Convective Cloud Climatologies Constructed from Satellite Imagery

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ABSTRACT

Composites of satellite imagery are constructed for various hours and various summer months on Colorado State University's interactive processing system. Simple averages of visible wavelength imagery are considered as well as averages of bispectrally classified data. The classified images use both visible wavelength and infrared wavelength data to identify probable deep convection.

Results reveal the diurnal convective cycle over the Rocky Mountains and high plains in greater detail than has been previously possible. The convective frequency composites are compared with precipitation averages and differences between "normal" versus severe weather patterns are discussed. Practical forecasting applications for the composited data are suggested and discussed.

1. Introduction

The fact that mountainous terrain can enhance thunderstorm formation has long been established (e.g., Hallenbeck, 1922). In fact, in mountainous regions, the topography can force a repetitive, diurnal convective cycle in which initial activity forms along the mountain ranges early in the day, grows to thunderstorm proportions, and finally moves out onto the plains during the late afternoon. This cycle has been understood in a broad sense for quite some time (e.g., Cook, 1939). In such topographically affected regions, the local forecaster must consider this cycle and its day-to-day variations in timing and intensity.

As a first step in trying to quantify the convective cycle, it is tempting to look at precipitation statistics—the principal advantage being the availability of records over many years. However, the usefulness of resulting conclusions is limited by the relative sparsity of observing sites, combined with the rather "spotty" nature of convective precipitation. Indeed, the best way to document convection, in general, might be to observe it explicitly via some remote sensing device such as radar or satellite.

Several convective climatologies for the Rocky Mountains have been developed over the years based on radar data. In the early 1960s investigators at Colorado State University (CSU) produced a variety of studies concerning the incidence of hail in northeast Colorado (e.g., Schleusener and Grant, 1961). Many different parameters were considered and results included hailstorm paths from echo inception through hail occurrence. Wetzel (1973) stratified radar echoes by the time of day using grid-squares (similar to the method used by Beckwith, 1958), confirmed the existence of the diurnal convective cycle, and added additional information regarding preferred regions for convection. At about the same time, Henz (1973) clarified the cycle more fully by identifying ten regions along the front range of the Colorado Rockies (labeled "hot spots") where convection seems to form regularly. In fact, during the 1970–72 convective seasons, 41% of all thunderstorm echoes, and 73% of all severe storm echoes, originated at those locations. Karr and Wooten (1976) examined radar echoes for the area within 125 nautical miles of Limon, Colorado, for June–August of 1971 and 1972 for diurnal characteristics and relationships to terrain. These authors found that echoes first form over the east slopes of the Rockies at about 1000 Mountain Standard Time (MST), after which echo frequency increases with time, while the location of maximum echo frequency moves east, roughly along a terrain feature known as the Palmer Lake Divide.

Radar-based climatologies have certain drawbacks. First, radars are usually calibrated to detect precipi-

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tation size particles, and thus miss the initial congestus formation. Additionally, low-level ground targets interfere with radar beams, so that convection in mountainous regions (especially the initial stages) may go undetected. For these reasons, several investigators have tested the feasibility of using satellite imagery for cloud climatologies. In the first such satellite study, Kornfield *et al.* (1967) used the technique of multiple exposure of photographic film to "composite" full-earth mosaics of all types of cloudiness from ESSA III and V imagery. In more recent work, Phillip (1979) subdivided Colorado and the surrounding area into five regions. She then used satellite imagery to subjectively tabulate cloud cover, and its change, on an hour-by-hour basis. Reynolds and Vonder Haar (1979) employed an interactive image processor to calculate percent cloud cover (and other aspects of cloud distribution) over two different regions of the Rocky Mountain high plains.

Recently, interactive computer techniques in image compositing have been applied at CSU to study the topographic convective cycle. Such studies have been carried out by Klitch and Vonder Haar (1982) and Weaver and Kelly (1982). More detailed descriptions of sections of these works can be found in Klitch (1982) or Kelly (1983). This paper will summarize and build on these recent works. It will show the utility of satellite composite imagery in depicting and predicting the areal/temporal variation of the diurnal convective cycle over the Rockies and adjacent plains.

2. Data

a. Electronic processing

Satellite data used in this study are from the Geostationary Operational Environmental Satellites (GOES). Any digital data discussed were collected at CSU's Direct Readout Satellite Earth Station (DRSES), and Laserfax images were supplied courtesy of the National Weather Service and the U.S. Air Force.

The data were processed through CSU's Interactive Research and Imaging System (IRIS). The main data processor on the system is a DEC VAX 11/780, and image processing is carried out on a two-station, COMTAL Vision One/20, which has a video camera input device for digitizing photographic data. Both stations have several graphics planes available for use. These graphics planes may simply be thought of as clear sheets onto which an infinite variety of tracings and/or graphics can be interactively added. The graphic planes can then be overlayed onto the image planes. Another IRIS feature used heavily in the current study is the COMTAL "ROAM" capability. This option allows the operator to interactively move the image around on the screen. For a more complete description of the CSU system, see Green and Kruidenier (1982).

Composite images were constructed by simply averaging together several pictures. However, before this process was carried out, a renavigation of the imagery was performed to eliminate geographical mismatches due to satellite wobble, navigation parameter errors, etc. Briefly stated, this renavigation worked in the following manner. First, a cloud-free, and very clear visible wavelength (VIS) satellite image was identified for use in constructing a reference overlay. Next, many geographical features (e.g., rivers, ridge lines, etc.) were traced onto a graphic plane from this image. The reference graphic was then overlayed onto each image used in this study, and the ROAM employed to match, or calibrate, each image separately to the reference image. Finally, once the landmarks matched precisely, the renavigated image was set aside for the averaging. Our estimates suggest that the relative navigation accuracy in the final set is about ±2.5 km. We should also note that the infrared wavelength (IR) images were renavigated by simply roaming each IR image by the same amount as the corresponding VIS image had been shifted.

