SATELLITE-DERIVED SURFACE TEMPERATURES AND THEIR RELATIONSHIPS TO LAND COVER, LAND USE, SOILS AND PHYSIOGRAPHY OF NORTH-CENTRAL FLORIDA

BY

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By

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Relationships between satellite-derived surface temperatures and surface materials in north-central Florida were examined using subsets of four day and three night Heat Capacity Mapping Mission (HCMM) thermal infrared scenes. The images were mapped to the Universal Transverse Mercator coordinate system and corrected for atmospheric attenuation and thermal emission. The images were selected to provide day and night coverage for the fall, winter and spring seasons. From these data, overlayed HCMM and Landsat multispectral scanner (MSS) images, isotherm maps, color-coded temperature maps and enhanced greyscale images were
produced and used in conjunction with black and white and color infrared air photos, Landsat MSS and Thematic Mapper images, and land use, soils and physiographic maps to examine the influence of surface features on surface temperatures.

These data show that surface temperatures are largely controlled by a combination of surface moisture availability and vegetation density. Natural land covers show a daytime temperature gradation reflecting the importance of these factors, with wettest land covers such as marshes and wetlands displaying the coolest temperatures and sparsely vegetated forests on well drained soils registering the highest surface temperatures. The nighttime data reveal that land cover has less of an influence on surface temperatures, with surface moisture being the primary factor determining temperatures.

Modifications of natural land cover exert a significant influence on surface temperature patterns. Agricultural lands, because of their areal extent and high surface temperatures, have the most profound influence on temperature patterns. Commercial forestry practices, particularly clearcutting, lead to increased day surface temperatures, as do urbanization and surface mining. Night surface temperatures are less influenced by cultural land covers. Bare agricultural lands and clearcuts generally exhibit the lowest surface temperatures, and urban areas tend to have a localized warming influence.
Soil drainage classes show a strong correspondence to surface temperatures, particularly in the daytime data. Well drained soils exhibit the highest day and lowest night surface temperatures. The results also indicate that the sensitivity of thermal data to moisture, vegetation cover and soil drainage characteristics make it a potentially useful data source for coastal plain physiographic studies.
CHAPTER I
INTRODUCTION AND OBJECTIVES

All objects having temperatures above absolute zero emit electromagnetic radiation (EMR) at a rate determined by the temperature and emissivity of the object. This emitted EMR offers a valuable source of information that can be remotely sensed and used to measure or infer surface properties not easily obtained from other data sources. Of particular interest to researchers in several disciplines is EMR emitted in the thermal infrared (IR) wavelengths. Geographers and climatologists have used IR data to examine energy balances over urban areas to better understand the influence of urbanization on climate. Measurement of temperature variations determined from IR data have shown great potential for improving crop management practices such as irrigation and pesticide application by allowing the identification of stressed vegetation and regions of low soil moisture. IR data have also been employed by agricultural meteorologists for frost forecasting. The ability to estimate regional evapotranspiration (ET) rates using remotely sensed surface temperatures has potential benefits to agronomists, soil scientists and hydrologists. Geologists have found that thermal data are complementary to
the visible and reflective infrared data that have been in use since the beginnings of aerial photography. Geothermal mapping, rock type differentiation, structural mapping and physiographic mapping all potentially benefit from the use of IR data.

This study utilizes IR data obtained by the Heat Capacity Mapping Mission (HCMM) satellite to examine a study area in north-central Florida. The primary purpose of this study is to examine relationships between satellite-observed temperature patterns and surface features in the study area, and variations in these relationships through time.

To date, temperature pattern studies of the Florida peninsula have concentrated on the central and southern portions of the state and were intended to aid in detecting cold-prone agricultural regions (Allen et al., 1983; Chen et al., 1979; 1982; 1983; Shih and Chen, 1984). Most of these studies utilized coarse resolution geostationary satellite (GOES) data for nocturnal winter time periods. This study extends previous investigations to the northern part of the Florida peninsula, using higher resolution data and day and night imagery from various times of the year. The results of this investigation will provide an increased understanding of the influence of land cover and land use patterns on the distribution of surface temperatures in north Florida. This information will be helpful in evaluating the potential of IR data for mapping land cover,
physiography and soils in the region. It will also provide insight into inadvertent climatological changes produced by the alteration of the natural landscape by human activities.

The following aspects of surface temperature patterns will be examined in detail:

- Relationships between vegetative land covers and surface temperature patterns. Of particular interest is the ability to differentiate between various land covers on the basis of surface temperatures.

- Modification of surface temperature patterns by human activities. Specifically examined are modifications related to urban and industrial land uses and agricultural and forestry practices.

- Relationships between satellite-derived temperatures and soil type and physiographic features.
CHAPTER II
PHYSICAL BASIS OF THERMAL REMOTE SENSING

The temperature measured by hand-held, aircraft or satellite thermal radiometers is the apparent radiant temperature of the object. The apparent radiant temperature differs from the kinetic temperature, or that measured by a thermometer, by its dependence on a number of factors, including kinetic surface temperature, atmospheric conditions, sensor characteristics and the nature of the earth's surface that is being examined. These factors will be briefly discussed below.

Factors Governing Surface Temperatures

The temperature of the earth's surface is governed by balances between incoming and outgoing radiative fluxes (Rosenberg, 1974; Oke, 1978; Price, 1982). These fluxes can be described by the following energy balance equation:

\[ R_n = H + LE + G \]

where \( R_n \) is the net radiative flux at the earth's surface, \( H \) is sensible heat flux, \( LE \) is the latent heat flux, and \( G \) is the heat flux into the ground. Net radiative flux is dependent on the incoming and outgoing shortwave and
longwave radiation balances. The shortwave balance can be represented by the following equation:

$$\text{Rswb} = \text{Rsw} (1 - a),$$

and the longwave balance by

$$\text{Rlwb} = \text{Rlwd} - \text{Rlwu}$$

where the Rswb is the shortwave radiation balance, Rsw is incoming shortwave (both solar and diffuse) radiation, a is shortwave albedo, Rlwb is the longwave radiation balance, and Rlwd and Rlwu are the downward and upward longwave radiation fluxes. These equations can be combined to give Rn:

$$\text{Rn} = (1-a) \text{Rsw} + \text{Rlwb}.$$
\[ H = -pc(Kh)(dT/dz + DALR) \]

where \( p \) is the density of air (gm/cm\(^3\)), \( c \) is the specific heat of air at constant temperature and pressure (J/Kg/K), \( dT/dz \) is the temperature gradient (K/cm), \( Mh \) is molecular diffusivity of air (approximately 0.21 m\(^2\)/s), \( Kh \) is the eddy conductivity (m\(^2\)/sec), and DALR is the dry adiabatic lapse rate.

Transfers of sensible heat can also be described using a resistance approach analogous to Ohm's Law (Rosenberg, 1974):

\[ H = -60pc \frac{(Ts - Ta)}{ra} \]

where \( p \) and \( c \) are the density and specific heat of air, \( Ts \) and \( Ta \) are the surface and air temperatures and \( ra \) is the atmospheric resistance factor. Resistance will increase with increasing windspeed or turbulence as the height of the laminar boundary layer is decreased and mixing in the overlying turbulent layer increases.

The second term on the right side of the energy balance equation is latent heat transfer. Latent heat fluxes are the result of evaporation (EV) and transpiration (TR) with evaporation being described by

\[ EV = -pL(Kw)dq/dz \]

where \( p \) is as defined above, \( L \) is the latent heat of vaporization (J/kg), \( Kw \) is the eddy diffusivity for water
vapor \( (m^2/s) \) and \( dq/dz \) is the vapor pressure gradient. Latent heat exchanges from transpiration can be estimated using a resistance approach:

\[
TR = -pL(0.622)/P((es-ea)/(ra+rs))
\]

where \( p \) and \( L \) are as defined above, \( P \) is photosynthetic fixation of energy \( (W/cm^2) \), \( es \) and \( ea \) are stomatal and atmospheric vapor pressures and \( ra \) and \( rs \) are atmospheric and stomatal resistances. Atmospheric resistance depends on windspeed as described above. Because water vapor from plants must pass through leaf stomata, the \( rs \) term depends on stomatal characteristics.

