On the Use of GOES Thermal Data to Study Effects of Land Use on Diurnal Temperature Fluctuation[1]

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ABSTRACT

Geostationary Operational Environmental Satellite (GOES) infrared data were used to study the effect of land use on the diurnal surface temperature fluctuation. Five major land use types in southern Florida: the sandy soil agricultural area; the Everglades Agricultural Area (EAA); the conservation areas; the Natural Everglades Area (NEA); and Lake Okeechobee; were observed. The average daytime and nocturnal surface temperatures of sandy soil in agricultural areas was lower than that of organic soil in agricultural areas. The average temperature of organic soil in agricultural areas was lower than that of organic soil in conservation areas. The surface temperature in the wet marsh area was much lower than that in a large water-storage lake. A land use change in the EAA, and an increase in the water storage in Lake Okeechobee and the conservation areas could influence the microclimate.

1. Introduction

The state of Florida is unique among southeastern states in that it has a different set of hydrological cycle system constraints. In particular, in south Florida the effects of agricultural activities in the Everglades Agricultural Area (EAA), for example, and of water supply and storage (e.g., in Lake Okeechobee and the conservation areas), contribute to problems of water availability necessary to meet the expanding and competitive needs of the state's urban, industrial, and other agricultural communities. Water users in south Florida face two critical problems. The first is the increase in domestic water use due to the 45% population increase during the past decade. The second problem is the uneven rainfall distribution. The yearly rainfall cycle in south Florida consists of a rainy season from May through October, accounting for approximately 75% of the total rainfall, and a six-month dry season.

To help cope with these problems, the climatic impacts of changes in agriculture activities in the EAA, and of increased water storage in the Conservation Areas and Lake Okeechobee, need to be described briefly to help understand the possible effects of microclimate modification.

The EAA consists of about 200 000 ha of fertile organic soil overlying a hard limestone formation. When these organic soils are drained, the soil subsides about 2.5 cm per year. Based on the current rate of subsidence and the agricultural practices in operation, soil depth in about 87% of the area will become shallower than 90 cm, and nearly 50% of the area in the year 2000 will have 30 cm or less soil over bedrock (Stephens, 1974). Thus, a change in agriculture in the area is predictable for the near future. This change will probably take two directions. The first will be to farm on the remaining, shallower organic soils, and may also include rockland farming. The second direction will be the aquacultural production system. The impacts of these potential changes on microclimate need to be investigated further.

The functions of the conservation areas include water storage to serve urban, municipal, and agricultural areas; the Everglades National Park; freshwater recharge of the water table; prevention of saltwater intrusion; and fish and wildlife preservation. Here also, the assessment of the impacts of increased water quantities on microclimate in the conservation areas should be carried out in order to properly evaluate the results of back-pumping plans in the future.

Lake Okeechobee is the major reservoir for water storage and a main source of water supply to south Florida, which includes the EAA, Everglades National Park, and the lower east coast. The lake is currently under stress from both nutrient loading and an increase of the lake's regulation stage to provide for additional water storage; this latter change may affect the microclimate.

An important parameter in microclimate modification is the diurnal surface-temperature fluctuation. The impact of surface temperature had been discussed in relation to freeze damage to crop production in south Florida (Johnson, 1970; Kidder *et al.*, 1977), to crop water-stress indicators (Jackson *et al.*, 1981), and to soil temperature (Shih *et al.*, 1982). Conventional

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methods used to observe surface temperatures relied mainly on point ground-observations rather than satellite sensing. As a result of this areally-restricted data, large-scale variation of surface temperature is difficult to predict. Recently, remote-sensing techniques have been applied to the study soil temperature (Schmugge, 1978), and to estimate nocturnal temperature (Chen *et al.*, 1979, 1982). The question remains, can satellite-detected diurnal temperature fluctuation be used to infer land use changes? Therefore, the main purpose of this investigation is to study the effect of land uses on the diurnal surface-temperature fluctuation with GOES thermal infrared data. The specific objectives are twofold: 1) to analyze the variation of the daytime and nocturnal surface temperature in relation to land uses; and 2) to discuss possible microclimate modification resulting from changes of land use and water storage.

