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SATELLITE CLOUD DATA AS INPUT TO CLOUD SEEDING OPERATIONS

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INTRODUCTION

Droughts have produced economic hardships in many sections throughout the United States in recent years, especially in areas where agricultural production is significant. The repercussions have led to increased interest in cloud seeding to augment rainfall for agricultural use during severe water shortages.

Knowledge of two climatic factors is important in assessing the probability of significantly enhancing precipitation over a specific location during occurrences of below-normal rainfall. One is the time-space distribution of naturally occurring precipitation during droughts. Huff and Semonin (1975) and Huff (1979) found that, even during extended growing-season droughts in Illinois, opportunities existed to increase agricultural water supplies by cloud seeding.

The second factor whose analysis can aid the development of a cloud seeding program is a cloud climatology of the area. Several such studies have used ground-based observations (e.g., Changnon and Huff, 1957). Cloud distribution can also be studied with weather radar and satellite data. The former was used by Bark (1975) to survey precipitating clouds over western Kansas. Satellite data have been used to produce cumulus cloud climatologies for selected regions in the Midwest (Stodt and Grant, 1976; Marotz and Henry, 1978). Simultaneous observations of clouds using digital radar and SMS/GOES satellite data were conducted on a limited basis at Miles City, Montana during HIPLEX (Poellot and Reynolds, 1979).

One aspect of cloud alimatology studies not intensively studied hitherto is the difference in cloud characteristics, over an area the size of a state, between years of abundant and meager rainfall. The purpose of the present study is twofold: 1) determine May-September cloud cover amounts and cumulus cloud sizes from satellite data for representative normal, wet and dry years in Florida; and 2) analyze the relation of the derived cloud data to precipitation values and an index of drought. This type of information can be a valuable input in the planning stages of a weather modification program aimed at ameliorating agricultural water shortages.

DATA AND METHODOLOGY

The five months from May to September are generally the most critical for water supplies in Florida. Monthly rainfall data for each year, 1970-1977, for the seven climatic divisions of Florida, obtained from the National Climatic Center, showed that in May-September 1973 the mean rainfall in all divisions was very near the long term average. Total departures from normal were less than 63.5 mm in each division; in one (the Florida panhandle) the departure was only 4.1 mm. This normal rainfall year in Florida was followed by a generally wet May-September period in 1974, with total divisional departure +269.7 mm. The year 1977 was very dry in all but extreme southern Florida, and total rainfall departure from normal in the May-September period was -297.9 mm.

Because low rainfall is not the only factor involved in drought conditions, an index devised to measure the severity of drought was also used. The Palmer Drought Index (Palmer, 1965), is calculated for each climatic division on a monthly basis, and incorporates temperatures as well as precipitation. Positive values of the index indicate above-normal moisture conditions, and negative values result during dry periods. Values between -3 and -4 represent severe droughts.

The DMSP satellite, passes over Florida at 00, 06, 12 and 18 EST; a complete description of orbital characteristics and data products is given by Dickinson et al. (1974). The data are archived at the Space Science and Engineering Center, University of Wisconsin, Madison. Images (transparencies) from the 1200 EST overpass were chosen for several reasons. First, a harmonic analysis of June-August Florida hourly rainfall data by Schwartz and Bosart (1979) revealed a strong peak in the diurnal cycle in the late afternoon at most locations in the state, but heaviest rainfall intensities generally occur slightly earlier in the day throughout the state. Secondly, over the FACE (Florida Area Cumulus Experiment) region in southern Florida the maximum development of the cumulus layer occurred in the afternoon (Johnson, 1978). Sky photographs obtained by Johnson between 0900 and 1400 EST during the summer of 1975 revealed a very consistent sequence: 1) small, widely scattered cumuli first appear near 0900; 2) the cumulus layer increases; 3) as the layer deepens in the early afternoon, clusters of cumulus clouds generally extend vertically enough to produce rain over the peninsula. Therefore, the 1200 EST DMSP data correspond closely to the time of maximum cumulus development and occurrence of highest intensity rainfall over large sections of the state.