The last term in the radiation balance equation is ground heat flux, and is a function of the mean temperature gradient and the ability of a soil to transmit heat:

\[
G = -k \ (dT/dz)_{avg}
\]

where \( k \) is thermal conductivity \( (W/m/K) \), and \( (dT/dz)_{avg} \) is the mean temperature gradient. The value of \( k \) varies with both depth and time for a given soil, although if bulk averages are required, \( k \) varies with soil particle conductivities, soil porosity and soil moisture. The dependence on porosity and soil moisture is the result of differences in the thermal properties of air and water in pore spaces. Temperature change resulting from the addition of heat to a volume of material is related to the volumetric
heat capacity (C) (J/m³/Kelvin). Heat capacity is the amount of heat necessary to raise the temperature of a cubic meter of a material by 1 K. The total temperature response of a soil is given by the ratio between thermal conductivity and volumetric heat capacity, and is termed thermal diffusivity (m²/s). Thermal diffusivity gives the amount of time required for temperature changes to travel through a soil. Thermal diffusivity is increased by the initial addition of moisture to a soil because of increased thermal contact between particles and the expelling of air (a poor conductor of heat). Beyond an approximately 20% soil moisture content (by volume) thermal diffusivity declines as thermal conductivity levels off and heat capacity continues to rise (Oke, 1978).

The above thermal characteristics determine the diurnal temperature fluctuations of soil, and can be combined to provide another thermal descriptor of the earth's surface, thermal inertia. Thermal inertia is defined as follows:

\[ P = \sqrt{Kcp} \]

where \( K \) is thermal diffusivity, \( c \) is specific heat and \( p \) is density. Thermal inertia is the resistance of a material to temperature change; materials with large thermal inertias, such as wet soils or water bodies, will display smaller diurnal temperature ranges than will those with small thermal inertias.
Satellite Measurement of Surface Temperature

As previously mentioned, all materials with a temperature above absolute zero emit EMR. The amount of EMR emitted by a perfect emitter, or blackbody, is given by Planck's equation:

\[ L = C_1(W)^5/(\exp(C_2/WT) - 1) \]

where \( L \) is the spectral exitance for a given wavelength \((W/m^2/micron)\), \( C_1 \) is \( 3.74 \times 10^{16} \) \( W/m^2 \), \( W \) is the wavelength of the EM energy in meters, \( C_2 \) is \( 1.44 \times 10^2 \) m K and \( T \) is temperature in degrees K. This formula shows that the amount of energy emitted by a perfect blackbody is temperature and wavelength dependent. The maximum wavelength \((W)\) at which energy is emitted is given by the Wien Displacement Law:

\[ W = C/T \]

where \( C \) is \( 2.989 \times 10^3 \) m K, and \( T \) is temperature in degrees Kelvin. Total exitance of a blackbody is given by the Stefan-Boltzmann Law:

\[ M(\text{total}) = a T^4 \]

where \( a \) is \( 5.669 \times 10^8 \) W/m\(^2\)/K. Because natural objects are not perfect blackbodies the above equations must be corrected for the varying emissivity characteristics of different materials. The emissivity of a material is given
by the ratio between the spectral exitance of the material and a true blackbody. The closer the emissivity is to 1.0, the closer the apparent radiant temperature of an object will be to the true kinetic temperature.

In most thermal remote sensing applications, the quantity measured by the sensor is spectral radiance, and the Planck equation is solved for temperature. The temperature derived from the inverted Planck equation, when not corrected for emissivity or atmospheric attenuation, is termed the apparent temperature. Correcting for emissivity variations is difficult when aircraft- or satellite-based sensors are used because a wide variety of surface features with varying emissivities contribute to the measured radiance. Because most vegetated and urban surfaces have emissivities greater than 0.95, emissivity variations will be relatively minor over such land covers (Taylor, 1979; Artis and Carnahan, 1982). For sensors with large instantaneous fields of view the radiance is an average of several emitters on the earth's surface, a fact that tends to reduce the significance of emissivity differences.

**Atmospheric Attenuation and Emission**

If emissivity variations can be assumed to be equal, relative temperature differences can be readily obtained by thermal sensors, but atmospheric attenuation and emission of thermal infrared EM radiation make the determination of
actual surface temperatures difficult, and can lead to greater errors than do emissivity variations. Attenuation of infrared EM radiation is wavelength dependent and primarily caused by line absorption by water vapor, carbon dioxide and ozone, and by continuum absorption between spectral lines by carbon dioxide and water vapor (Chahine, 1983). Most sensors are designed to utilize wavelengths that avoid the main spectral absorption lines. Continuum absorption varies mainly in response to changes in atmospheric moisture, with the carbon dioxide component being almost constant spatially and temporally. Thermal emission is related to the amount of water vapor present and the temperature profile of the atmosphere.

Radiation received by the satellite can be determined by use of the radiative transfer equation. There is a linear relationship between radiation emitted at the surface and radiation received at the satellite (Schott and Volchok, 1985):

\[ L(h) = t(h)eL(T) + t(h)rLd + Lu(h) \]

where \( L(h) \) is the radiance reaching the sensor at altitude \( h \) (W/cm\(^2\)/sr), \( t(h) \) is the transmission to altitude \( h \), \( e \) is the emissivity of the surface, \( L(T) \) is the blackbody radiance associated with an object on the ground at temperature \( T \) (W/cm\(^2\)/sr), \( r \) is the reflectivity of the surface \( (r = 1-e) \), \( Ld \) is the downwelling sky radiance (W/cm\(^2\)/sr) and \( Lu(h) \) is
the upwelled radiance from the air column between the surface and the sensor at altitude $h$ (W/cm$^2$/sr). These values are integrated over the range of wavelengths measured. Corrections for atmospheric effects are generally accomplished using a numerical approximation of the radiative transfer equation, with atmospheric soundings providing the necessary temperature and humidity data (Schott, 1979; Leckie, 1982; Price, 1983b; Suits, 1983; Vukovich 1983; 1984).

**Sensor-Related Inaccuracies**

Several types of satellite-based imaging sensors are used to measure IR. Commonly they utilize an oscillating mirror to direct incoming radiation to a detector that converts incoming watts of EMR to output voltages. A well-designed detector has a linear or near-linear calibration curve relating incoming radiation to output volts. The voltages are then sampled during ground processing to integer values that can be related to specific measured radiances or temperatures.

Modern sensors have stated accuracies of approximately 0.1 K, though noise from the sensor itself and associated electronics can degrade this accuracy somewhat. A common measure of the signal-to-noise ratio of a sensor is noise equivalent temperature difference (NETD). NETD is a measure of the temperature change required to produce a voltage
change equal to the noise, and in a well designed sensor it should be constant over the full range of possible temperatures (Short and Stuart, 1982). Inaccuracies in measured temperatures or radiances may be caused by post-launch changes in sensor calibration. These calibration changes may be the result of sensor contamination or degradation over time. It may be possible to correct for calibration changes using data collected by the sensor or by comparing satellite temperatures to those collected on the ground, but these changes are often poorly understood and accurately compensating for them is difficult (Barnes and Price, 1980).

Though not an inaccuracy per se, spatial resolution is also important in determining the temperature measured by a radiometer. The larger the field of view of the sensor, the more complex will be the mixture of objects viewed by the instrument. The result is that small features with very high or low temperatures may be masked by the temperature of surrounding features because of the averaging effect of the sensor.

Surface Characteristics Influencing Surface Temperatures

As discussed above, the radiant temperature measured by thermal sensors is a function of the kinetic temperature and emissivity of a surface, atmospheric temperature and humidity characteristics, sensor calibration and surface
energy fluxes. The radiant temperature measured by a sensor is the composite surface temperature of all objects within the sensor's field of view, and therefore represents a complex mix of surface features. Vegetation canopy structure and terrain characteristics exert important influences on remotely-sensed surface temperatures.

**Canopy structure.** Canopy structure can be described in terms of vegetation geometry, leaf area and vegetation distribution and density. The structure of natural vegetation canopies is generally complex, and radiation budgets over vegetated areas are likewise more complex than those over non-vegetated surfaces. As incoming solar radiation is reflected, transmitted and absorbed by multiple leaf layers, trunks, stems, ground litter, bare soil and undergrowth, it is changed in spectral content and amount.

Reflectance of EMR is controlled by a number of factors including leaf area, shape and orientation, proportion of diffuse versus direct sunlight and solar illumination angle (Ahmad and Lockwood, 1979). Reflectances are spectrally variable over vegetated surfaces. In the visible wavelengths blue and red light tend to be absorbed by chlorophylls and carotenoids more than is green light. Over the entire visible spectrum absorption is generally between 80% and 90%. Between 0.7 and 1.0 microns, reflectance is generally 40-45% for most plants. Beyond the visible range the reflectance is controlled largely by water content, with
absorption increasing with increasing leaf moisture. Average reflectances for the entire EMR spectrum are on the order of 12-18% for forests and 17-26% for croplands (Monteith, 1973).

Where soils are visible through the vegetation reflectance is also dependent on soil spectral characteristics. Maximum reflectances are found over smooth, fine-grained, light-colored soils. Most dry soils exhibit a smooth, gradually increasing reflectance from the visible to reflective infrared wavelengths (Swain and Davis, 1978). Changes in spectral characteristics are primarily related to organic content, mineral composition and soil moisture. Reflectivity, particularly in the IR, will usually decrease with increases in these factors.