Images collected at the DRSES range in brightness count from 0–63 for VIS data, and 0–255 for IR. The program that composites the imagery performs a pixel by pixel average of these count values. [A pixel (Picture Element) is (the size of) an image data unit.] Various portions of the studies utilized VIS and/or IR imagery. Additionally, several sets of composites were constructed from data from the 1981 and 1982 seasons which had been bispectrally classified. For these images, VIS and IR data were combined to show regions of ground versus deep convection versus "other" cloudiness. The IRIS has a capability to mask user-designated portions of an image either above or below a given threshold brightness count. Masks can be assigned any brightness value between 0 and 255.

b. Classifying methodology

Deep convection was assumed to have cold tops in the IR imagery ($\leq$ approximately $-30°\mathrm{C}$) and a "bright" appearance in the VIS. The idea was to include convective clouds which had reached about the 500–400 mb height; clouds which were already or might soon become thunderstorms. The scope of the study did not allow for investigation of individual elements (e.g., the life stage of individual clouds, the estimated rainrate of separate elements, etc.) Some subjectivity in the IR threshold was allowed for deference to the meteorologist's judgment upon study of the VIS photos. Convective areas were then assigned a digital value of 255 (white). Similarly, areas of no cloud were assigned a count value of 0 (black). All other clouds were set at 70 (or dark gray).[1] For a more complete description of the technique, see Kelly *(1983)*. These so-called "classified" images were then averaged for July and August separately. The results were used to help interpret the VIS composites, since regions appearing very bright on the classified composites represent areas where bright pixels occur frequently and are, therefore, areas where deep convection was frequently found. Thus, the classified composites represent a kind of convective frequency. However, it is cautioned that, while moderately bright areas on the composites may be regions of moderately frequent convection, they may also be significantly contaminated by a number of "other cloud" members in the average. Figure 1 illustrates the envelope of convective days which might have occurred for any given brightness value on a classified composite. For example, if a pixel in the average had a brightness value of 255, all of the days in the sample averaged must have had convection. However, for a brightness count of 150, there could be as many as 60% or as few as 44% convective days in the sample with remaining brightness being attributable to other cloud days. This ambiguity was allowed so that convection could be emphasized while still retaining the ability to study the behavior of low cloudiness on the plains. Doing so was a mistake. Because we allowed all types of other clouds (e.g., cirrus, middle decks, low stratus, etc.) we were not able to make definitive statements about early morning low cloudiness. Instead, we simply introduced a bit of ambiguity into our data of primary interest (deep convection). Thus, future work along the lines should and will be done with a simple yes/no (white/black) classification for deep convection. If we require information on some other category (say low clouds), a separate yes/no composite will be constructed for it. Unfortunately for the present work, we had nearly completed the study before this fault became evident.

Lastly, composites were constructed for the 1982 data set based on severe weather days. Both VIS and classified composites were constructed for this stratification. A severe weather day was defined as any day on which a tornado, 1.9 cm (¾″) hail, or 25.7 m s^{-1} (50 kt) wind occurred in Colorado. This information came from both the National Weather Service and PROFS (Program for Regional Observing and Forecast Systems—a federally-sponsored research program in Boulder, Colorado charged with developing improved forecast techniques) logs. Both these data sets are biased toward events on the eastern plains and near population centers.

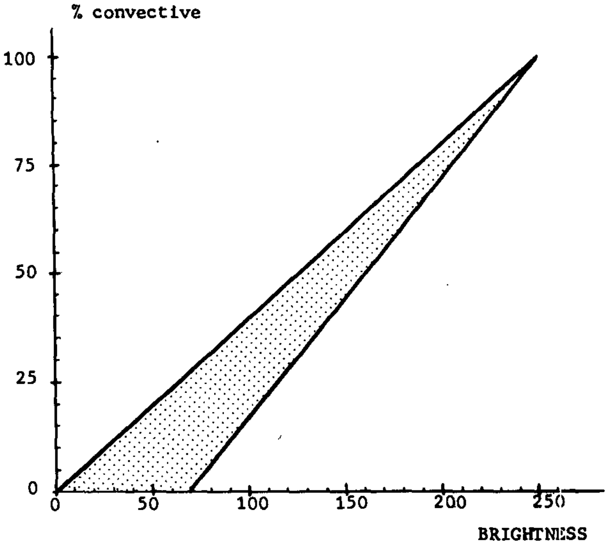

FIG. 1. (Brightness-convection conversion applies to composite imagery described in text). Ordinate gives the envelope of the percentage of days in the sample set which may have been convective for a given pixel brightness count (abscissa). For example, if a pixel has a brightness count of 150 on a composite image, the set of images composing the average could have had as many as 60% convective days (the rest being "no cloud" or "other cloud"), or as little as 44% convection. This ambiguity is discussed in text.

3. Colorado summer weather patterns

As summer approaches, and the polar jet drifts gradually northward, Colorado (like most of the nation) finds itself beneath generally weak flow aloft. The air mass becomes stagnant, synoptic-scale forcing becomes weaker, and mesoscale factors such as topography begin to play an increasingly important role in the daily weather cycle. Fronts may occasionally move into the state and become stationary—a regime that is conducive to severe thunderstorms over a one to two day period (Doswell, 1980). However, the more normal behavior is the diurnal cycle discussed in Section 1.

Moisture arrives in central and eastern Colorado over a variety of paths. During July and August, midlevel moisture can advect into the state from the southwest by way of the southwesterly "monsoon" flow (Hales, 1974). Low-level moisture may be transported northward from the Gulf of Mexico via the low-level jet (Bonner, 1968); then be drawn directly westward by weak synoptic mechanisms or by the diurnal, upslope circulation (Johnson and Toth, 1982). It may also be transported by indirect methods. For example, Gulf moisture could be precipitated onto the plains of Kansas and Nebraska, then evapotranspiration and northeasterly flow behind a stationary front could complete the transport into Colorado.

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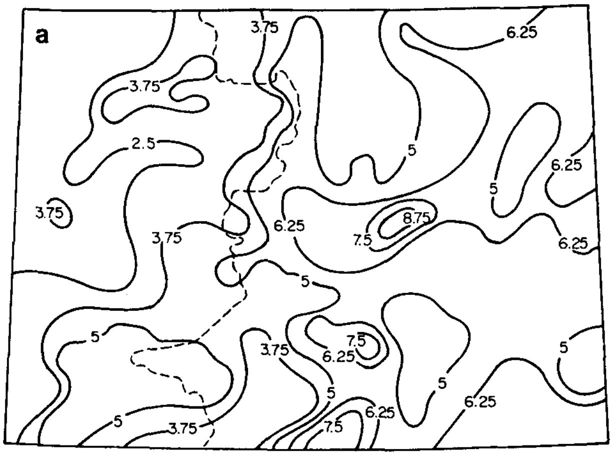
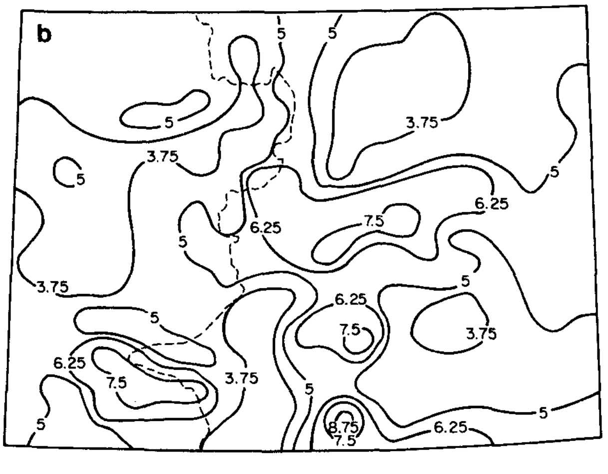
[1] These "other" cloud areas also included cumulus at its initial stages, when the cloud tops were not cold enough to present a signature in the IR. By giving these regions a lower weight in the compositing scheme, a more representative picture of convective frequencies can be produced. The weighting value of 70 for the other clouds was chosen arbitrarily as a dark grey shade sufficiently different from 255 as to be quite obvious. Any other low count would have served as well.