For the 459-day study period (three May-September periods), the 378 available noon satellite images provided 82 percent time coverage. Missing dates were spread quite evenly through the study period so no large time gaps occurred. The minimum number of images available for any of the 15 months was 20, in May and June of 1977. Seventy-six percent of the images (288) had a theoretical resolution of 0.6 km at satellite subtrack and a scale of 1:7,500,000. The remainder of the images (90) had a resolution of 3.7 km or 0.4 km, and a scale of 1:7,500,000 or 1:15,000,000. On two-thirds of the images Florida was within one-third of the image width from the center, and at or near the edge on only 8 percent of the images. Therefore, near-maximum resolution was available over the study area for most of the data.

Accurate location of Florida on the images was relatively simple because of its shape. The northern boundary could be delimited by recognizable physical features, relatively straight lines of the border and known scale of the imagery. Overall location accuracy probably equaled or exceeded that given by Dickinson et al. (1974).

The study area was divided into 59 cells for data recording purposes (Fig. 1); cells 58 and 59 cover the Keys. Each cell is approximately 55.4 km in north-south extent and 48.2 km wide, equivalent to 0.5 degrees latitude by 0.5 degrees longtitude in the center of the study area. For each cell on each day the percent of total cloud cover, cumuliform cover and stratiform cover were determined visually, and the diameter of the most frequently occurring size of cumulus cloud per cell was recorded. Measurement techniques and possible error magnitudes are discussed in Marotz and Henry (1976). To help insure consistent results, the results of the two analysts, working under 5X magnification, were cross-checked; periodic reanalyses of a previously studied image reduced possible time biasing.

CUMULUS CLOUD COVER

Because modification of cumulus clouds has the greatest potential for enhancing summer water supplies in Florida, results of the cumuliform cloud data analysis will be emphasized. For the total 15-month study period, data cells with cloud cover values of 21-25 percent are most common (Fig. 2). The 36 of the 59 cells (61%) in this category, cover all the northwestern portion of the state and most of the interior of the peninsula. Highest values occur in a concentrated area in the northern portion of the peninsula and in scattered areas in central Florida.

Minimum cloud cover in the two southernmost cells and in the nine category-III cells, generally results from two coastal effects. All these cells except one are on the coast and include water surfaces as well as land. With very few exceptions, the satellite images showed significantly lesser development of cumulus clouds over water than over adjacent land; many times the water portion of the cells was cloudless while the land portion was substantially cloudy. A second consistent cloud pattern is a lack of cumulus clouds a few kilometers inland, produced by the sea breeze convergence and land-induced convection that are common over the Florida peninsula in summer. Both effects have also been observed in aerial photography and examined in various modeling schemes (e.g., Planck, 1969; Pielke, 1974). The only category-III cell in the interior of the peninsula contains Lake Okeechobee, which has been observed to inhibit cumulus development by reducing convection and even, in some instances, producing subsidence over it (Pielke, 1974). The lake appeared on many of the DMSP images as a hole in the cloud cover.

Percent noontime cumulus cloud cover and its areal distribution were generally similar in 1973 (average) and 1974 (wet), but consistently less throughout the state in 1977 (dry). (Fig. 3). High and low values for 1973 are 35 and 10 percent, for 1974 are 31 and 9 percent, but for 1977 23 percent in the northern part of the state to 9 percent in the Keys.

CUMULUS CLOUD COVER IN AVERAGE, WET AND DRY YEARS

Maximum cumulus cover throughout the state for the three years occurred in 1973 (average rainfall) in 51 of the 59 data cells. Cloud cover in 8