2. Materials and methods

a. Experimental site descriptions

The observations of the effect of land use on surface temperature fluctuation were conducted in the regions shown in Fig. 1. The six regions were a sandy-soil area, the Everglades Agricultural Area, Conservation Area 1, Conservation Area 2A, the Natural Everglades Area (NEA), and Lake Okeechobee. The land use and environmental conditions are described below:

1) SANDY SOIL AREA

The sandy soil area (Site A, Fig. 1) includes several hundred thousand hectares, and is located west of the EAA. The average ground elevation is about 4.5 m above mean sea level (MSL), the entire region is nearly level, and land use is mainly pasture and sugarcane.

2) EVERGLADES AGRICULTURAL AREA

The EAA (Site B, Fig. 1) contains approximately 200 000 ha of organic soil (histosols). Land use in 1980 was about 75% for sugarcane production and 25% for truck crop and pasture production. The average ground elevation is about 3 m MSL and the entire region is nearly level.

3) CONSERVATION AREA 1

Conservation Areas 1, 2, and 3 in the eastern and southern portion of the Everglades occupy a shallow, saucer-like basin covered with sawgrass, red bays, willows, myrtles, and mixed varieties of grasses. The conservation areas are surrounded by levees, and inflows and outflows are controlled by pump and gravity-flow systems; an exception is that the western portion of Conservation Area 3A is not encompassed by levees. Conservation Area 1 (Site C, Fig. 1) has 57 000 ha and is located east of EAA.

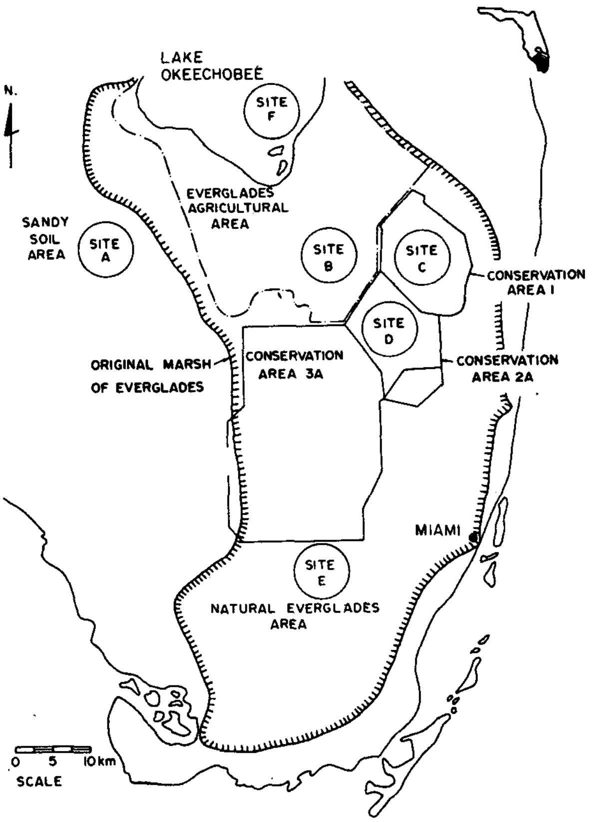

FIG. 1. Locations of study regions in south Florida.

4) CONSERVATION AREA 2A

Conservation Area 2A (Site D, Fig. 1) occupies 45 000 ha and is located south of Conservation Area 1.

5) NATURAL EVERGLADES AREA

The NEA (Site E, Fig. 1) covers several hundred thousand hectares, and is located south of Conservation Area 3A in the Everglades National Park. Vegetation in Site E is similar to those in the conservation areas, except that the NEA is not surrounded by levees and it has no water control.