Whatever the method of arrival, it is this moisture, combined with orographic effects, which dominates the precipitation pattern in summer.

The 30-year mean values of precipitation for July and August in Colorado are shown in Fig. 2. The data are based on statistics from 162 stations across the state. Maxima are found along the Raton Mesa, Palmer Lake Divide, and the front range between the two (see Fig. 3). Another maximum occurs in southwestern Colorado near the San Juan Mountains and is more pronounced in August. Thus, with minimal synoptic forcing, precipitation maxima are colocated with the junction of east–west ridges and the eastern slopes of the Rockies. A subjective comparison between the precipitation means and the 1982 composite imagery will be made in Section 4.



COLORADO
Mean July precipitation in cm. The Continental Divide is indicated by dashed line.



COLORADO
Mean August precipitation in cm. The Continental Divide indicated by dashed line

FIG. 2. Mean Colorado precipitation in centimeters for the period 1951–1970 for the months of (a) July and (b) August. Results are based on data from 162 surface sites. Dashed line is Continental Divide.

4. Discussion of results

a. *Qualitative description*

Figures 4 and 5 show the images generated by the compositing technique for August 1982. It should be reemphasized that the VIS composites are simply pixel-by-pixel averages of visible wavelength brightness values—values which result from a variety of clouds. While more visual detail is preserved in the higher-resolution "VIS composites", only limited information can be gleaned from VIS data alone regarding cloud type. However, when examined in conjunction with the bispectrally classified composites, the following rather definitive statements regarding convection and convective regions may be made.

The composite imagery reveals the convective cycle in great detail. Comparison of the developing convection at 1700 GMT with the map of physiographic features (Fig. 3) shows convection beginning along the high mountain ranges in Colorado. Although Klitch (1982) found no strong correlation between convective development and terrain height along the somewhat flat topography (i.e., gradually rising terrain and rolling hills) of eastern Montana and western North and South Dakota, she did suggest a relation between convection and the sun-relative slope angle of the ground. In this case, the earliest congestus appears along the rugged slopes of the Rockies, avoiding the high mountain valleys. This may furnish additional evidence that the slope angle is more important than terrain height in forming convection. Here a distinction should be made between upslope winds and the mountain plains circulation induced by the early heating of east-facing slopes illustrated by Dirks (1969) and Phillip (1979). Convective triggering occurs along the Continental Divide as well as along other mountain ranges such as the San Juans, the Sangre de Cristos, etc. The location and timing of this development specifically agrees with those found by Kelly (1983).

As the convective cycle continues, convection expands over the mountains. By midafternoon the activity begins to move/develop slowly eastward onto the plains. Also, development begins along the Palmer Lake Divide in east-central Colorado. The remainder of the afternoon is characterized by a decrease of convective frequency in the mountains and an increase over the eastern plains. However, notice that convection in northern Colorado and southeast Wyoming along the Cheyenne Ridge is relatively infrequent. It should also be mentioned that, subjectively, the July evolution is much the same as that in August, though the data are not shown.

Figures 6 and 7 illustrate the convective cycle on severe weather days. Several differences between the severe versus the more general cycle are apparent, including strong development in northern Colorado and along the Cheyenne Ridge in the severe case.

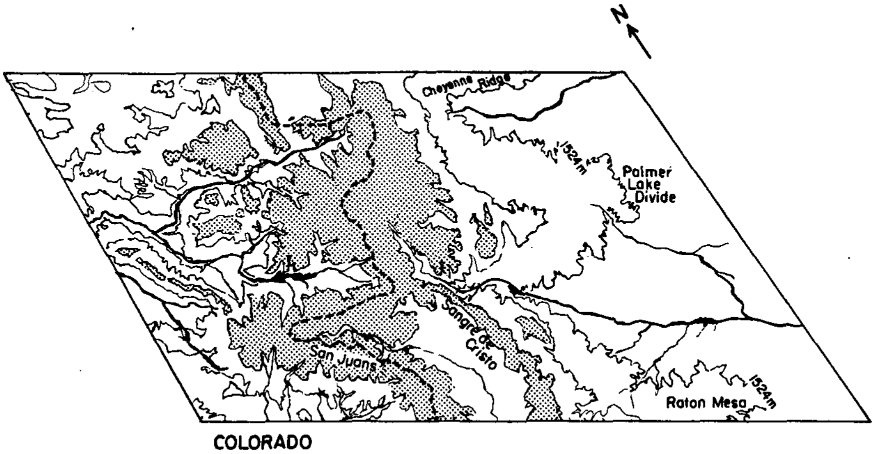


FIG. 3. Map of Colorado terrain. Physiographic features in an approximate GOES-W Satellite Projection. The 1524 m (5000 ft) and 2286 m (7500 ft) terrain height contours are shown by solid lines. Areas above 3048 m (10 000 ft) are stipled. The eastward extension of the 1524 m (5000 ft) contour in extreme northern Colorado follows the so-called Cheyenne Ridge; that in central Colorado, the Palmer Lake Divide; and in southern Colorado, the Raton Mesa. Dashed line is Continental Divide.

Also, there seems to be a more rapid eastward translation of activity on severe days, and an almost total clearing in western portions of Colorado. This could result from stronger flow aloft—a feature which is expected on severe weather days. Additionally, the clearing to the west might be partly due to drier, midlevel air.