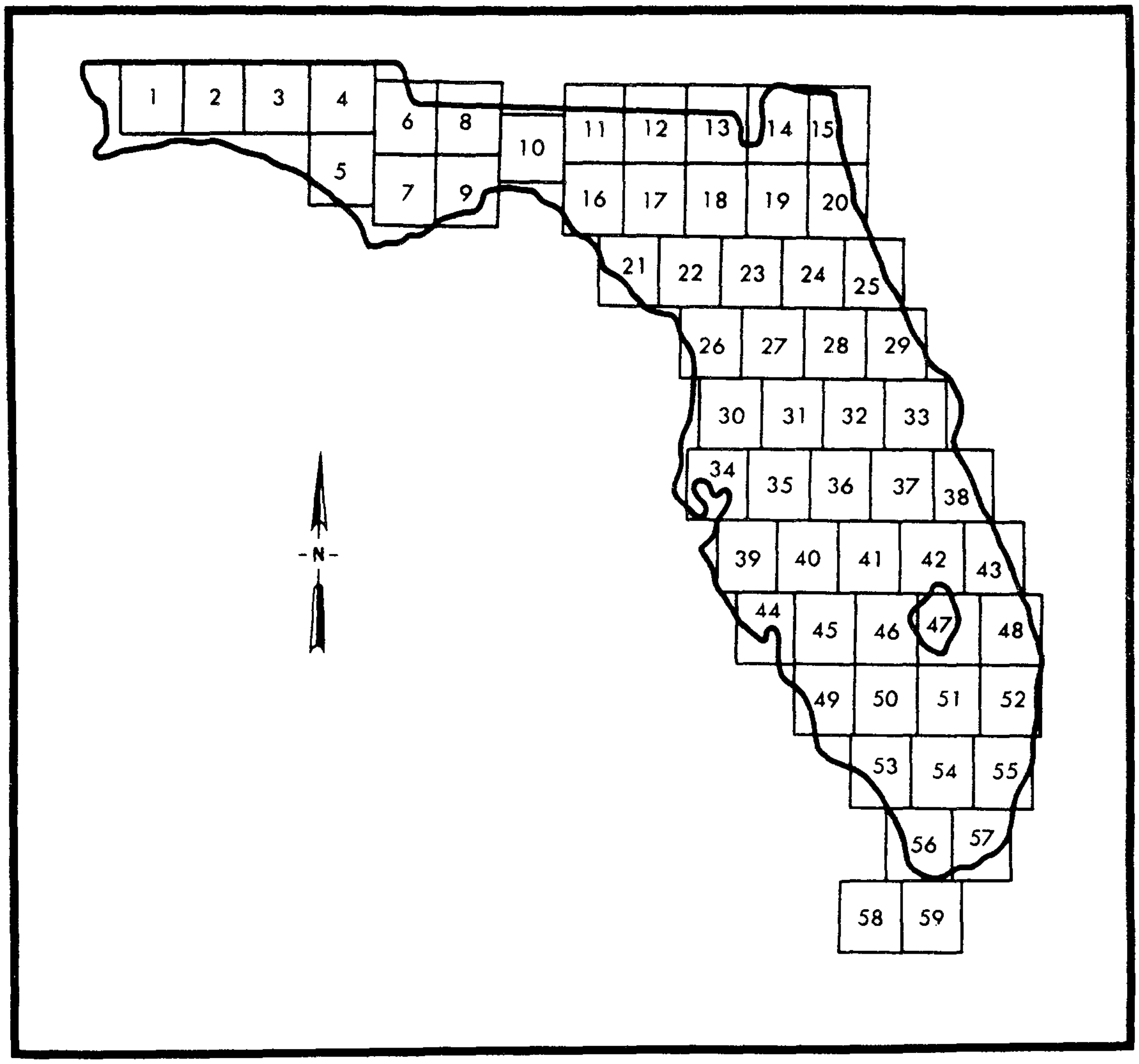

FIGURE 1. Study Area and Grid System

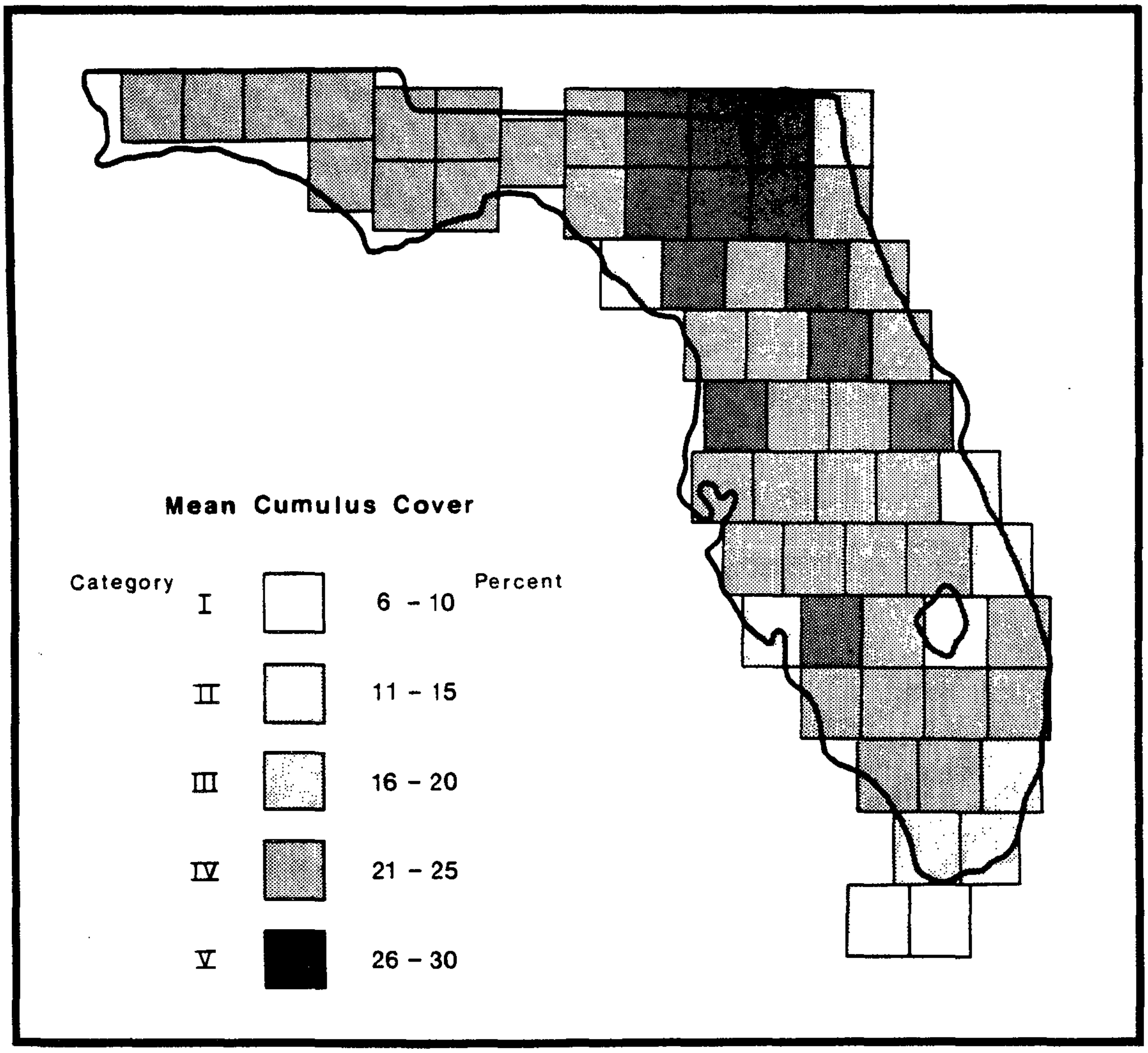

FIGURE 2. Cumulus Cloud Cover for Total Study Period

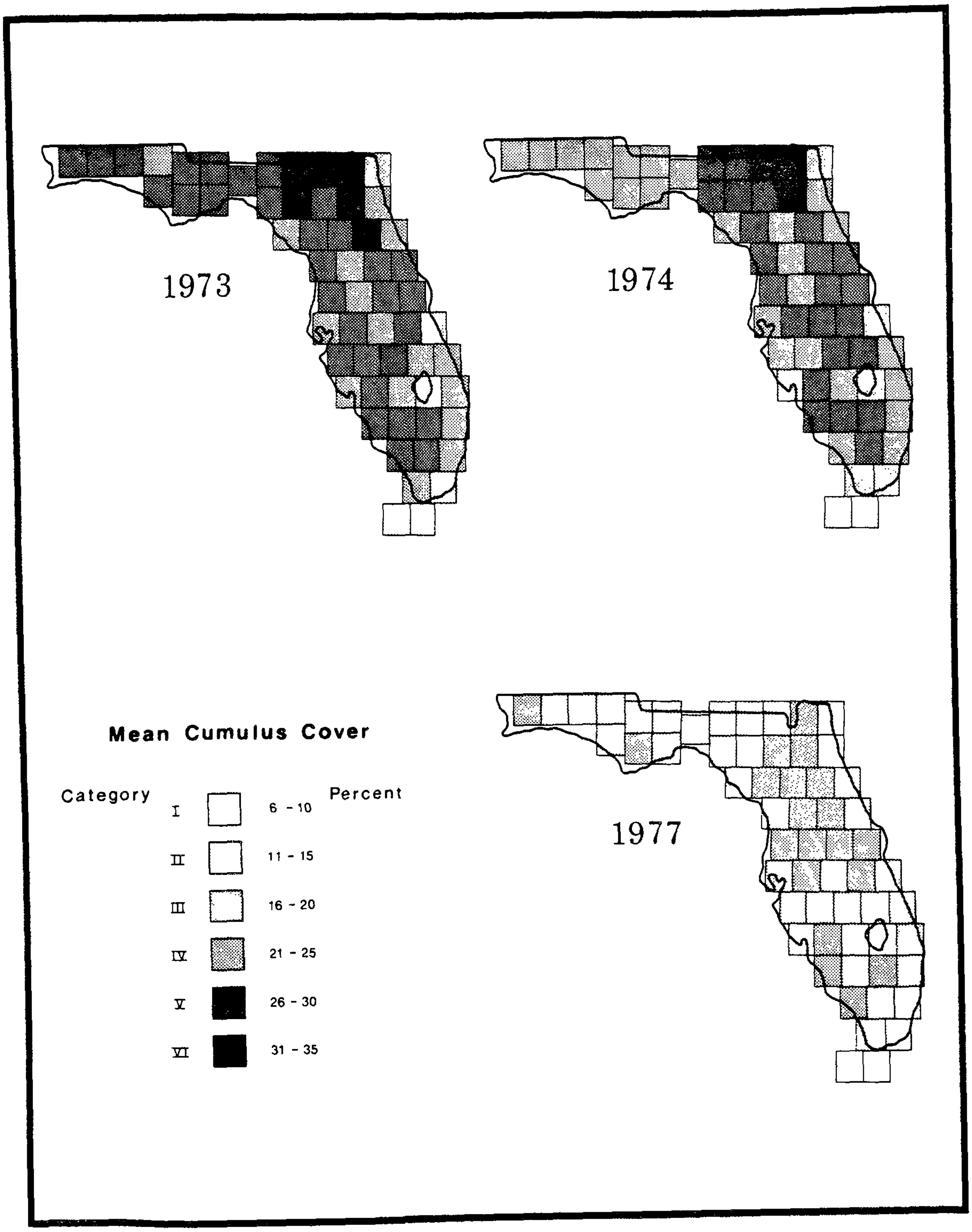

FIGURE 3. May - September Cumulus Cloud Cover

cells in 1974 (wet) exceeded those of the previous year, but by only 1 percent in 5 of the cells and by 2 percent in the others. In 1977 (dry) no area was cloudier than in the other two years.

Thus, the largest differences in cloud cover existed between the normal and driest periods. Differences between 1973 and 1977 were approximately 10 percent in the northern portion of the state, 6 percent around Lake Okeechobee, and 2 percent in the extreme south. For the same three regions, differences between the wettest and driest summers were 6 percent in the north, 5 percent around the lake and 1 percent in the Keys. The greatest difference in cloud cover in any cell was 15 percent, in cell 13 between 1973 and 1977.

Maximum statewide cumulus cover values for the average, wet and dry periods were 35, 31, and 23 percent, respectively. Minimum cloud cover values show much less variability: a value of 10 percent in 1973 was followed by 9 percent in the other two years. Although the 1 percent difference is slight, the highest minimum occurred in the normal rainfall year, while the wettest and driest periods had identical minima.

Mean cloud covers for the three May-September periods differ significantly at the 0.01 level by a Student's t-test. The cumulus cover means in the wettest and driest months differ statistically in May, July, August and September, but not in June. (1974 respectively).