6) LAKE OKEECHOBEE

Lake Okeechobee (Site F, Fig. 1) is about 55 km long and 48 km wide, with the long axis running north–south; the surface area is about 180 000 ha. Lake Okeechobee is the second-largest freshwater lake in an area wholly within the United States. Its average depth is approximately 3 m and it has an average storage volume of 5.4×10^9 m^3. Elevations of the lake bottom range from sea level to approximately 4.6 m MSL. The basin is saucer-shaped, with more than 50% of the bottom being at 1.5 m MSL or lower. The southwest and western shores of the lake consist of extensive marsh areas, a small marsh area is found along the northwestern shore.

b. *GOES thermal infrared data*

The data we use are thermal infrared (IR) (10.5–12.6 μm) temperatures obtained by the Visible and Infrared Spin-Scan Radiometer (VISSR) of the Geostationary Operational Environmental Satellite (GOES) stationed over the equator at 75°W, referred to as GOES-East (Bristor, 1975). The data were obtained from the National Environmental Satellite, Data, and Information Service (NESDIS) by computer-to-computer linkage through 1200 baud lines between the Fruit Crops Department, University of Florida, and the National Meteorological Center at Suitland, Maryland. The resolution of the IR data for the Florida sector (24.5°N to 30.5°N latitude, 79° to 85°W longitude) is approximately 8 km (north–south) and 6 km (east–west), or 4800 ha. Border effects caused by the low resolution of the VISSR were avoided by averaging only 4 pixels at the center of each region. The area of study within each region was about 19 200 ha. 12 and 18 January 1981 were chosen for three reasons: First, the 1980–81 dry season (November through April) was a severe drought condition in south Florida, water storage in the conservation areas was less than normal, and the environmental conditions in the conservation areas were mixed with both dry and wet marsh land. Second, the lowest temperatures recorded during the 1980–81 dry season occurred on these two dates. Third, solar radiation measured at the University of Florida, Belle Glade weather station (located within the EAA) were 401 and 435 cal $\mathrm{cm}^{-2}\ \mathrm{day}^{-1}$ for 12 and 18 January, respectively. These values were close to the theoretical solar radiation for cloudless skies as estimated by Budyko (1963) for January at this latitude. Thus, the dates chosen were cloud-free.

The hourly thermal infrared data for 12 January 1981 were plotted for Sites A, B, and C (Fig. 2), and Sites D, E, and F (Fig. 3). For 18 January, data for Sites A, B, and C (Fig. 4); and Sites D, E, and F (Fig. 5) were plotted. The maximum possible length of sunshine at 26°25′N around 15 January is 10.6 h. In this study, daytime temperatures were computed from 0800 to 1800 EST as shown in Figs. 2, 3, 4, and 5; nocturnal temperatures were calculated from 0100 to 0700, and 1900 to 2400 EST; and the diurnal temperatures were estimated from 0100 to 2400 EST.

Several errors can be encountered when GOES data are used to estimate the surface temperature. One of these is the inherent limitation existing in the satellite system. For instance, each sweep of the sensor may not return to the same area in successive images, and hence each identically-positioned pixel in successive images can detect a different set of conditions. Atmospheric moisture and particulates which absorb, reradiate, and attenuate surface fluxes, will also cause some errors in the surface temperature estimation. Another error is associated with the accuracy which can

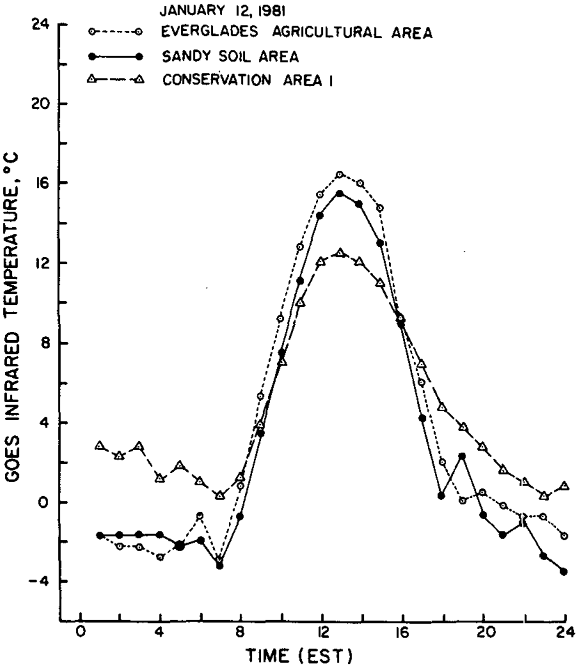

FIG. 2. GOES infrared data, 12 January 1981, for sandy soil area, Everglades Agricultural Area, and Conservation Area 1.