Longwave radiation is also absorbed, reemitted and reabsorbed within the canopy. Sutherland and Bartholic (1976) examined the effect of crop geometry on emissivities for crops. Crop geometry affects the total emissivity of areas sensed by aircraft or satellite radiometers because of differing amounts of soil and vegetation in the field of view of the sensor. The authors found that total emissivity was insensitive to crop geometry when crop height-to-spacing ratios were greater than 1, and therefore errors in radiometrically measured temperatures were small.

Kimes (1980; 1983) and Kimes et al. (1980) found that for row crops, the amount of soil visible through vegetation
influenced the measurement of canopy temperatures. Because soil temperatures are often much higher than vegetation temperatures, a composite temperature of an area may not accurately reflect true canopy temperature. Over a soybean canopy with a 35% ground cover, it was found that composite nadir temperatures differed by as much as 11 C from canopy temperatures. Ground temperatures for the same canopy were as much as 15 C higher than air temperatures (Kimes, 1980). High soil temperatures also contribute to steep vertical temperature gradients within the canopy, particularly when wind speeds are low (Kimes et al., 1980). These steep temperature gradients over bare soil occur because incoming solar radiation raises soil temperatures significantly over those of the overlying air.

The influence of irregular tree canopies on radiometer-derived imagery has been examined by Balick and Wilson (1980) and Fritschen et al. (1982). Balick and Wilson utilized high resolution imagery and temperature profile data for Alamos Canyon, New Mexico, to examine night canopy temperatures. Most notable in the imagery was that trees displayed significantly higher temperatures than the underlying bare ground. It was found that tree-crown temperature remained very close to that of the surrounding air, while being 3 to 5 C warmer than the ground. This is the inverse of the daytime situation of ground temperatures being warmer than canopy temperatures.
Terrain characteristics. Terrain characteristics important in determining surface temperatures include elevation, slope and proximity to large water bodies. Elevation and slope are important in controlling cold air drainage, particularly under stable winter nocturnal conditions. The relationship between decreasing temperature and increasing elevation in mountainous regions is well known, and must be corrected for in thermal modelling of ET or thermal inertia (Price, 1983a; 1985; Kahle, et. al, 1984).

Fritschen et al. (1982) investigated temperature characteristics of a forested valley in Washington using nighttime infrared imagery and found that forest structure and elevation as well as local meteorological conditions were responsible for observed temperature patterns. As in Balick and Wilson (1980), tree tops were found to be warmer than the underlying ground. In the Washington study cold air drainage was found to be the controlling factor in tree-crown temperature variations. Near the center of the valley where the cold air layer was thicker only tree tops protruded through the cold air and appeared warmer than the surrounding area. In elevated areas such as on small hills or valley slopes more of the tree extends above the cold air layer and is evident on the imagery. Additionally, areas with older, taller trees were highlighted on the imagery because they too were able to protrude through the cold air layer.
Mahrt and Heald (1983) found that terrain features were important in controlling surface temperatures even in areas of low relief. Using aircraft IR data over agricultural areas in eastern Colorado and western Oklahoma they found that terrain curvature as well as elevation was important in controlling surface temperature. It was suggested that large concave curvatures lead to more effective trapping of cold air than do convex curvatures. The effect of terrain variables on temperature was significant even during periods of relatively high windspeeds.

Location relative to water bodies is also important in controlling surface temperatures. The moderating influence of water bodies on temperatures is well known, and often taken advantage of by farmers in frost-prone areas. This moderating influence is caused by the large heat capacity of water bodies. Advection of moisture and heat downwind of large water bodies is important in influencing temperature patterns, particularly under cold weather conditions. Bill et al. (1977) examined the moderating influence of Lake Apopka, Florida on downwind surface temperatures under winter nocturnal conditions. With windspeeds less than 1 m/s no downwind influences were observed. Windspeeds on the order of 4 m/s lead to temperature increases as much as 5 °C over surrounding areas.
CHAPTER III
PREVIOUS INVESTIGATIONS USING THERMAL DATA

Urban Climate and Meteorological Studies

Growing recognition of the influence of urban areas on climate and meteorology, particularly on the radiation balance of urbanized areas, has led to the use of remotely sensed thermal data for studying urban climate. Remotely sensed information on reflected shortwave and emitted longwave radiation offers a number of advantages over ground level measurements of these phenomena. These advantages include the synoptic view and coverage of large areas by aircraft and satellite sensors as well as the spatial integration of surface temperatures within the sensor's field of view. Also valuable is the ability to use remotely sensed IR data along with meteorological data to calculate various surface characteristics such as thermal inertia, moisture availability and sensible heat loss.

The heat islands of a number of large cities have been examined using aircraft and satellite thermal data. Matson et al. (1978) utilized NOAA 5 satellite data (1.1 km resolution) to examine heat islands over fifty cities in the eastern United States. The authors found urban-rural temperature differences ranging from 2.6 to 6.5 C. A
detailed examination of St. Louis revealed that the highest temperatures were experienced in areas in which the greatest building density and industrialization were found. Temperatures were up to 3.1 °C higher in these areas than in the surrounding rural areas. Examination of Baltimore and Washington, D.C., showed that core areas displayed the highest temperatures, with differences from surrounding rural areas being as high as 5.2 °C. Several urban heat corridors corresponding to major traffic arteries were also visible in the area.

Price (1979) used higher resolution HCMM (0.6 km) data to detect urban-rural daytime temperature differences in the northeastern United States ranging from 16.5 °C for New York City to 6.8 °C for Montpelier, Vermont. The fact that these temperatures are much higher than those found by Matson et al. (1978) is partially because the HCMM imaging time is closer to the period of the day when surface heating is at a maximum, while the NOAA 5 sensor acquired mid-morning and early evening imagery when temperature differences are not at their peak.

More detailed investigations of urban heat islands using remotely sensed data have been carried out for the cities of Baltimore, Maryland, Los Angeles, California, and St. Louis, Missouri. Pease et al. (1976) utilized high resolution aircraft IR scanner data to study the urban area of Baltimore. The authors used isoline maps of surface albedo,
emitted IR energy, absorbed energy, net radiation and
temperature of the urban area along with numerical modeling
to determine the relative importance of surface moisture,
surface material thermal properties, surface aerodynamic
roughness and albedo in controlling the urban heat island.
Model results indicated that surface wetness variations in
the summer and absorption of radiation by vertical surfaces
in the winter were most responsible for modelled urban
temperature variations. Both modelling and remotely sensed
temperatures indicated that the urban heat island does not
display a monolithic nature, but instead consists of several
relatively warm and cool areas throughout the city.
Examination of the imagery showed that during the day
vegetated areas within the city were the coolest areas
(except for water surfaces), while commercial and industrial
land exhibited much higher temperatures. The higher
reflectivity of vegetated areas along with increased latent
heat exchanges appeared to be responsible for the lower
temperatures observed in these parts of the city.
Residential areas, because of their higher reflectance, also
were generally cooler than heavily built-up areas.

Carlson et al. (1981) examined the cities of Los Angeles
and St. Louis, using HCMM data as input into numerical
models to study the relationship between urban temperature
distributions and surface energy balance, moisture
availability and thermal inertia. As in other studies,
highest day temperatures were found over the most heavily industrialized or commercialized areas where vegetation cover was minimal. Vegetated areas, mostly because of ET potential, were the coolest areas (excepting water bodies) within the Los Angeles and St. Louis urban areas. Nighttime temperatures in Los Angeles displayed less contrast than did day temperatures. Areas close to the Pacific Ocean were generally cooler at night than areas 10-15 km inland, and a weak correspondence was found between areas that were warm in the day and those that were warm at night.

In both St. Louis and Los Angeles a strong correspondence between the moisture availability and temperature pattern was observed. Areas of high moisture availability were generally cooler during the day because more of the energy budget was partitioned as latent rather than sensible heat flux, resulting in lower radiant temperatures. The authors noted a striking lack of detail in the thermal inertia maps for St. Louis and Los Angeles. Thermal inertia has often been considered as one of the more important thermal properties responsible for the distribution of the nocturnal urban heat island. That this does not appear to be important in influencing Los Angeles and St. Louis heat island patterns appears to follow current thinking on the causes behind the formation of urban heat islands (Goward, 1981). Because thermal inertia did not appear to be important, Carlson et al. considered moisture availability
to be the most important factor in determining the distribution of urban temperature patterns.

On the basis of findings of Willis and Deardorff (1978) and Lamb (1978), Carlson and DiCristofaro (1981) proposed that satellite-derived heat flux maps be used to aid in modelling plume dispersion from industrial smokestacks. Willis and Deardorff (1978) and Lamb (1978) found that plume dispersal was related to boundary layer turbulence that in turn is related to surface heat flux. They found that the greater the turbulence, the more a plume is dispersed both horizontally and vertically, producing a smaller concentration downwind of the source. Carlson and DiCristofaro suggested that heat flux maps calculated from remotely sensed data would provide a good source of data for predicting plume concentrations and dispersal over a terrain with a complex heat flux pattern, as is normally found.