Average noontime cumulus cover over the FACE region, approximately by the mean for the six data cells (46, 47, 48, 50, 51, 52) that closely correspond to the experimental cloud seeding region, was 25 percent in 1973, 1 percent less in 1974; and 19 percent in 1977. The maximum value for any cell was 30 percent cumulus coverage in cell 46 in September, 1974, while the lowest value was 12 percent in cell 47 in May, 1977. Generally, cloud cover in southcentral Florida changed more between the three Mays than between the other months studied, a maximum difference of 21 percent for cell 52 between 1973 and 1977, when the average cloud cover changed less than 2 percent and cell 47 had no change.

CORRELATION OF CLOUD COVER WITH PRECIPITATION

Spearman (nonparametric) rank correlations were used to test the strength of relations between mean monthly afternoon total cloud cover, cumulus cover and cumulus cloud size (diameter) and total precipitation and the Palmer Drought Index (PDI). Because PDI values are most readily obtainable for climatic divisions (Fig. 4), also cloud data for each division were determined from data cells that approximately correspond to the area of a division.

Roughly one-third (13 of 42) of all rank coefficients proved significant at the 0.05 level. (Table 1). Only in the Everglades and Keys divisions are there no strong relations. The total-cloud-cover category has the greatest number of significant correlations (6) and the highest coefficient (+0.76). Cumulus cover has the lowest valued and least number