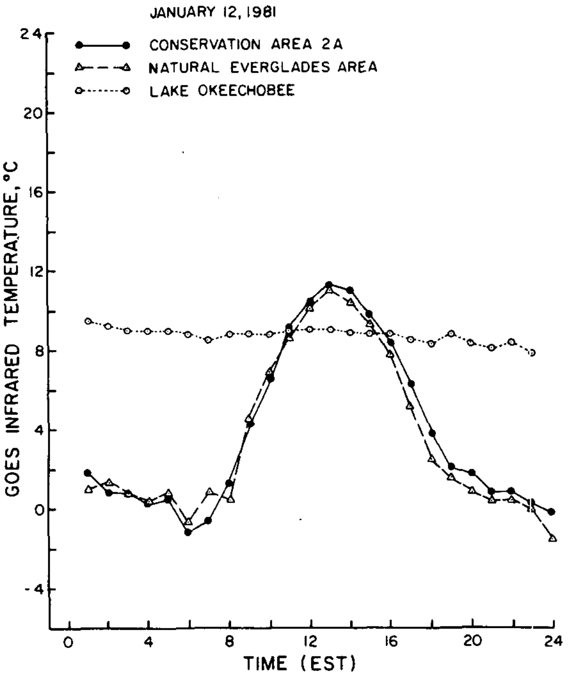

FIG. 3. GOES infrared data, 12 January 1981, for Conservation Area 2A, Natural Everglades Area, and Lake Okeechobee.

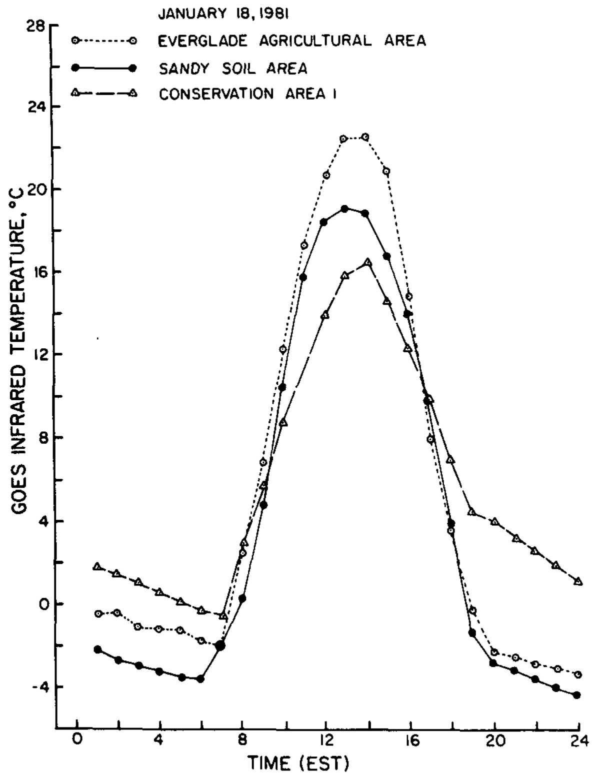

FIG. 4. As in Fig. 2, but for 18 January 1981.

be achieved in image overlay and alignment during data manipulation and analysis. This error can be minimized to one pixel or less when there is a good landmark (such as Lake Okeechobee in this study) having a distinct temperature pattern for identification.

c. Hydrological data for Sites C, D, and F

The stage, water surface area, and water storage on 12 and 18 January 1981 for Lake Okeechobee, and Conservation Areas 1 and 2A, are presented in Table 1. The average depth of Lake Okeechobee at this time was 2.4 m; since the lake's surface area is 180 000 ha, about 95% of the surface was underwater during this study period.