Many of the differences between the "severe day" composites and the more general cycle discussed in this section are subjective in nature. This is also true regarding the interpretation of the general cycle composites discussed above. It should be noted that digital difference fields were generated via a COMTAL function allowing the direct subtraction of one image from another. Examination of these results (not shown) simply confirmed the subjective impression discussed here. As will be outlined in the concluding remarks, there is a great deal of practical utility in the subjective use of composite photos by forecasters. However, before discussing those aspects of the data, the following section will address certain of the statistical characteristics derived from the composites.

b. *Statistical description of the composited data*

1) THE 1982 DATA SET

Some behavioral aspects of the convective cycle (see Section 3) can be verified by statistical analysis of the composite brightness fields, while some cannot. Table 1 shows the mean brightnesses, standard deviations, and coefficients of variation[2] for the 1982 composite imagery. The values are computed by averaging all brightness counts in each of the full images. This being the case, one would expect the mean composite brightness values to increase with time in a cycle where convection increases. While this is generally true, notice that the mean brightness of the VIS and classified composites actually decrease between 1515 and 1715 GMT. This is due to the high frequency of nonconvective cloudiness over the mountains and in eastern Nebraska during the early morning. After 1715 GMT, the mean brightness counts increase as is consistent with the diurnal convective cycle.

The standard deviation (SD) and coefficient of variation (CV) generally measure the same data characteristic—namely, the dispersion of the brightness counts about the mean. The CV is simply the standard deviation normalized by the mean. Use of this dimensionless quantity allows different averages to be compared with the same "yardstick".

Composite images in regions where there are preferred locations for convective cloudiness should be expected to have a higher SD and CV than those where convection is more random. This point can be clarified. Consider a fairly large region, composed of thousands of pixels, in which convection is completely random. In such a region, eventually, each pixel would have convection a few times, and the averaged image would tend toward some overall gray shade as more cases are added. On the other hand, consider a region in which some pixels have a high probability of convection, while others do not. In this case, the mean will be some intermediate value, there will be large individual deviations from this mean, and the

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[2] Coefficient of variation: CV = 100 × (standard deviation/mean). It represents a "normalized" spread of the data around the mean.

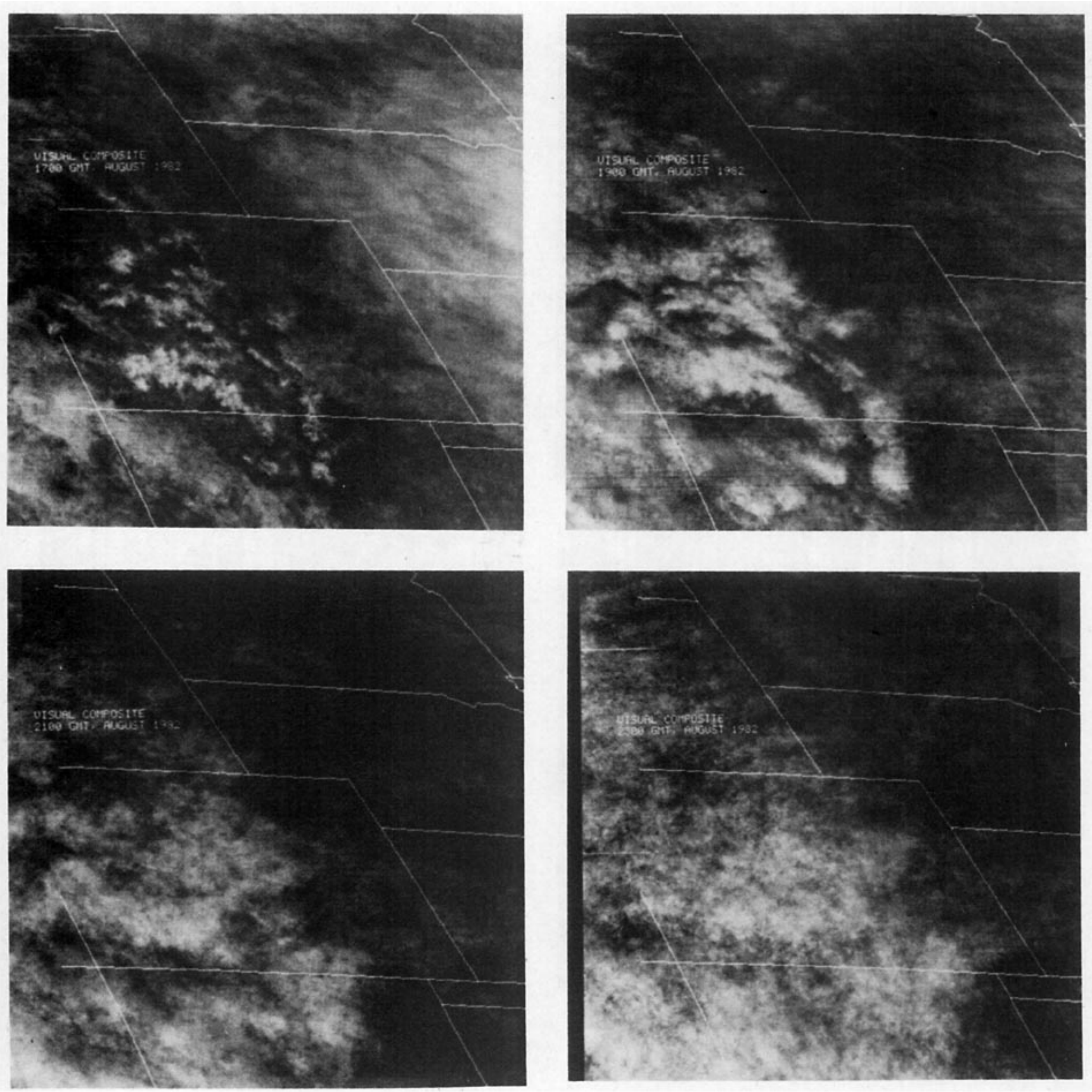

FIG. 4. Computer-averaged, visual wavelength satellite imagery for various hours of August 1982. Hours shown are 1700, 1900, 2100 and 2300 GMT. For a complete interpretation see text.

overall spread will thereby be large. For example, study the coefficients of variation for Colorado (with many stark terrain features) versus those for Nebraska (a relatively flat region where local generation is more nearly random). Note that in nearly every case, the CV for Colorado is substantially larger than that for Nebraska at the same time. However, as the afternoon progresses, and the Colorado activity moves off into the plains, the CVs for the two regions become more nearly the same. We suspect that, had the sample set been larger, the differences in the CVs (for the early times), would have been even greater.

Another interesting feature of the statistical data is that the CVs for the VIS composites were all relatively low compared to those for the classified images. We interpret this difference as reflecting the difference in the two composite types. The first is an average of albedo values, while the second is an average of artificially constructed images—images which can have a maximum of only three different brightness counts depending on convection/cloudiness.