Vukovich (1983) utilized HCMM data to examine temperature and reflectivity patterns over St. Louis. As found elsewhere, the lowest temperatures were over water bodies, in the case of St. Louis, along the Mississippi River and Horseshoe Lake. Low temperatures were also evident in vegetated areas because of increased evapotranspiration over these surfaces. Highest temperatures were found in heavily built-up commercial or industrial districts, areas that also displayed low reflectances. It was also noted that day surface ground temperatures measured by the HCMM satellite
were more readily influenced by small scale land use patterns than were nighttime temperatures.

Agricultural Applications of Thermal Data

Satellite-derived thermal data have been utilized for a number of non-urban studies, particularly in agricultural regions. Thermal data have shown potential for use in mapping vegetation stress, soil moisture, ET and frost potential in agricultural regions. Important in most agricultural applications of IR data is the influence of surface and subsurface moisture on radiant temperature patterns. Water affects surface temperatures in two ways. First, moisture changes the thermal properties of a soil (i.e., heat capacity, thermal diffusivity, thermal inertia, and thermal conductivity). The changing of thermal properties of a material can be particularly influential in determining nighttime temperature patterns. For example, at night, wet soils will usually be warmer than their drier counterparts because of their higher thermal inertia. Second, surface water availability controls the amount of ET occurring at the surface. Over vegetated surfaces there is greater potential for increased ET when soil moisture is high, resulting in decreased temperatures as more energy is used in latent heat exchanges as opposed to radiative or sensible transfers.
Crop Moisture Stress

One of the most promising uses of thermal data is for the detection of moisture stress in crops. The availability of moisture to vegetation has been shown to be important in determining the surface temperature of crop canopies. The temperature of a plant leaf is controlled largely by latent heat releases during transpiration. As water availability decreases, leaves lose their turgidity and begin to wilt. To avoid dehydration, leaf stomata begin to close either partially or fully. As this closure of the stomata occurs, evaporative water losses decrease, as do latent heat exchanges, and sensible heat exchanges become more important in controlling leaf temperatures (Byrne et al., 1979; Sumayao et al., 1980; Keener and Kircher, 1983). The result is higher leaf temperatures for vegetation undergoing moisture depletion.

Pinter et al. (1979) established that midday radiant leaf temperatures of diseased cotton and sugarbeet plants were 3 to 5°C higher than those of adjacent healthy plants. Temperature increases were related to a root-rot disease that affected water uptake and therefore transpiration rates. These temperature differences were observable over a wide variety of soil moisture conditions, even when plants were wilting. Gardner et al. (1981) examined crop temperatures and their relationships to plant phenology and yield for a differentially irrigated corn crop. It was
revealed that optimal yield decreases with moisture stress, and therefore canopy temperatures could be used to aid in predicting crop yields. Additionally it was noted that after crop cover is complete crop temperature data could be used to monitor phenological development throughout the growing season.

Idso et al. (1977) outlined the potential for the use of thermal remote sensing for agricultural water management, soil moisture surveillance, evaporation measurement, crop yield prediction and irrigation scheduling. Soil moisture was found to be correlated with midafternoon-presunrise canopy temperature differences for a number of different crops. An empirically-based equation for calculating 24-hour evaporation using incoming and outgoing thermal radiation was developed and found to be useful for a wide variety of soil and crop types. Using a combination of a moisture stress index termed the stress degree day (SSD) along with the standard growing degree day (GDD), it was discovered that grain yields could be predicted for a variety of moisture stress conditions. The combination of the SSD and GDD measurements could also be used to aid in efficient irrigation scheduling.

Paloscoia and Pampaloni (1984) examined the use of surface temperatures of corn and wheat crops derived from measurements of emitted microwave EMR. The authors found that microwave-derived temperatures could be used in two
ways to evaluate crop moisture stress. The first method used a normalized microwave radiometer-measured temperature along with the air vapor pressure deficit to calculate a moisture stress index. The second utilized the difference between vertical and horizontal components of the emitted microwave radiation to define a polarization index. Both methods proved to be sensitive to moisture stress in crops.

**Evapotranspiration**

The measurement of ET rates is important in water budget studies, particularly for irrigated cropland. Because of the difficulty in obtaining regional estimates of ET rates using standard in situ methods, there have been several attempts to apply remotely sensed thermal data to this problem.

Heilman et al. (1976) used crop temperatures obtained from aircraft scanner IR data in energy balance equations to estimate ET rates over soybean, sorghum and millet crops. Latent heat exchanges derived from the aircraft data were between 62.5% and -43.6% of lysimeter-derived measurements. A primary cause of differences between modeled and lysimeter-derived measurements was in errors in the measurement of remotely-sensed surface temperature because of atmospheric effects.

Soer (1980) used aircraft IR scanner and meteorological data as input into energy balance and aerodynamic equations
to estimate regional ET over grasslands in the Netherlands. Momentary ET calculated from satellite data and meteorological parameters was compared with modelled 24-hour ET to relate daily to momentary ET over the study area. Estimates of ET obtained using remote sensing techniques were within 30% of measurements made using water balance estimates in the study area. The accuracy of calculating ET was mainly dependent on obtaining accurate crop surface temperatures and emissivities, and on using accurate surface roughness coefficients in the aerodynamic equations.

Price (1980; 1983a) discussed the physical basis behind the modelling of ET using HCMM data and derived equations for obtaining a 24-hour average using day-night paired temperature images and meteorological data. Flux rates calculated using HCMM data covering a southwest Idaho study area produced results comparable to those obtained by numerical simulations. It was established that farmed areas exhibited a high variability in evaporative flux, most likely because of the mixture of irrigated and non-irrigated land in the region.

Reginato et al. (1985) demonstrated that in areas where screen-height air temperature, incoming solar radiation, windspeed and vapor pressure data are collected, it should be possible to calculate ET rates on a field-by-field basis using aircraft scanner data. Comparisons of the remotely sensed ET measurements with those obtained using lysimeters
showed a high correlation (r=0.9) between the two methods. The ability to extend ET measurements over large areas was found to be dependent on clear sky conditions and the ability to accurately extrapolate wind speed and air temperature measurements beyond the locality of the meteorological station.

Klaassen and van den Berg (1985) used an energy balance method for calculating ET over grasslands in the Netherlands using NOAA Advanced Very High Resolution Radiometer (AVHRR) data. A split-window technique to correct for atmospheric attenuation that is commonly used to derive sea-surface temperatures was used to calculate radiant surface temperatures. ET measurement inaccuracies were found to be related mainly to inaccurate windspeed and air temperature measurements. To avoid these problems air temperature and wind speed at the 50 m level were modeled. This provided better predictions of mesoscale windspeed and temperature by avoiding the near-surface atmospheric layer where complex surface energy and momentum fluxes dominate. The models allowed calculations of ET that were on the average of 7 W/m² less than surface observations and with RMS errors of 34 W/m², a result that is within the range of surface measurement inaccuracies of ET. These results indicate that satellite-derived ET fluxes can be used not only to find ET differences but to calculate actual ET rates.
Soil Moisture

Differences in the thermal characteristics of wet versus dry soils provide a means for mapping soil moisture using temperatures obtained from passive microwave or IR sensors (Idso et al., 1975; Schmugge, 1978). The large heat capacity and thermal conductivity of water mean that moist soils will have higher thermal inertias than will dry soils. These differences are detectable by the use of remotely sensed diurnal temperature measurements, particularly when there is minimal vegetative cover (Price, 1977; Kahle, 1977; Pratt and Ellyett, 1979; Price, 1985).

Schmugge et al., (1977) discovered that coarse resolution (25 km) Nimbus-5 microwave radiometer data are sensitive to near-surface soil moisture. Examination of agricultural regions in Illinois, Indiana, Texas and Oklahoma showed that an inverse relationship exists between soil moisture expressed as percent field capacity and satellite brightness temperature. These relationships hold true only under conditions of minimal ground cover, because vegetation absorbs most of the emitted microwave EMR.

Heilman and Moore (1980) examined relationships between surface temperatures derived from hand-held and aircraft radiometers and soil moisture. Soil water content correlated highly ($r=0.9$) with day-night temperature differences measured using a hand-held radiometer with percent covers from 30-90%. Aircraft scanner data were used
with equations derived from hand-held radiometers to test the potential for inferring soil moisture over wider areas. Maximum differences between predicted and observed soil moisture (measured as percent of field capacity rather than soil water content) were -24.5% and 5.3%, with the average being 1.6% for a wide variety of soil types. Maximum errors occurred where high-percent ground covers existed because soil temperature measurements were less accurate over these areas.