The surface of Conservation Area 1 was about 64% water, with an average of 30 cm; Conservation Area 2A was 51% water-covered, also with an average water depth of 30 cm. The highest elevation region in the conservation areas is located in the north. The 19 200 ha of GOES study areas (Sites C and D) were in the central portion of Conservation Areas 1 and 2A, and include areas with and without water.

d. Fourier-series analysis

The diurnal fluctuation of surface temperature can be considered as a periodic function of time with a variable period. In general any periodic function can be expressed by a Fourier series. The Fourier coefficients give an objective description of the variation in the magnitude of temperature fluctuation (amplitude), maxima, and minima. The Fourier series for temperature T verses time t, can be expressed as

$$T(t) = \frac{a_0}{2} + \sum_{i=1}^{\infty} [a_i \cos(iwt) + b_i \sin(iwt)], \qquad (1)$$

where

$$a_0 = \frac{1}{2\pi} \int_{-\pi}^{\pi} T(t)dt, \qquad (2)$$

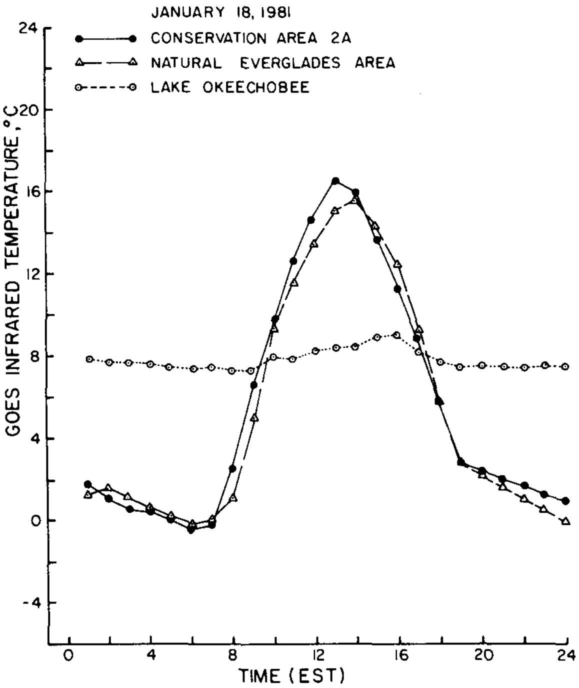

FIG. 5. As in Fig. 3, but for 18 January 1981.

TABLE 1. Hydrological data for Lake Okeechobee and Conservation Areas 1 and 2A.

Location	Parameters	Date 12 Jan 1981	 18 Jan 1981
Lake Okeechobee	Stage (m)	4.17	4.15
	Water surface area (ha)	172 200	171 200
	Water storage (ha-m)	418 600	411 600
Conservation Area I	Stage (m)	4.71	4.69
	Water surface area (ha)	37 000	36 000
	Water storage (ha-m)	12 000	11 900
Conservation Area 2A	Stage (m)	3.48	3.44
	Water surface area (ha)	24 000	22 000
	Water storage (ha-m)	7 600	6 900

$$a_i = \frac{1}{\pi} \int_{-\pi}^{\pi} T(t) \cos(iwt)dt, \tag{3}$$

$$b_i = \frac{1}{\pi} \int_{-\pi}^{\pi} T(t) \sin(iwt)dt. \tag{4}$$

Surface temperature varies from some value at midnight of the first day to some value at the midnight of the second day. To account for this, a slope term must be added to the Fourier series and Eq. (1) can be rewritten in the form

$$T(t) = T_0 + bt + \sum_{i=1}^{N} c_i \sin(iwt + \theta_i), \tag{5}$$

where

T_0 constant of surface temperature;
t time factor;
b the linear slope of the surface temperature;
N the number of diurnal data point divided by two;
i harmonic index;
c_i $[=(a_i^2 + b_i^2)^{0.5}]$ the magnitude of amplitude;
a_i Fourier cosine coefficient;
b_i Fourier sine coefficient;
w $360/p$;
p the period of the fundamental cycle; and
θ_i $\arctan(a_i/b_i)$, the phase angle.

Since each of the amplitude coefficients of a series make up a part of the variance and the sum of the squares of the amplitude coefficients, the amplitude is related to the total variance of the mean by the equation (Brooks and Carruthers, 1953)

$$\sum_{i=1}^{N} c_i^2 = 2\sigma_{\bar{T}}^2 , \tag{6}$$

where $\sigma_{\bar{T}}^2$ is the total variance of the mean, $\bar{T}$.