In examining the month-to-month variations of mean visible cloudiness (VIS composites) and convective cloud frequency (classified composites) we

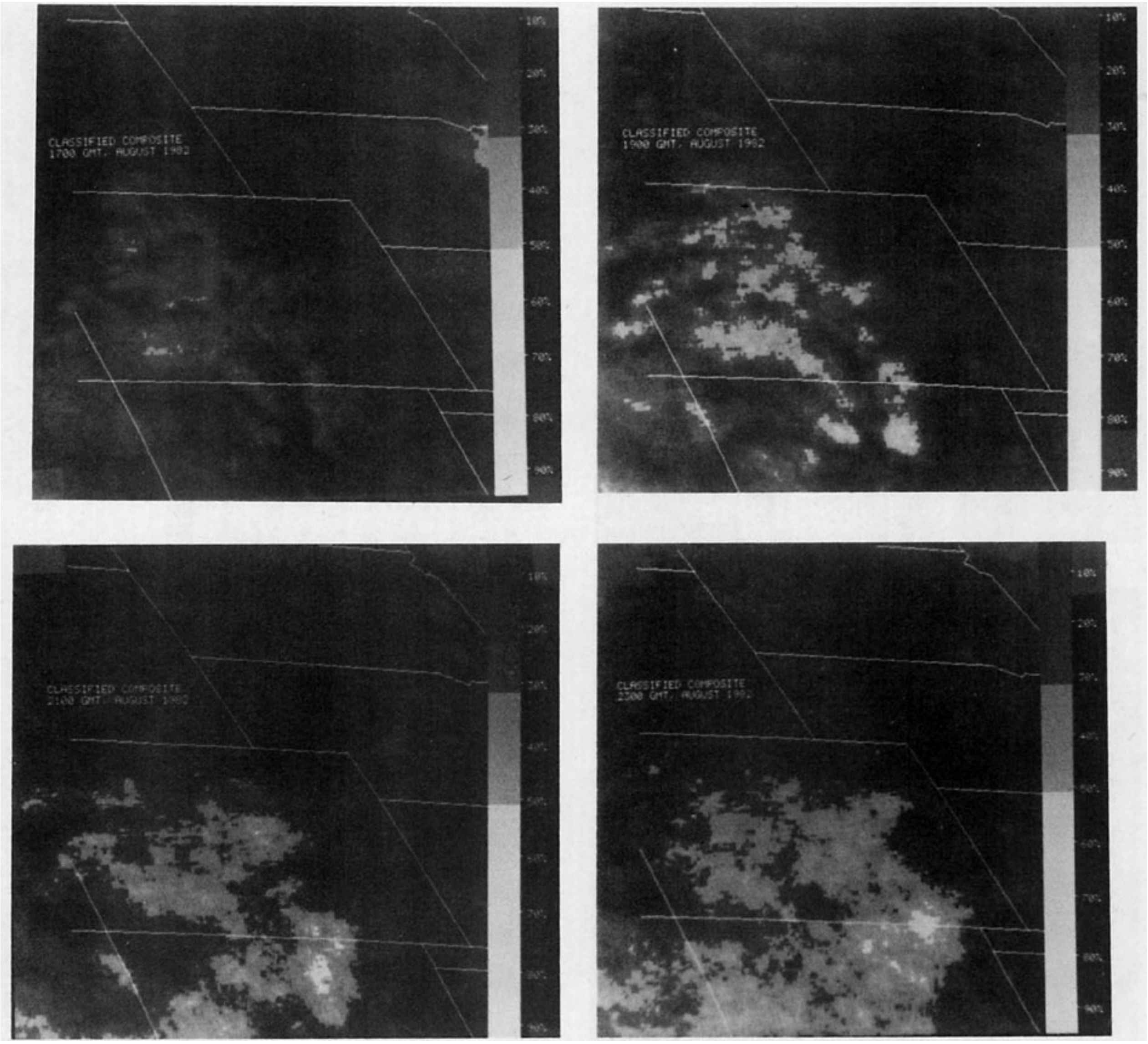

FIG. 5. Computer averages of brightness counts from the bispectrally classified data (described in text) for various hours of August 1982. Hours shown are 1700, 1900, 2100 and 2300 GMT.

reached two major conclusions based on these statistical data. The first concerns the VIS imagery. Even though there is a slight difference in the mean cloudiness for these cases, we assert that the differences between the July, August and severe weather case data are too small to be considered significant. This means that "cloudiness"—in the broadest sense—was the same for all cases. Second, in terms of mean convective cloud frequency, August had significantly more deep convection than July. However, there was no significant difference between the mean convective cloud frequency in August versus that of the severe set. The maps of precipitation (as a percentage of the 20-year mean) for July and August 1982 (Fig. 8) show that precipitation in August was generally much above normal, whereas in July the positive and negative anomalies appear to balance.

2) PREVIOUS YEARS

The compositing technique applied to the 1982 imagery evolved from earlier versions developed by Klitch (1982), Weaver and Kelly (1982) and Kelly (1983). For completeness, statistical results from these studies are discussed briefly in this section.

Klitch (1982) processed digital data from GOES-East for a region centered on eastern Montana, which included both the foothills of the Rockies and the northern plains of North and South Dakota. Her technique involved determining the frequency of

