameters from GOES-8 for 1997-1999.

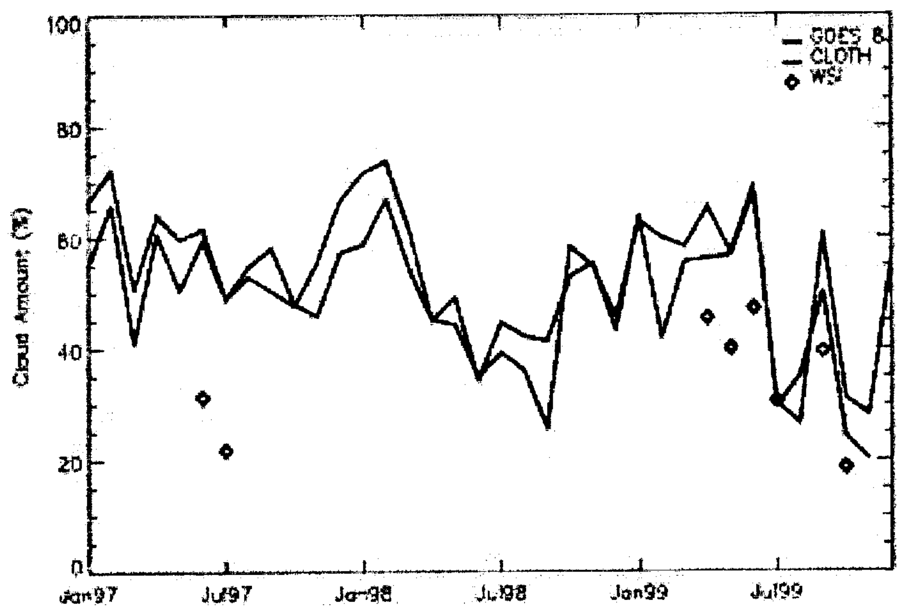

Figure 9. Time series of monthly mean daytime cloud amounts derived from GOES-8, radar, and WSI data, 1997-99, over the CF.

Discussion

Although there are some differences in the magnitudes of the cloud amounts, the seasonal variations in total cloudiness over the CF are consistent between the ARSCL and the LBTM products. The differences between the two datasets during a given month could result for a variety of reasons. The area represented by the radar may be different on average from that viewed by the satellite. Algorithms have been developed to screen out insect contamination in the radar returns, but some insect swarms may still be misclassified as clouds. The satellite retrieval may miss some very thin cirrus and small, scattered cumulus clouds that could be detected with the ARSCL. Although these and other problems may cause the observed cloud fraction differences, a more detailed examination of the differences is needed.

WSI-derived cloud amounts are consistently lower than both ARSCL-derived and LBTM-derived cloud amounts. One reason for this may be the difference in the derivation methods; also, the WSI doesn't necessarily sense the same portion of sky per level of atmosphere than would be reflected in the 0.3° grid box. Finally, some "monthly" averaged data points for WSI only contained a few days out of the month, so the same days are not always included between WSI and the other two monthly averages. However, from May to June 1999, the only complete months of data for the WSI were still considerably smaller than the LBTM- or ARSCL-derived quantities. More data from the period in question would be necessary to work out a complete comparison.

These results serve as the start of an ARM-focused satellite climatology of cloudiness. To place them in context of the longer-term surface observations, the mean total cloudiness was computed from the surface-based 10-year cloud climatology of Warren et al. (1986). The atlas maps provide monthly or seasonal mean values for 5° latitude-longitude regions. To compare with the LBTM results, average seasonal total cloud amounts were computed using the 5° atlas boxes between 30°N and 45°N, 90°W and 105°W. The boxes in the middle row were weighted by a factor of two and the upper and lower boxes were weighted by unity in the averages. Beginning with winter, the resulting seasonal means are 59.2, 53.8, 45.2, and 45 percent. Each of these values is within 1 percent of the means generated from Figure 2. However, they include both nighttime and daytime data. Warren et al. (1986) report a mean diurnal cycle in total cloud cover that is typically at a maximum value around local noon except during summer when the phase of the cloud cover is highly variable. The mean amplitude is around 6 percent. While this result suggests the daytime averages should overestimate the 24-hr means, except during summer, it is also important to note that thin cirrus clouds are often missed by surface observers at night. Thus, the actual magnitude of the diurnal variation may be smaller than suggested from the surface observation atlas. Nevertheless, the comparisons with the radar and surface observations are consistent. If the radar results are considered as the true cloud fraction, then the LBTM underestimates the cloud amount by 2 - 3 percent during the daytime. This difference could explain why the daytime LBTM results agree with the 24-hr long-term surface observations instead of exceeding them by 3 - 4 percent.

The radiative properties of the clouds should be relatively unaffected by the potential underestimates in cloud fraction for both day and night. A 3 percent underestimate in cloud fraction would translate to a 5 percent decrease in mean cloud optical depth, but would leave the mean albedo and outgoing longwave radiation (OLR) virtually the same. The fluxes depend on the application of limb-darkening models and bidirectional reflectance models SW that are sensitive to the scene classification, but do not differ significantly for changes of 3 percent cloud cover, especially for the OLR both day and night. The mean values of total SW albedo do not include the albedos for SZA > 80°, however. Typically, the difference between a complete daily average albedo and one that excludes data for SZA > 80° is approximately 2 percent. Thus, multiplying the 3-yr mean by 1.02 yields 30.5 percent a value is that is probably more accurate than the 29.9 percent value. It can be compared to the properly weighted results from ERBE for the area bounded by 90°W and 105°W, 32.5°N and 42.5°N. The annual mean albedos from ERBE for this area varied from 29.2 percent (1988) to 33.4 percent (1985). The 3-yr mean value from GOES-8 is similar to the 1987-1989 average albedo of 30.6 percent from ERBE.

Summary and Future Research

The daytime cloud properties and SW albedos from December 1996 to November 1999 are available on two different grids centered on the ARM CF. Initial comparisons with climatology and some limited ARM surface products indicate that the GOES-derived products are reasonably accurate and should be valuable for modeling and climatological studies. However, more validation studies will be performed to better quantify the uncertainties in each parameter. This paper has focused only on a limited set of parameters. A variety of others are available for use by the scientific community.

The comparisons performed here also highlighted areas for improvement in the cloud and radiation products from GOES. Improved nighttime cloud detection and height determination algorithms (e.g., Smith et al. 1996) are being implemented. These should significantly increase the accuracy of the derived cloud amounts and altitudes for the nighttime data, correcting much of the underestimate in amount reported here. A new cloud reflectance parameterization has been developed that should improve the reliability of the retrieved cloud optical depths. Research is also underway to improve the daytime cloud detection procedures by including the GOES-8 3.9-µm channel and by using the 1-km visible data. These additions should enhance the detection of low scattered clouds and thin cirrus. New narrowband-broadband conversion functions are also being developed using Clouds and the Earth's Radiant Energy System project broadband data to increase the accuracy of the albedo and OLR values from GOES. These improved products will become available later during 2001.

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