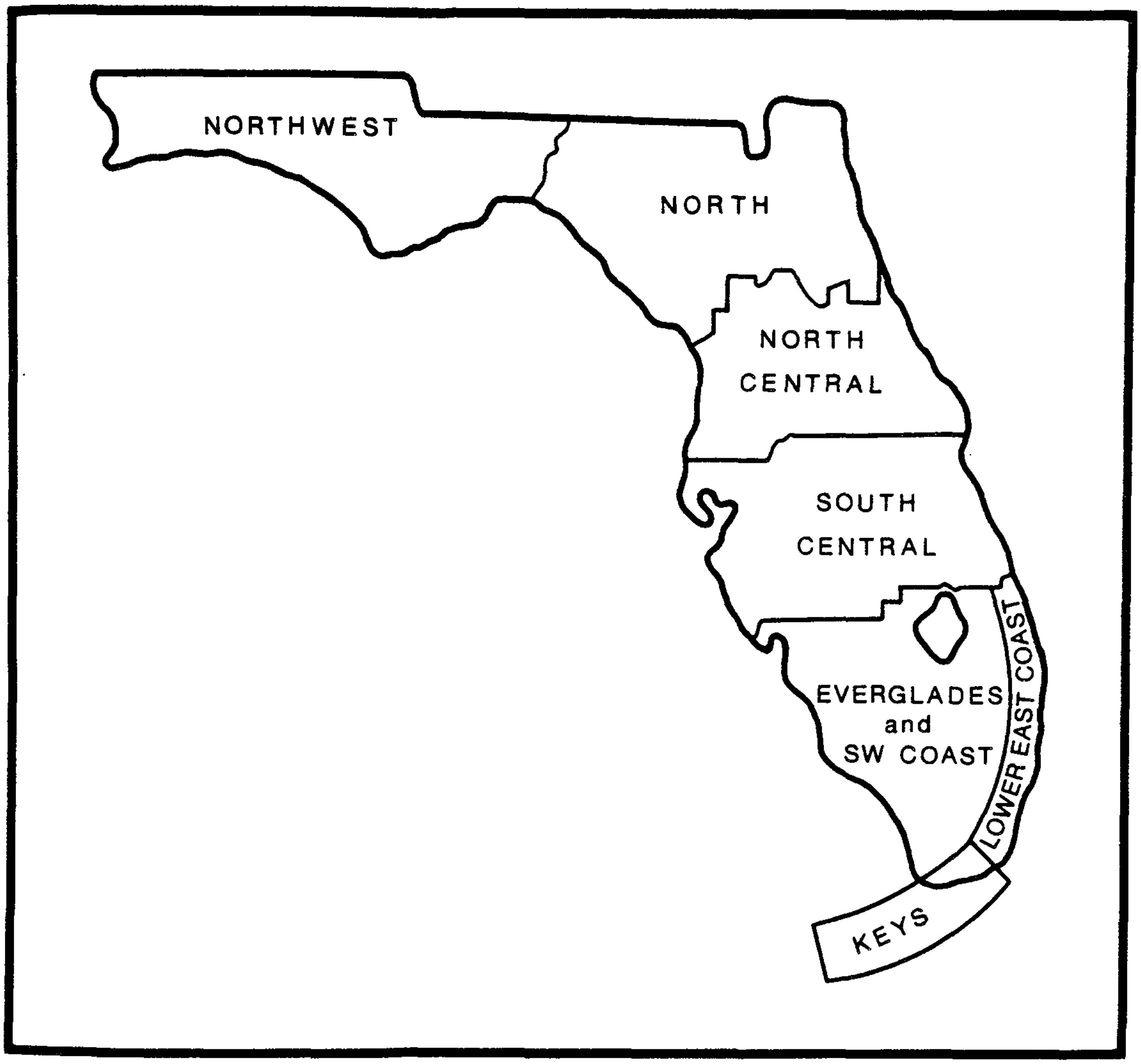

FIGURE 4. Climatic Divisions of Florida

TABLE 1

Rank Correlations (Spearman) of Three Cloud Parameters with Precipitation and the Palmer Drought Index (PDI). Only correlations significant at the 0.05 level are shown.

Climatic Division	Relation	Coefficient
Northwest	Total Cloud Cover with Precipitation	+ 0.76
	Total Cloud Cover with PDI	+ 0.59
North	Total Cloud Cover with Precipitation	+ 0.69
	Cumulus Cloud Cover with PDI	+ 0.52
	Cumulus Diameter with Precipitation	+ 0.53
	Cumulus Diameter with PDI	+ 0.72
North Central	Total Cloud Cover with Precipitation	+ 0.57
	Cumulus Diameter with PDI	+ 0.56
South Central	Total Cloud Cover with Precipitation	+ 0.70
	Total Cloud Cover with PDI	+ 0.63
Everglades and Southwest Coast	No significant relationships	
Lower East Coast	Cumulus Cloud Cover with Precipitation	- 0.57
	Cumulus Diameter with PDI	- 0.53
	Cumulus Cloud Cover with PDI	- 0.71
Keys	No significant relationships	

of significant coefficients. In the Lower East Coast division, in contrast to the others, all values are negative, indicating that in southeast coastal Florida cumulus cover was greater when precipitation was reduced, and cumulus size and cover increased when drought was stronger.

SUMMARY AND CONCLUSIONS

Cloud cover and cumulus sizes, obtained from visual analysis of afternoon DMSP satellite images for representative average, wet and dry May-September periods in Florida, show wide variability in space and time. Noontime cumulus cover was greatest over most of the state in the normal rainfall year. Only in the interior of the peninsula and along the southeast coast did cumulus cover in the wet year exceed that of the normal rainfall year. No part of the state in 1977 (dry) had more cumulus cover than the other two years. Mean cumulus cloud cover values for the three May-September periods differed significantly, which was also true when the wettest and driest of the Mays, Julys, Augusts and Septembers were compared. Only between the wettest and driest Junes were the monthly means of cumulus cover similar.

Generally, cumulus cover was greatest in the northern portion of the peninsula. Minimum values occurred in the extreme south and in scattered coastal locations. Over the FACE cloud seeding area, cumulus mean values for the normal, wet and dry periods were 25, 24 and 19 percent, respectively.

Correlations between afternoon cloud cover and cumulus size with total precipitation and a drought index showed positive relationships in four of the state's seven climatic divisions and negative values in the southeastern division, while two divisions exhibited no significant relationships.

Detailed, large-area cloud climatologies are necessary first objectives in summertime cumulus modification programs. Reynolds et al. (1978) have outlined how specific needs can be partially met by meteorological satellite data. DMSP satellite data can be important input, for although they indicate only the cloud cover at one instant, the high resolution allows detection of very small cumulus. This is valuable in developing an understanding of the relationships of cloud cover and moisture conditions.

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