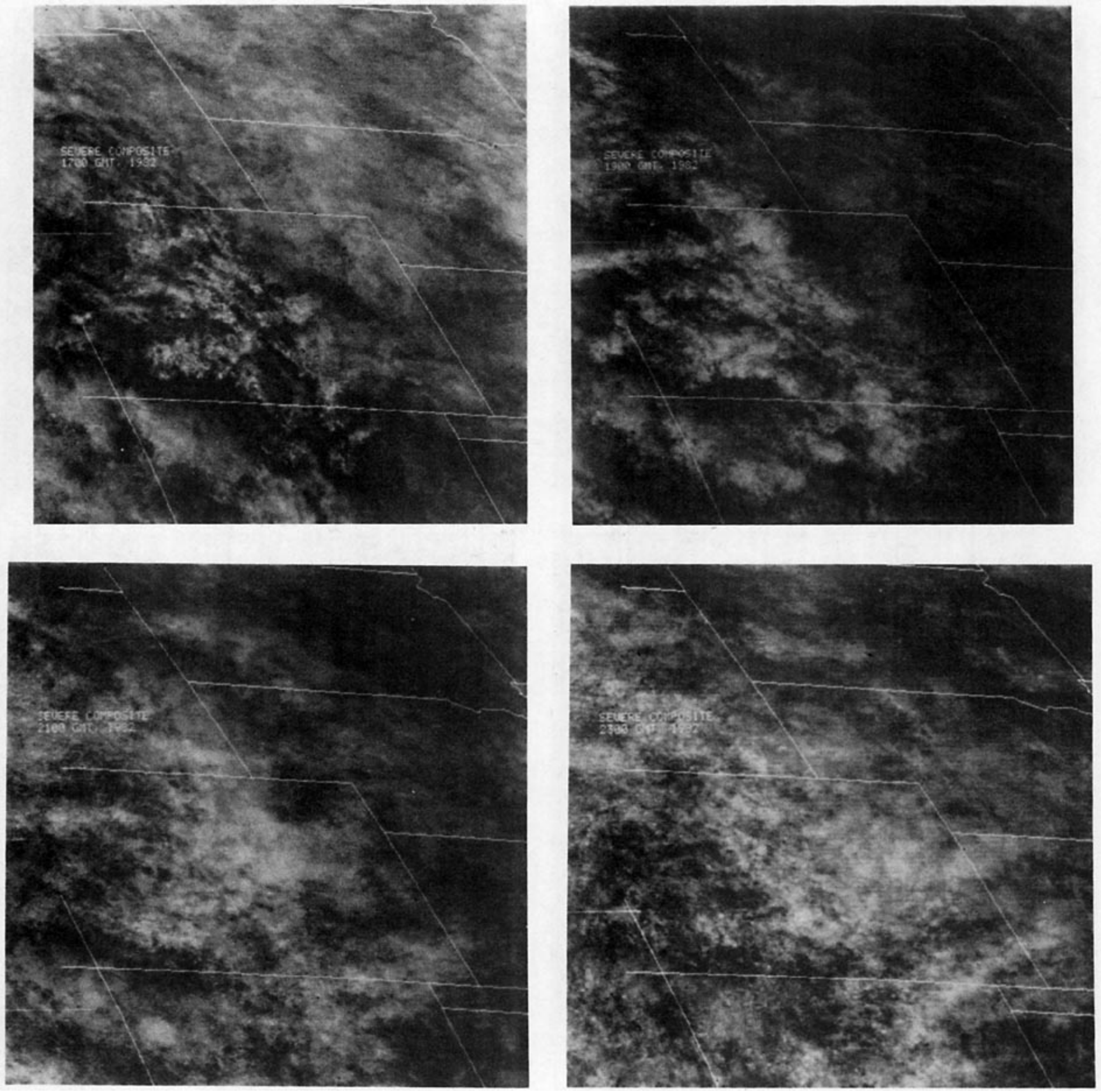

FIG. 6. As in Fig. 4 except sample set includes only severe weather days from both July and August.

pixels with count values greater than a selected threshold. The threshold for the visible data was chosen low enough to include nearly all the clouds in the image, whereas the IR threshold corresponded to a temperature of −20°C. This IR value was selected to bias the composite toward deep convection. The statistical results are shown in Table 2.

Because the 1979 and 1980 visible composites were processed differently, they cannot be directly compared to the other visible composites (different means, SDs, etc.). Nevertheless, they do demonstrate the increase of mean visible cloudiness along the foothills and high plains from late morning to early afternoon. Nonconvective clouds were not included in the 1979 and 1980 infrared composites; therefore (all other things being equal), the 1982 mean cloud frequencies (the classified composites) ought to be a little higher. Considering the subtle difference in compositing technique and the fact that a different geographic region was examained, the infrared mean cloud frequencies for 1979 and 1980 compare favorably with those from the other years.

The 1981 composites were created by digitizing laserfax imagery (i.e., hard copy photographs). The

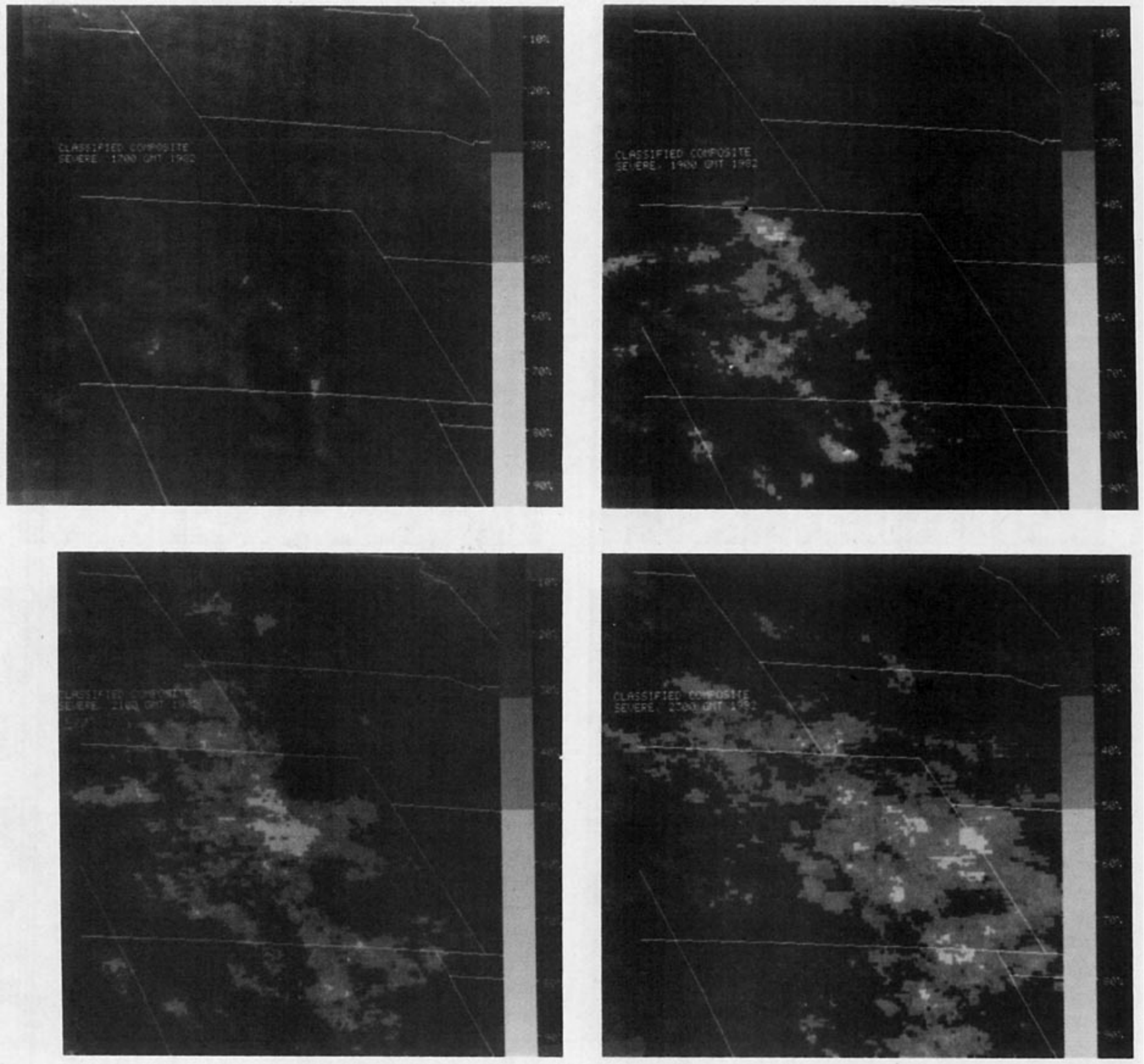

FIG. 7. As in Fig. 5 except sample set includes only severe weather days from both July and August.