Heilman and Moore (1982a; 1982b) used HCMM data to estimate soil moisture and depth to groundwater in southeastern South Dakota. Surface temperatures, after correction for variations in percent vegetative cover, correlated well with percent of field capacity. Correlations between HCMM-derived surface temperatures and depth to groundwater were made using 5 dates from June to September, with highest correlations found using the September data. It was noted that, since correlations between surface temperature and both groundwater and soil moisture were high, it was not possible to separate the influences of the two different factors.

The thermal structure of an agricultural region in the Beauce Plateau in France was examined by Cheevasuvit et al. (1985) using NOAA polar orbiter thermal data. In this region the thermal structure was divided into at least three distinct sections. Regions of homogeneous temperature
correlated well with regions of equal soil water status, indicating that the thermal structure of a region can provide an indication of moisture status on a regional scale.

**Cold-Prone Area Mapping**

Satellite-derived IR data have been used to examine nocturnal temperature patterns over agricultural regions to determine areas that are particularly prone to cold weather damage. Chen et al. (1983) established that under clear skies, winter nocturnal temperatures measured by GOES were highly correlated \((r>0.80)\) with shelter-height temperatures. Maximum differences between satellite-derived and shelter-height temperatures were greatest in the early evening and decreased as the night progressed, with satellite temperatures being consistently lower.

Chen et al. (1979) examined nocturnal temperature patterns over the Everglades agricultural area south of Lake Okeechobee in Florida using GOES IR data. Satellite temperatures were generally equal to shelter-height temperatures or lower by about 1.2°C. The warming influence of Lake Okeechobee was evidenced by the fact that for a one-pixel distance around the lake temperatures remained above freezing while surrounding areas did not. That the agricultural area was colder than surrounding areas was attributed primarily to the strong radiative cooling of the
drained organic soils in the region. These soils also exhibit higher emissivities than sandy soils, and therefore should release energy at higher rates.

Chen et al. (1982) examined the influences of soils and water on cold-prone areas in peninsular Florida using nighttime GOES data. Coldest areas were most often found in regions of low soil moisture content. These areas were generally areas of well drained to excessively drained sandy soils along the Central Florida Ridge. Warmer sites were usually in wetter areas dominated by lakes, swamps or poorly drained soils. The influence of moisture on surface temperatures was particularly evident on one night, when the northern part of the state exhibited higher temperatures than did the southern end of the state because of frontal rainfall in the north.

Allen et al. (1983) compared HCMM and GOES data for mapping surface temperatures, and used HCMM apparent thermal inertia (ATI) imagery to predict nocturnal cold-prone areas in peninsular Florida. The greater resolution of the HCMM data (0.6 by 0.6 km) as opposed to the GOES (6 by 8 km) proved to be useful in providing a more detailed picture of surface temperature distributions in the peninsula. HCMM data were however limited for operational use by the relative infrequency of the satellite's repeat cycle. HCMM ATI imagery corresponded well with the general soils map of the state. Areas containing well drained, sandy soils
exhibited higher thermal inertias than did less well drained areas, and likewise these areas tended to be have the lowest temperatures at night.

Regional frost mapping in Southern Victoria, Australia, was attempted using HCMM data by Kalma et al. (1983). Five winter images were obtained under conditions of low wind speed and cloud cover. It was determined that realistic distributions of temperature could be obtained from the HCMM data, with lowest nighttime temperatures found in narrow valleys, basins and depressions, and over fallow lands, pastures and orchards. Higher temperatures were observed over urban and built-up areas, forested areas, water bodies and swampy areas. The authors concluded that HCMM data did not have sufficient spatial resolution to be useful for local frost mapping, though future systems with higher resolutions would be useful.

Geologic Applications of Thermal Data

IR data have been widely used by geologists for mineral exploration, geologic mapping, structural mapping and geomorphology. The primary use of thermal data is in the calculation of thermal inertia and temperature-difference images, or as single-date imagery. The resulting images are then interpreted manually. Several models have been developed for calculating thermal inertia using as input diurnal radiative temperatures, albedo and surface
meteorological parameters, but these models are generally applicable only to areas where there is little or no vegetation cover or evaporating water and therefore will not be discussed here (Price, 1977; Kahle, 1977; Pratt and Ellyett, 1979; Kahle et al., 1984; Price, 1985).

Single-date IR imagery has shown potential for detecting mineralogical and chemical differences because of the differing emissivities of various surface materials (Goetz and Rowan, 1981). Lyon (1972) used an aircraft-mounted non-imaging infrared spectrometer to show that mineralogical and chemical differences on the surface can be detected using IR data. Vincent and Thomson (1972) likewise demonstrated that rock types could be discriminated using ratios of the IR radiance from two thermal bands. Abrams et al. (1984) demonstrated that color composite images produced using the HCMM day visible-reflected infrared and day and night IR data were valuable aids for geologic mapping.

The primary difficulty in discriminating rock types and mineralogy using remotely sensed data is that the surface should be largely unobscured by vegetation to obtain good spectral signatures. In areas where vegetation cover is found, thermal data are useful for structural and geomorphic mapping. Sabins (1969) evaluated the usefulness of IR imagery for structural mapping in southern California. The area was arid, with most of the vegetation being found in irrigated fields. When compared to standard panchromatic
aerial photographs of the area, the IR imagery displayed the greater contrast of the two forms of data, a fact attributed to greater nighttime thermal emissivity variations than daytime visible reflectance variations. The utility of the IR imagery to structural mapping was demonstrated by the fact that anticlines not visible in the photographs could be recognized because of alternating beds of warm sandstones and cool siltstones.

Structural mapping of the Front Range and adjacent plains in Colorado was carried out by Offield (1975) using aircraft IR scanner data. Several circular and linear topographic features in the Front Range were clearly visible on the thermal data, often more so than on visible photography. The visibility of these topographic features is caused by thermal shading (temperature contrasts) related to cumulative heating effects between dawn and the imaging time. In the plains areas, temperature contrasts were best displayed in the pre-sunrise imagery and were related to varying agricultural practices, drainage patterns and moisture patterns along structural features.

Though Sabins (1969) and Offield (1975) used high resolution aircraft scanner data for structural mapping, the potential of coarser resolution satellite IR data has been demonstrated by Schneider et al. (1979). Enhanced nighttime NOAA AVHRR data were used to study the regional geomorphology of an area covering North and South Dakota and
parts of Minnesota, Montana and Wyoming. Visible in the imagery were the Missouri Escarpment, Coteau des Prairies, several rivers and recessional moraines. The authors considered moisture variations to be the most important factor in determining temperature differences. North facing slopes receive less incoming sunlight than do south facing slopes and therefore retain moisture longer. This moisture in turn increases the thermal inertia of materials on the northern slopes, leading to a shaded-relief effect. Elevation was also an important determining factor in temperature. Topographic profiles and corresponding temperature profiles displayed high negative correlations, with major escarpments and valleys being clearly visible.

**Land Cover Mapping**

Thermal infrared data collected by satellite and aircraft scanners can be used as input into pattern recognition algorithms for land cover mapping. Thermal data potentially offer additional information when combined with the normally used visible and reflective infrared data, and may result in classification accuracy increases. Though current uses of thermal data for land cover classification are limited by poor spatial or radiometric resolution or by spatial resolution differing from simultaneously collected visible and reflected infrared data, a few attempts to utilize thermal data in classification schemes have been carried out.
Ormsby (1982) found that inclusion of the Landsat 3 IR band along with MSS4, 5, 6 and 7 improved classification accuracies. IR data were particularly useful for aiding in differentiating between urban and bare ground classes. Price (1981) used principal component analysis to show that additional information is provided by the Landsat MSS IR data. Price however urged caution in the use of IR data for multispectral classification because of its dependency on slope, aspect and the thermal characteristics of the surface. These dependencies may vary within as well as between land covers and therefore may lead to spurious classification results.

Byrne et al., (1981) found that HCMM visible and near infrared and IR data could be used to monitor intermittently flooding marshes in Australia. HCMM data were used to map free water, woodland, damp grass and soil and dry areas. The authors proposed that thermal data could be used to monitor intermittently flooded marshlands because of the sensitivity of the thermal band to moisture changes.
CHAPTER IV
STUDY AREA AND METHODOLOGY

Study Area

The area examined in this study includes approximately 45,600 km² of north-central peninsular Florida (Fig. 1) and was selected because of the wide variety of natural and cultural land covers found within its boundaries. The largest urban areas within the region include Jacksonville, St. Augustine, Daytona Beach, Palatka, Starke, Lake City and Gainesville. The other main cultural land covers include a phosphate mining operation near White Springs, two heavy mineral mines to the east of Starke and extensive agricultural regions in the western portion of the study area and in the Hastings area east of the St. Johns River. The remainder of the study area consists primarily of disturbed and undisturbed woodlands.
Figure 1: Study area.
Soils and Vegetation

Three major soil groups are found within the study area, the North Florida Flatwoods, Central Florida Ridge and Central and South Florida Flatwoods Soils (Table 1 and Fig. 2). North Flatwoods soils are primarily poorly drained spodosols and entisols. Central Florida Ridge soils include entisols, ultisols and alfisols, and are generally well to excessively drained, with the exception of the Eureka-Emeralda-Terra Ceia association found in Alachua and Marion counties. The Central and South Florida Flatwoods soils are primarily histosols and entisols. Most of these associations are poorly drained except for the coastal sands.