The percentage of the total variation in the series of the temperature fluctuation accounted for by the ith harmonic is given by:

$$\text{percent of the } i\text{th harmonic} = (c_i^2 \times 100)/2\sigma_{\bar{T}}^2. \tag{7}$$

Another method of estimating the magnitude of the amplitude is to combine the estimates of the first- and second-harmonic amplitude coefficients together, or

$$c_{1,2} = (c_1^2 + c_2^2)^{0.5}. \tag{8}$$

3. Results and discussion

a. Statistical analysis of the GOES thermal data

The means and standard deviations for daytime, nocturnal, and diurnal surface temperatures are shown in Table 2.

1) SANDY SOIL AND THE EAA

The surface temperature in the sandy soil (Site A) was lower than that in the organic soil (Site B) of the EAA. As mentioned earlier, both sites have similar land use. In general, the sugarcane in south Florida is harvested between November and April; by the middle of January about 40% has been harvested. Jackson *et al.* (1981) indicated that vegetation temperatures over much of the area should not differ greatly from air temperatures, whether the vegetation is alive or senescent. The thermal inertia effects of the vegetation itself should be small compared to the soil. The observed surface temperature differences in both regions could be due to differing soil characteristics such as color and thermal conductivity. Color has a considerable effect on the degree of reflection (albedo) of incoming solar radiation, and dry, light-colored soils reflect more than moist, dark-colored soils (Kohnke,

TABLE 2. Average GOES daytime, nocturnal, and diurnal surface temperatures (°C) for different land use conditions.

Sampling location	Parameter	12 January 1981			18 January 1981		
		Daytime[a]	Nocturnal[b]	Diurnal[c]	Daytime[a]	Nocturnal[b]	Diurnal[c]
Sandy soil	Mean	8.5	−1.7	3.0	12.0	−3.0	3.9
	Std. dev.	5.9	1.4	6.6	6.6	0.8	8.8
EAA	Mean	9.8	−1.4	3.8	13.9	−1.7	5.4
	Std. dev.	5.7	1.1	6.8	7.5	1.0	9.4
Conservation Area 1	Mean	8.3	1.7	4.7	10.8	1.7	5.8
	Std. dev.	3.9	1.1	4.2	4.5	1.6	5.6
Conservation Area 2A	Mean	7.4	0.6	3.7	10.7	1.1	5.5
	Std. dev.	3.3	1.0	4.2	4.5	1.0	5.8
NEA	Mean	6.9	0.4	3.4	10.2	1.0	5.2
	Std. dev.	3.5	0.8	4.1	4.7	0.9	5.7
Lake Okeechobee	Mean	8.8	8.6	8.7	8.1	7.5	7.8
	Std. dev.	0.2	0.6	0.5	0.6	0.1	0.5

[a] 0800–1800 EST. [b] 0100–0700, and 1900–2400 EST. [c] 0100–2400 EST.

1968). The organic soil absorbed more solar radiation, resulting in a higher surface temperature than the sandy soil. The average daytime temperatures during 12 January 1981 were 8.5°C for sandy soil and 9.8°C for organic soil (Table 2). For 18 January 1981, the average daytime temperatures were 12.0 and 13.9°C for the sandy soil and organic soil, respectively. In general, the surface temperatures of the organic soil were about 1.3 to 1.9°C higher than the sandy soil. This surface temperature difference is clearly depicted in Figs. 2 and 4. The reversal in temperature between the EAA and the sandy soil area at 0600 and 1900 EST in Fig. 2 is probably caused by error in the system.

Thermal conductivity for dry sand is 0.00046 cal $\mathrm{cm^{-1}\,s^{-1}\,{}^{\circ}C^{-1}}$, while that of humus is 0.00027 cal $\mathrm{cm^{-1}\,s^{-1}\,{}^{\circ}C^{-1}}$ (Chang, 1968). Therefore, other things being equal, the quantity of heat conducted by a sandy soil will be approximately twice as much as by an organic soil. Organic soils tend to hold the absorbed heat near the surface during periods of heating, resulting in a higher (than sandy soil) surface temperature. The surface temperature of the organic soil will be lower at night because less heat will be conducted upward to replace the radiative heat loss. However, the average nocturnal surface temperatures of organic soil were about 0.4°C on 12 January and 1.3°C on 18 January, higher than that of sandy soil. We feel that this reversal of the expected result occurred because the EAA is a water-controlled area and is dissected with canals containing open water; it also has a higher water table (about 60 cm depth, Shih *et al.*, 1983). These are important factors retarding nocturnal radiative cooling. Conversely, the sandy soil is not a water-controlled area, has no exposed surface water, and is dry because the water holding capacity of sandy soil is low (Carlisle *et al.*, 1978). Therefore, it had a lower minimum temperature than the organic soil. After the freeze on 12 January, the sugarcane in the sandy soil region had more severe damage than that in the EAA.