photos were digitized through the IRIS's video input device which assigns count values between 0 and 255 brightness (instead of the more usual 0–63 scale assigned to VIS data). As in the 1982 study, Kelly (1983) simply averaged the visible imagery. For his convective composites, he subjectively classified the IR into regions of convection versus nonconvective cloud versus ground, using the visible data as a guide (Kelly's method of classifying was similar to that used in the present study). He composited images for three times of day during the months of June and July. In addition to his set of averages over Colorado he constructed a set centered on Nebraska (flat terrain) for comparison.

The numerical values which result from digitizing images in this manner depend on many factors including laserfax transfer function, photo developing, camera lens aperture, forward and back lighting, etc. By the time the image has been digitized, it has been through several, not well defined transfer functions. Thus, it is highly unlikely that a digitized laserfax image would have the same numerical values as the original digital data. The 1981 composites were not meant to be directly compared to composites produced from digital imagery, but were made in this manner to demonstrate that such a technique can provide valuable information, especially in situations where the digital data are not readily available (such as at Weather Service Forecast Offices). Thus, while the mean cloud frequencies for 1981 appear to compare

TABLE 1. Statistical parameters for the 1982 satellite composite data.*

Image type	Time (GMT)	July			August			Severe		
		Mean	SD**	CV***	Mean	SD**	CV***	Mean	SD**	CV***
Full image										
VIS	1515	33.7	3.3	9.8	38.1	4.3	11.3	37.1	4.6	12.4
VIS	1715	25.8	2.3	8.9	29.5	3.0	10.2	27.4	2.8	10.2
VIS	1915	30.0	3.1	10.3	31.1	3.6	11.6	30.9	3.2	10.4
VIS	2115	35.5	3.7	10.4	38.4	5.2	13.5	38.0	4.6	12.1
VIS	2315	45.4	4.5	9.9	50.6	6.5	12.8	49.5	5.4	10.9
COMP	1515	36.0	11.7	32.5	42.5	13.0	30.6	37.2	12.7	34.1
COMP	1715	20.1	9.6	47.8	34.8	15.9	45.8	28.6	18.8	65.8
COMP	1915	34.5	13.9	40.3	36.1	21.4	59.4	39.3	22.6	57.5
COMP	2115	42.6	17.4	40.8	47.0	25.5	54.2	57.4	27.0	47.0
COMP	2315	51.1	16.2	31.7	59.8	23.8	39.8	67.0	24.6	36.7
Colorado only										
VIS	1515	32.0	3.6	11.3	36.0	3.6	10.0	35.6	3.7	10.4
VIS	1715	25.2	2.5	9.9	28.6	3.1	10.8	26.5	3.0	11.3
VIS	1915	31.3	3.2	10.2	33.0	4.6	13.9	33.0	4.0	12.1
VIS	2115	37.5	3.2	8.5	41.6	5.0	12.0	41.3	5.0	12.1
VIS	2315	46.5	3.4	7.3	54.4	5.4	9.9	52.6	5.4	10.3
COMP	1515	40.0	14.1	35.3	47.8	16.0	33.5	41.8	14.9	35.6
COMP	1715	23.5	11.9	50.6	37.6	18.0	47.9	32.4	18.3	56.5
COMP	1915	39.3	16.0	40.7	46.6	24.8	53.2	52.6	25.6	48.7
COMP	2115	51.2	16.8	32.8	60.0	24.7	41.2	71.7	28.7	40.0
COMP	2315	56.1	14.1	25.1	72.7	19.2	26.4	76.3	26.5	34.7
Nebraska only										
VIS	1515	35.0	2.5	7.1	43.1	3.3	7.7	42.0	3.1	7.4
VIS	1715	24.7	1.5	6.1	32.6	3.1	9.5	29.8	2.3	7.7
VIS	1915	28.0	1.8	6.4	29.8	2.3	7.7	30.2	2.2	7.3
VIS	2115	32.2	2.6	8.0	34.2	2.0	5.8	36.2	2.9	8.0
VIS	2315	41.6	3.5	8.4	45.2	2.7	5.9	48.3	3.9	8.1
COMP	1515	35.0	8.3	23.7	41.3	8.6	20.8	38.8	11.6	29.9
COMP	1715	15.9	5.5	34.6	45.7	17.5	38.3	41.3	17.9	43.3
COMP	1915	30.6	7.5	24.5	28.6	11.5	40.2	32.2	10.0	31.1
COMP	2115	32.7	9.9	30.2	30.3	8.2	27.1	48.5	14.0	28.9
COMP	2315	40.8	11.1	27.2	43.2	10.5	24.3	65.7	15.9	24.2

* VIS composites adjusted for solar incidence angle.
** SD—Standard deviation.
*** CV—Coefficient of variation expressed as a percent.

favorably with those from other years, objective comparisons to composites of digital data, especially the higher-order statistics, should be avoided.

c. *Comparison of the 1982 composite imagery with precipitation statistics*

Despite the fact that the 1982 composite imagery represent only one year, regions of high convective cloud frequency (i.e., Fig. 5) are coincident with the mean precipitation maxima (Fig. 2) which were described and discussed previously. Although the frequency of severe storms in Colorado decreases from July to August (Maddox *et al.*, 1981), the general synoptic patterns (i.e., weak flow aloft, stagnant air masses, etc.) and mean precipitation patterns remain the same.