A wide variety of vegetation communities typical of northern Florida are found within the study area (Fig. 3). The dominant vegetation community in the region is pine flatwoods. This community consists of longleaf, slash and pond pines with an undergrowth of herbs, palmetto, shrubs and small trees. Many flatwoods contain small hardwood forests, prairies, swamps and cypress in poorly drained areas. Longleaf pine-turkey oak forests are common on well drained uplands. Undergrowth is often minimal, consisting primarily of wire grass. The excessively well drained areas of the Ocala National Forest contain sand pine communities. Old dunefields in Marion and Levy County are also covered by this community. Mixed hardwood forests are found in Levy
TABLE 1

North-central Florida soils.

Soils of the North Florida Flatwoods

<table>
<thead>
<tr>
<th>No.</th>
<th>Association</th>
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<tr>
<td>6</td>
<td>Centenary-Leon-Plummer Association</td>
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<td>7</td>
<td>Chipley-Kureb-Lakeland Association</td>
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<tr>
<td>8</td>
<td>Coastal Beach and Dunes Association</td>
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<td>9</td>
<td>Coxville-Ocilla-Portsmouth Association</td>
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<td>10</td>
<td>Ichetucknee-Chaires-Chiefland Association</td>
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<td>11</td>
<td>Leon-Pelham-Mascotte Association</td>
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<tr>
<td>12</td>
<td>Plummer-Rutledge Association</td>
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<tr>
<td>13</td>
<td>Tidal Marsh and Tidal Swamp Association</td>
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Soils of the Central Florida Ridge

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<td>Arredondo-Kendrick-Millhopper Association</td>
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<td>17</td>
<td>Astatula Association</td>
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<td>18</td>
<td>Blanton-Susquehanna-Fuquay Association</td>
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<td>19</td>
<td>Blichton-Flemington-Kanapaha Association</td>
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<tr>
<td>20</td>
<td>Candler-Apopka-Astatula</td>
</tr>
<tr>
<td>21</td>
<td>Eureka-Emeralda-Terra Ceia Association</td>
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<tr>
<td>22</td>
<td>Jonesville-Pedro Association</td>
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</table>

Soils of the Central and South Florida Flatwoods

<table>
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<td>Coastal and Beach Dunes Association</td>
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<td>26</td>
<td>Istokpoga-Samsula Association</td>
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<tr>
<td>32</td>
<td>Paola-St. Lucie-Daytona Association</td>
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<td>34</td>
<td>Pomona-Wauchula-Placid Association</td>
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<td>35</td>
<td>Riviera-Winder Association</td>
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<td>36</td>
<td>Tidal Marsh and Tidal Swamp Association</td>
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<tr>
<td>37</td>
<td>Wabasso-Felda-Pompano Association</td>
</tr>
</tbody>
</table>

See Figure 2 for accompanying map.
Figure 2: North-central Florida soils. After Caldwell and Johnson, 1982.
LEGEND

1 COASTAL STRAND
2 PINE FLATWOODS
3 SAND PINE
4 LONGLEAF PINE - TURKEY OAK
5 CYPRESS
6 SWAMP FOREST
7 MANGROVE & COASTAL MARSH
8 MIXED HARDWOOD FOREST
9 FRESH WATER MARSH

Figure 3: Vegetation of north-central Florida.
After Davis, 1980.
and western Alachua and Marion counties. These forests are mostly located on uplands with clayey soils and contain oaks, magnolias, hickories, sweetgums and maples.

Swamp forests are found along the St. Johns, Suwanee, Oklawaha and Santa Fe rivers. Maple, bay, cypress and gum trees are common in swamp forest communities. Fresh water marshes are located in some of the lower, poorly drained areas. Mangrove swamp forests and coastal marshes are common along the Gulf coast in saline or brackish waters. Smaller extents of this community are found along the east coast inland waterway from Daytona to Jacksonville. The east coast barrier islands are dominated by coastal strand vegetation. These communities usually consist of pioneering grasses and shrubs near the shore with forests increasing towards the lagoon side of the barriers.

Physiography

The physiography of the region is quite diverse, primarily being controlled by solution of the limestone bedrock and by the presence of Plio-Pleistocene shoreline features. This region has been described and mapped in some detail by several authors, most notably White (1958; 1970) and Brooks (1981b) (Fig. 4). The following descriptions are taken primarily from a physiographic map and accompanying pamphlet by Brooks (1981b). More detailed information on the physiography and geology of the region can be found in
Cooke (1945); Pirkle (1956); Puri (1957); Pirkle et al. (1963); Bermes et al. (1963); Clark et al. (1964); Pirkle et al. (1965); Williams et al. (1977). The study area includes four physiographic regions of the state, the Sea Island District in the northeast, the Ocala Uplift District in the west, the Central Lake District in the center-south, and the Eastern Flatwoods District in the east (Fig. 4). In the following discussion the numbers and letters in parentheses refer to the sections found on the physiographic map.

Sea Island District. The Sea Island District is divided into three subsections. The Okefenokee Upland is an undissected upland with poorly organized drainage. Included in this subsection is the Okefenokee Basin (1a), with elevations ranging from 36 to 46 m. Vegetation in this subsection is primarily marsh and cypress, grading into poorly drained flatwoods. Two subsections are dominated by two depositional marine features, the Lake City Ridge (1b) and Trail Ridge (1c). Elevations on the Lake City Ridge reach 62 m, and the primary vegetation community is pine flatwoods. Trail Ridge is one of the more notable physiographic features found in northern Florida, being a relict barrier with elevations from 46 m to a maximum of 73 m in the uplifted southern portion. Pine flatwoods are common on the northern parts of the ridge, and longleaf pine-turkey oak and sand pine are found on the southern end of the ridge. The remaining area of the Okefenokee
Figure 4: Physiographic divisions of north-central Florida. After Brooks, 1981b.
subsection is the High Flatwoods (1d), and consists of a poorly drained area with elevations between 43 and 58 m. The vegetation consists mainly of pine flatwoods and extensive areas of riverine swamps.

The second subsection of the Sea Island District is the Duval Upland and includes the St. Mary’s Upland (2a), Black Creek Basin (2b) and Penney Farms Upland (2c). This area has elevations generally between 8 and 30 m and includes several subdued paleo-beach ridges and marine terraces. Vegetation communities include pine flatwoods on poorly drained marine terraces, swamps along river basins and longleaf pine-turkey oak communities in the better drained southern sand hills.

The third subsection is the Northern Coastal Strip (3a-3g). This area is primarily the result of Pleistocene and Holocene sea level fluctuations, with most elevations being below 10 m, though some beach ridges can reach as high as 22 m. Numerous beach ridges and dune fields are found within this subsection. Vegetation communities include salt water marsh, pine flatwoods, and longleaf pine-turkey oak.

Ocala Uplift District. The western portion of the study area falls within the Ocala Uplift District. The region is one in which Tertiary limestones are at or near the surface and solution is a dominating force in shaping landforms. The Big Bend Karst subsection is a low-relief surface generally less than 6 m in elevation. Dune fields are found
in the Keaton Beach Coastal Strip (5b4) and longleaf pine-turkey oak communities are dominant in this area. Horseshoe Beach Coastal Strip (5b5) is a low limestone plain with very swampy pine flatwoods. The Cedar Keys Coastal Strip (5b6) contains a number of drowned relic dunes, with a maximum elevation of 16 m found on one dune. The Waccasassa Coastal Strip (5b7) is another low limestone plain vegetated with hardwood forest and mixed flatwoods and swamps.

Inland of the coastal strip lies an area of poorly drained terraces including the Waccasassa Flats (5c4), Mallory Swamp (5c2) and San Pedro Bay (5c1). Elevations range from 30 m in the north to below 17 m in the southern Waccasassa Flats. Vegetation communities include pine flatwoods in the Waccasassa Flats and grade into swamps and low pine flatwoods in San Pedro Bay and Mallory Swamp. Proceeding further inland one encounters the Suwannee River Valley subdistrict. The Upper section (5d1) is a youthful valley characterized by high bluffs, rock shoals and rapids. The Lower section (5d2) displays less relief and is characterized by swamp forest bordered by well drained plains.