2) EAA AND CONSERVATION AREA 1

The surface temperature in Conservation Area 1 (Site C) was higher than that in the EAA (Site B). As mentioned in Section 2, both regions have organic soils. This temperature difference (Figs. 2 and 4) could be due to the fact that the moisture content in the organic soil was different between the two areas. Conservation Area 1 had 60% of its area under about 30 cm of water (Table 1). However, the water table in the EAA was at about 60 cm depth (Shih *et al.*, 1983). The albedo of a wet surface is much lower than that of dry land. Thus, the organic soil in the EAA absorbs more solar radiation than that in Conservation Area 1. The average daytime temperatures (Table 2) in the EAA were 1.5°C on 12 January, and 3.1°C on 18 January, both higher than in Conservation Area 1. High water contents in the organic soils tend to reduce the magnitude of temperature change during periods of heating and cooling (Oliver, 1962). The nocturnal temperature in the Conservation Area 1 is about 3°C higher than that in the EAA (Table 2).

3) CONSERVATION AREAS AND NATURAL EVERGLADES AREA

The surface temperature in Conservation Area 1 (Site C) was higher than that in Conservation Area 2A (Site D), although both areas have similar vegetation and organic soil. The major difference between the two areas was that both the water surface and water storage in Conservation Area 1 were about 60% greater than in Conservation Area 2 (Table 1). This may result in a difference in the temperature patterns in the two conservation areas (Figs. 2–5).

The surface temperature in the NEA (Site E) was slightly lower than that in Conservation Area 2A (Table 2). Both areas have similar vegetation and organic soil, but the NEA is not surrounded by levees for water storage. Thus, the water surface area and water storage in the NEA could be less than that in Conservation Area 2A, resulting in a lower surface temperature in the NEA.

4) LAKE OKEECHOBEE AND THE CONSERVATION AREAS

The surface temperature of Lake Okeechobee (Table 2) was higher than that in the conservation areas. This could be due to the water surface area, water storage and water depth in Lake Okeechobee, which are much larger than that in conservation areas (Table 1). In other words, the volumetric heat capacity in Lake Okeechobee is greater than that in the conservation areas. This greater heat capacity results in a higher thermal inertia which governs the cyclic responses of surface temperature (Figs. 3 and 5).

b. Harmonic analysis of the GOES thermal data

The surface temperature variations in the sampling sites were also analyzed by using the Fourier-series technique defined in Eq. (5). The Fourier coefficients, amplitude, phase angle, and percent of variance for each harmonic are listed in Tables 3 and 4 for 12 January and 18 January 1981, respectively. The Fourier-series analysis showed that two harmonics explained over 96% of the variance, except for Lake Okeechobee where they explained over 84% of the variance. Thus, the parameters in the first two harmonics were important factors in analyzing the diurnal surface temperature fluctuation. The combined amplitude, as computed by Eq. (8), is an important parameter in confirming the relationships between diurnal surface temperature and land use conditions discussed in the previous sections.

TABLE 3. Harmonic analysis of cyclic components of surface temperature from GOES thermal infrared data for 12 January 1981.