While the long-term, mean precipitation patterns do not change significantly from July to August, the actual monthly precipitation may vary substantially. Figure 8 shows the observed precipitation for July and August 1982, as a percentage of the average. The regions with high precipitation anomalies also have high cloud frequencies in the 1982 composites. Although some concurrence between high cloud frequencies and positive precipitation anomalies is expected, composite satellite imagery is not necessarily an accurate indicator of rainfall. In comparing the 1979 cloud frequency statistics to those for 1980, Klitch and Vonder Haar (1982) noted that the slight reductions in cloudiness from 1979 (a typical to wet season) to 1980 (a severe drought) were not commensurate with the immense decreases in rainfall. The 1982 composites imply that where clouds are more

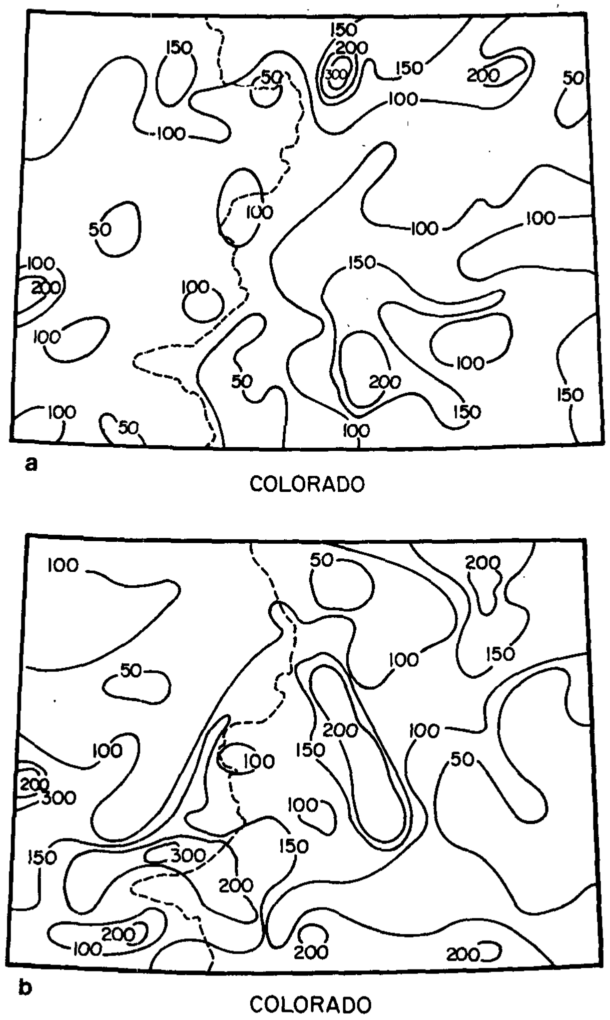

FIG. 8. Precipitation in Colorado for (a) July and (b) August 1982 expressed as a percentage of the 1951–1970 average (Fig. 2). Results are based on data from 162 surface sites. Dashed line is Continental Divide.

frequent, it rains more. Because the original imagery was processed to emphasize deep convection, the classified composites compare well with precipitation maps.

5. Summary and final comments

Results from these studies have shown that satellite data can be used effectively in a climatological sense. The topographically dominated, diurnal convective cycle in Colorado has been revealed in greater detail than ever before. Not only have the general features of the cycle been reestablished, but also point-specific details may be seen in the composites. Forecasters at various locations throughout the state can easily see the differences between their station location and others. It has also been shown that important differences exist between the general convective cycle and that which occurs on severe weather days. These differences include a more rapid eastward movement of convective activity on severe days, as well as more significant development in northern Colorado. Finally, the study has demonstrated that, for a specific set of data, a fairly effective, bispectral scheme might be designed which matches areas of rainfall. This may be seen by comparing the classified composite with the 1982 rainfall data (as discussed in Section 4c). One can envision a technique which, by first estimating VIS/IR convective threshold values, then checking the estimate through monthly averaging

TABLE 2. Statistical parameters, 1979–1981 data sets.

Month	Year	Image type*	Time (GMT)	Mean	SD**	CV***
			Colorado Centered			
June	1979	VIS	1800	62.7	21.7	34.6
		VIS	2200	90.3	27.0	29.9
		IR	1800	30.1	16.7	55.5
		IR	2200	62.0	21.7	34.8
July	1979	VIS	1800	62.0	33.9	54.7
		VIS	2200	63.6	22.0	34.3
		IR	1800	17.1	17.5	102.0
		IR	2200	25.4	16.7	65.9
June	1980	VIS	1800	62.7	27.2	43.0
		VIS	2200	68.6	23.9	34.8
		IR	1800	8.6	9.9	11.5
		IR	2200	13.9	11.4	81.4
July	1980	VIS	1800	57.8	19.5	33.4
		VIS	2200	60.4	21.3	34.9
		IR	1800	21.2	13.7	64.6
		IR	2200	26.4	13.3	50.3
June	1981	VIS	1545	75	32	23
		VIS	1745	63	28	17
		VIS	1945	111	36	27
		COMP	1515	16	13	81
		COMP	1715	27	30	111
		COMP	1915	34	19	56
July	1981	VIS	1545	63	31	21
		VIS	1745	71	30	18
		VIS	1945	150	27	19
		COMP	1515	19	11	58
		COMP	1715	15	18	120
		COMP	1915	43	32	74
			Nebraska Centered			
July	1981	VIS	1745	114	24	19
		VIS	1945	118	21	22
		VIS	2145	123	22	18
		IR	1715	28	16	57
		IR	1915	28	14	50
		IR	2115	33	19	58

* Image Type: VIS = Visual Average (Count Range 0–255); IR = Infrared Average (Count Range 0–255); COMP = Classified Composite (Count Range 0–255).

** SD—Standard deviation.

*** CV—Coefficient of variation expressed as a percent.

techniques, a climatologically-based set of rainfall thresholds might be developed for a specific region for specific months. Threshold values could easily be used to extract regional rainfall estimates from satellite data in a very straightforward manner.

Certain practical applications of this research include:

1) The composite information can be used as a training product to familiarize newly arrived forecasters with this important diurnal phenomenon;

2) Results can furnish a foundation upon which to begin the actual forecast;

3) Familiarity with the "normal" cycle might help to identify particularly unusual days. These would include either unusually active *or* unusually quiet days—both are important;

4) Aid in forecasting for data sparse areas;

5) Provide a "first-guess" field for cloud albedo in radiation models;

6) Provide another source of data for climate sensitive projects.

With the many potential benefits to forecasters, climatologists, and (perhaps) modelers, it seems important that similar cloud climatologies be generated for longer time periods and for other regions. The authors recommend that future studies generate several types of composites to avoid the ambiguity in the three-shade components of the classified composites. Particularly in other geographically-affected regions (e.g., mountainous areas, sea coasts, etc.), it would benefit the meteorological community to have such precise information.

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