The Northern Peninsula Plains (5e1-5e4) are found inland of the Suwannee River Valley and are karst plains generally between 18 and 30 m elevation. Vegetation types include pine flatwoods, mesic hammock and freshwater marsh. Notable in the southern part of this region are several prairies and
lakes resulting from solution of the limestone bedrock at the water table. Examples are Paynes, Sanchez and Levy Prairies, and Orange Lake and Lochloosa Lake. The Wellborn Uplands (5f1-5f3) are the westward dissected extremity of the Lake City Ridge. Maximum elevations here exceed 70 m.

Bordering the Sea Island District are the Northern Peninsula Slopes (5g1-5g4). This area is a transitional zone from the plateau region to the east and includes numerous karst features. Vegetation communities include mesic hammock and pine forests, with longleaf pine-turkey oak found in the better drained areas. Overall this area is well drained via surface or subsurface streams or sinks, and elevations vary from 60 m at the eastern edge to lows of 27 m in karst depressions. Included in this subsection are Newnans Lake and San Felasco Hammock.

The east-central portion of the Ocala Uplift district includes the Marion Hills subsection (5h1-5h5). The area is characterized by hill systems ranging from 24 to over 60 m in elevation. Karst landforms are also common within this subsection. Areas of sandy soils support longleaf pine-turkey oak communities, while hardwood forests are found elsewhere, particularly in the Fairfield Hills region east of Orange Lake. The Oklawaha Valley (5i) is characterized by river swamp bordered by poorly drained flatwoods. The Newberry Sand Hills (5j) are dominated by a large forest of longleaf pine-turkey oak forests with elevations mostly between 24 and 45 m.
Central Lake District. The Central Lakes District is an area of active sinkhole development that is part of the central Florida ridge system. The northern part is an area of perched lakes and prairies and includes Lake Santa Fe (4a). Vegetation primarily consists of pine flatwoods and swamp forest in this part of the District. The Interlachen Sand Hills (4b) region is located to the east of Lake Santa Fe in Putnam and Bradford counties. Elevations here reach 67 m, and numerous sinkhole lakes are present. The primary vegetation community in this well-drained region is longleaf pine-turkey oak.

South of the Interlachen area is the St. Johns Offset (4c). The St. Johns River jogs to the west here, and numerous springs are found in this area, as well as Lake George, the largest lake in northern Florida. The primary vegetation communities include pine flatwoods and river swamp forest with many cabbage palms. West of the St. Johns Offset is the Ocala Scrub (4d), much of which is within the Ocala National Forest. The area is a paleo-dune field covered by sand pine, longleaf pine and turkey oak. Elevations in the Ocala Scrub range from 50 m in the west to 25 m in the east. The Crescent City-Deland Ridge (4d) is an area of sand hills between Lake George and Crescent Lake.

Eastern Flatwoods District. The eastern coastal side of the study area falls within the Eastern Flatwoods District. Bordering the St. Johns River valley is the Palatka
Anomalies (1a1-1a6) subsection. This area is characterized by limestone solution, stream diversion and possible faulting. Elevations throughout this subsection are generally below 12 m, except in the area of the Palatka Relic Hills, where heights of 26 m are found. The primary vegetation communities are pine flatwoods and swamp forest.

East of the city of St. Augustine is found the St. Augustine Ridge Sets subsection (1b). Elevations are between 9 and 15 m, and the area is characterized by a series of barrier island deposits. The subdued ridges in the area are covered with pine flatwoods, and cypress is found in the intervening swales. To the south of the St. Augustine Ridge Sets lies the Volusia Ridge Sets subsection (1c). This subsection includes four distinct parts: the Talbot Terrace at about 12 m, an eastern boundary ridge at about 14 m, the Pamlico Terrace at about 8-10 m and the Atlantic Coastal Ridge with maximum elevations of 17 m. Several sets of beach ridges are found on the terraces and the vegetation primarily consists of pine flatwoods.

The Atlantic coast is included in the Central Atlantic Coastal Strip (1e1). The principal feature in the subsection is a coquina ridge forming the major portion of the barrier island along the coast. Inside of this barrier island is a lagoon system that is increasingly vegetated by salt water marshes as one travels north.
Data

This study uses data obtained from two satellite-based sensor systems, the Heat Capacity Mapping Mission (HCMM) radiometer and the Landsat Multispectral Scanner (MSS).

Heat Capacity Mapping Mission

HCMM data were selected for this study because of the closeness of the satellite's overpass to times of maximum and minimum surface temperatures and their increased resolution as compared to NOAA AHVRR or GOES data. The HCMM satellite was the first of a planned series of Applications Explorer Mission satellites to be placed in orbit. The satellite collected data from its April 26, 1978 launch until failure in September of 1980. The HCMM satellite was intended to provide data for the study of thermal properties of the earth's surface, and as such it carried instruments for measuring reflectivity in the visible and reflective infrared wavelengths (DAYVIS band) and for measuring emitted IR (Table 2). The IR channel had a NETD of 0.4 K at 280 K. The instantaneous field of view for the DAYVIS band was 500 m at nadir, and for the IR band it was 600 m at nadir, though both were resampled during ground processing to 481.5-m cells. The satellite orbit was designed to allow for day and night coverage of an area with 12-or-36-hour separation (depending on latitude) with mid-latitude imaging times of about 0230 and 1330 Local Sun Time (LST). The
orbit allowed for repeat coverage over an area every 16 days, though overlapping passes can reduce this time in some instances. Types of data collected by or derived from the HCMM satellite include day and night infrared radiances and surface temperatures, temperature difference and reflectivity images, and apparent thermal inertia images. These data are available in image and/or digital form (HCMM, 1980).

<table>
<thead>
<tr>
<th>TABLE 2</th>
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<tr>
<td>Sensor characteristics.</td>
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<table>
<thead>
<tr>
<th></th>
<th>HCMN</th>
<th>MSS</th>
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<tbody>
<tr>
<td>Band</td>
<td>Bandwidth</td>
<td>Band</td>
</tr>
<tr>
<td></td>
<td>(micrometers)</td>
<td>(micrometers)</td>
</tr>
<tr>
<td>DAYVIS</td>
<td>0.55 - 1.1</td>
<td>MSS4</td>
</tr>
<tr>
<td>IR</td>
<td>10.50 - 12.5</td>
<td>MSS5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MSS6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MSS7</td>
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Calibration problems with the HCMM thermal radiometer were noted after launch, and it was decided on the basis of ground measurements that satellite temperatures were 5.2 K too warm (Barnes and Price, 1980). As a result of this finding, all HCMM data processed after June 1978 had 5.2 K subtracted from them. Vukovich (1984) suggested that after June 1978 the satellite calibration was corrected and that
data from July 1978 to at least September 1979 were 5.2 K too low. Vukovich did find that calibrated and atmospherically corrected HCMM data were within 1 K of ground-measured surface temperatures.

Landsat MSS

The Landsat MSS has been in operation onboard five different satellites since 1972. The primary purpose of the Landsat satellites is to supply data for the study of geologic, hydrologic, vegetative and cultural features on the earth's surface. This system measures reflected visible and infrared radiation in four spectral bands (hereafter referred to as MSS4, MSS5, MSS6 and MSS7) between 0.5 and 1.1 micrometer wavelengths (Table 2). Additionally, Landsat 3 contained an IR band, though the data provided by this sensor were of poor quality. The instantaneous field of view of the sensor is 79 by 79 m, but because of the sampling rate of the sensor and processing of the data done on the ground, the area represented by each pixel is 56 by 79 m. Each MSS scene covers an area on the surface of the earth approximately 185 by 185 km, and every area between 82 north and south latitude was covered every 9 or 18 days depending on the number of satellites in operation at a time for Landsats 1, 2 and 3. The imaging time was at approximately 0930 LST so as to maximize topographic shadowing for geologic purposes and to minimize afternoon
convective cloud cover. These data are available in either digital or photographic image formats.

The satellite data used in this study are all in digital form (Table 3). The HCMM data sets were chosen to provide a representation of seasonal and day-night temperature variations. Unfortunately, because of cloud coverage no summer daytime HCMM data were available and many of the nighttime images were of reduced quality, as will be discussed in Chapter 5. The Landsat MSS data were collected on November 5, 1978, and corresponded to HCMM data collected on the same day.
TABLE 3
HCMM and Landsat data.