Sampling location	Harmonic	Fourier coefficient		Amplitude		Phase angle	Percent of variance
		Cosine	Sine	Harmonic	Combined		
Sandy soil	1st	−7.86	−2.56	8.27		4.40	80.5
	2nd	3.45	0.96	3.58	9.01	1.30	15.1
EAA	1st	−8.37	−2.01	8.61		4.48	81.8
	2nd	3.61	0.62	3.66	9.36	1.40	14.8
Conservation Area 1	1st	−4.92	−2.35	5.45		4.27	81.1
	2nd	2.14	0.97	2.35	5.94	1.15	15.1
Conservation Area 2A	1st	−4.94	−2.36	5.47		4.27	84.0
	2nd	2.11	0.53	2.17	5.89	1.33	13.3
NEA	1st	−4.89	−1.87	5.24		4.35	82.5
	2nd	2.11	0.50	2.16	5.67	1.34	14.1
Lake Okeechobee	1st	−0.19	−0.46	0.50		3.53	79.1
	2nd	0.07	0.11	0.13	0.52	2.54	5.2

The combined amplitude in the EAA was about 4–6% greater than that in the sandy soil area, mainly because the daytime temperature of the organic soil was higher than of the sandy soil. This implies that if a future rockland agricultural system were to be implemented in the organic soil area, lower temperatures, causing crop damage, may occur.

The combined amplitude in the EAA was about 58–67% greater than that in Conservation Area 1, mainly because of the difference in moisture content between the two regions. This supports the practice of using sprinkler systems for reducing frost and freeze damage during winter. This result also implies that if the EAA area were to be flooded for an aquacultural system in the future, the severity of freeze damage to crops could be reduced.

The combined amplitudes in the conservation areas were much higher than in Lake Okeechobee. This implies that increasing the water storage during the winter season in the conservation areas would reduce freeze damage of the vegetation, which could improve the ecosystem environment within the conservation areas. Similarly, increasing the water storage in Lake Okeechobee during the winter season also would improve the microclimate by increasing nocturnal temperatures.

4. Conclusions

GOES thermal infrared data were used to study the effect of land use on diurnal surface temperature fluctuations. Several conclusions were reached.

Fourier-series analysis showed that two harmonics explained over 96% of the variance, except in Lake Okeechobee where they explained over 84% of the variance. Thus, the parameters in the first two harmonics were important factors in analyzing the diurnal surface-temperature fluctuation.

TABLE 4. Harmonic analysis of cyclic components of surface temperature from GOES thermal infrared data for 18 January 1981.

Sampling location	Harmonic	Fourier coefficient		Amplitude		Phase angle	Percent of variance
		Cosine	Sine	Harmonic	Combined		
Sandy soil	1st	−11.03	−3.27	11.50		4.42	86.2
	2nd	3.88	1.66	4.22	12.25	1.17	11.6
EAA	1st	−11.63	−2.86	11.97		4.47	82.6
	2nd	4.70	2.03	5.11	13.02	1.16	15.1
Conservation Area 1	1st	−6.49	−3.35	7.30		4.24	85.6
	2nd	2.57	0.96	2.74	7.80	1.21	12.1
Conservation Area 2A	1st	−6.91	−2.67	7.41		4.34	83.7
	2nd	2.92	0.83	3.03	8.01	1.29	14.0
NEA	1st	−6.69	−3.04	7.35		4.29	84.3
	2nd	2.57	1.34	2.90	7.90	1.09	13.2
Lake Okeechobee	1st	−0.42	−0.48	0.64		3.86	72.8
	2nd	0.12	0.26	0.29	0.70	0.41	15.0

The average daytime and nocturnal surface temperature in the sandy soil area was lower than that in the organic soil of the Everglades Agricultural Area (EAA). The differences were about 1.3 to 1.9°C in daytime temperature, and 0.3 to 1.3°C in nocturnal temperature. This implies that more severe crop-damaging cold may occur in the future if rockland agricultural practices are implemented due to the subsidence of the organic soil.

The average surface temperatures in the EAA were lower than those in the conservation areas, ranging from 2.4 to 3.2°C in the daytime, and 3.1 to 3.4°C in the nighttime, respectively. This implies that if the EAA were flooded for an aquacultural production system in the future, the severity of crop freeze damage could be reduced.

The surface temperature of Lake Okeechobee was higher than that in the conservation areas, because the water surface area, water storage, and water depth in Lake Okeechobee were much larger than those in the conservation areas. This implies that an increase in winter water storage would also reduce freeze damage to the natural vegetation.

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