<table>
<thead>
<tr>
<th>Data</th>
<th>Date</th>
<th>Scene Id.</th>
</tr>
</thead>
<tbody>
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<td>AA193-185-201,2</td>
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<tr>
<td>HCMM</td>
<td>12-17-78</td>
<td>AA235-183-611,2</td>
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<tr>
<td>HCMM</td>
<td>03-28-79</td>
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<td>HCMM</td>
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<td>AA191-072-703</td>
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<td>02-01-79</td>
<td>AA281-070-603</td>
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<tr>
<td>Landsat MSS</td>
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<td>30245-15230</td>
</tr>
</tbody>
</table>
Meteorological and Ancillary Data

Atmospheric sounding data for dates corresponding to the HCMM imagery were obtained from the National Climatic Center at Asheville, North Carolina. These data were used as input into a radiative transfer model for correcting satellite-derived temperatures for atmospheric attenuation. Meteorological conditions on the imaging dates were obtained from National Oceanographic and Atmospheric Administration (NOAA) daily and three-hourly weather data and from 0700 surface weather maps. Remotely-sensed data used for land cover identification included 1983 and 1984 National High Altitude Mapping Program (NHAP) false color transparencies at 1:58,000 scale, black and white aerial photographs obtained between 1974 and 1979, Landsat MSS data collected in April of 1973 and 1974 and December 18, 1982 1:500,000 Landsat Thematic Mapper (TM) imagery. Additional data sources include soils, vegetation and physiographic maps and field inspections.

Image Processing and Analysis

The processing and analysis of the data can be divided into three stages: geometric correction, generation of output for interpretation and image interpretation. These steps will be discussed separately below.
Geometric Correction Procedures

All digital image processing was done using the Earth Resources Laboratory Applications Software (ELAS) at the University of Florida and Institute of Food and Agricultural Sciences Remote Sensing and Image Processing Laboratory and the IBM 7350 system running the High Level Image Processing System (HLIPS) software at the Northeast Regional Data Center. The ELAS modules used here are designated by their four letter acronyms and are described in the ELAS Users Guide (Graham et al., 1984).

The Landsat MSS data were used to provide information on land covers within the study area that could be then related to temperature variations as measured by the HCMM IR data. Several preprocessing steps were required before such information could be obtained from the satellite data.

Landsat MSS data are collected by a series of 24 detectors, 6 for each band, and because calibration differences occur between the detectors a striping effect is sometimes observed in the data. To correct for this calibration problem a destriping procedure (DSTB and DSTR) was used to minimize this detector variability. The MSS4 data contained a large number of missing scanlines and were therefore excluded from any further analyses.

As with all satellite imagery, platform instability and sensor characteristics produce geometric inaccuracies in the data. These inaccuracies were corrected by mapping the
satellite data to the Universal Transverse Mercator (UTM) projection. This mapping procedure involved selecting points in the satellite data and corresponding UTM coordinates from 1:24,000 quadrangle sheets. Such points were usually road intersections or small lakes. From these points a least squares technique was used to calculate a piece-wise linear mapping function that allowed Landsat data to be mapped to the UTM coordinate system. Fifty control points were selected from a 1865-pixel-by-1585 line Landsat subscene covering the central portion of the study area. These points were used to calculate a mapping function (OGCN) with a RMS error of 51 m, indicating that the corrected pixel locations are within 51 m of their actual UTM coordinates. A bilinear interpolation procedure was then used to resample the pixels from the original 56-by-79 m size to 79-by-79 m and to map the data to the UTM projection (OGEO).

The HCMM subscene, which is 512 pixels by 384 lines, was also geometrically transformed to the UTM coordinate system. It was first necessary to register the November 5, 1978 HCMM data to the corrected Landsat data of the same date to allow comparison of the two data sets. This registration was accomplished by first subdividing the 481.5-m HCMM pixels so they were approximately the same size as the corrected Landsat pixels. Next, 48 matching control points were chosen in each of the two images and a third-order
polynomial mapping function with a 137-m RMS error was calculated using the HLIPS registration procedure. The HCMM data were then registered to the Landsat MSS data using a cubic convolution interpolation algorithm. After completion of the registration procedure a counterclockwise skewing of approximately 7° of the resampled HCMM data was noted. This skewing did not notably affect the analysis of the imagery.

Since only the November 5, 1978 HCMM data were compared directly to the Landsat MSS data, the following approach was chosen for registering the remaining HCMM images to UTM coordinates and to each other. The non-subdivided November 5, 1978 data were chosen as the base map and registered to the UTM coordinate system using 51 control points found on 1:250,000 topographic maps. A linear mapping function with a 283-m RMS error was calculated, and bilinear interpolation was used to resample the data to the UTM projection (PMGC, PMGE). The remaining HCMM data sets were then overlayed to the corrected November 5, 1978 data (OCON, OVLA).

Though all HCMM data sets were overlayed using mapping functions with sub-pixel accuracy, visual inspection of the imagery showed that some areas were misregistered by one or two pixels. This misregistration was on the order of that obtained by Watson et al. (1982), and was caused by the difficulty in finding adequate control points in certain portions of the imagery. Fortunately most misregistered areas were not within the primary area of interest and therefore did not pose a serious problem for image analysis.
Production of Output for Interpretation

Several types of data display techniques were used for image interpretation in this study. These are discussed below and include overlaid Landsat MSS and HCMM images, isotherm and color-coded temperature maps and enhanced greyscale images.

Overlaid Landsat MSS and HCMM images. Overlaid Landsat MSS and HCMM images were used in conjunction with air photos to aid in relating individual HCMM pixels to specific land covers. Because the study area was larger than available digital Landsat MSS data, overlaid HCMM-Landsat data were only used over the central portion of the study area. Two methods of displaying the co-registered Landsat MSS-HCMM IR data were tested, contrast-stretched red-green-blue images (RGB) and intensity-hue-saturation images (IHS). RGB images are simply made by displaying three different image bands using the red, green and blue guns of the color output device. In an IHS display three bands are displayed as intensity (brightness), hue (color) and saturation (color purity) (Siegal and Gillespie, 1980; Schowengerdt, 1983). Landsat MSS5, MSS7, a linear combination of MSS5 and MSS7 known as the Transformed Vegetation Index (TVI) and the HCMM IR were displayed in different RGB and IHS combinations on the color display. An RGB image with the TVI displayed in red and the HCMM IR in green and blue proved to be the most useful for relating HCMM temperatures to the various land covers.
The TVI is one of several linear combinations of Landsat MSS bands that have been shown to be sensitive to green-leaf biomass and productivity over a wide variety of natural and agricultural land covers (Rouse et al., 1974; Tucker, 1979; Tucker et al., 1981; Curran, 1982; Myers, 1983; Jackson, 1983; Huete et al., 1984; 1985; Jensen and Hodgson, 1985). The TVI is calculated using the following formula:

$$TVI = \sqrt{((MSS7 - MSS5)/(MSS7 + MSS5)) + 1.0}$$

This results in an index between 0.0 and 1.33 that is then multiplied by 100.0 for display purposes (Fig. 5). The TVI offered better vegetation discrimination than did MSS5 or MSS7, while also allowing identification of water and urban areas. Color plots and slides of the resulting images were made for interpretation purposes.

**HCMM temperature maps.** Isoline and color-coded, atmospherically corrected temperature maps were produced from the geometrically corrected HCMM data. To obtain surface temperatures that were as close as possible to true surface temperatures, corrections for atmospheric attenuation and emissivity due to water vapor were done. Atmospheric corrections were made using Price's (1983b) radiative transfer model. A spatially constant surface emissivity of 0.97 was chosen based on emissivity values for vegetation and soils given by Taylor (1979) and Smith (1983). This model has been shown by Price (1983b) to
Figure 5: November 5, 1978 Landsat MSS TVI image.
correct apparent surface temperatures to within plus or minus 2.0 to 3.0 C of actual surface temperatures.

Input data for the model included atmospheric pressure, temperature and dew point at standard and critical radiosonde levels. The radiosonde data were collected by a NOAA meteorological balloon launched from Waycross, Georgia, approximately 180 km north of the center of the study area. Day HCMM data were corrected using soundings obtained at 0000 GMT the day after the satellite overpass. These soundings correspond to approximately 1830 LST on the day of the satellite overpass. Night HCMM data were corrected using soundings obtained at 1200 GMT the day of the satellite overpass. These data correspond to approximately 0630 LST on the day of the satellite overpass.

After atmospheric correction equations were derived from the model, lookup tables for converting HCMM digital numbers (DNs) to temperature were calculated using the following equation (HCMM, 1980):

\[ T(I) = K_1 / \ln(K_2 / (I - K_3) + 1) \]

where \( T \) is temperature in degrees K, \( I \) is the HCMM DN, \( K_1 \) is 14421.587, \( K_2 \) is 1251.1591 and \( K_3 \) is -118.21378. Additionally, 5.2 K were added to the raw HCMM temperatures to correct for radiometer calibration errors (Vukovich, 1984). New lookup tables of corrected temperatures were made using equations provided by Price's model. Based on
the assumption that canopy temperatures approximate air temperatures (Smith et al. 1981), comparisons of radiometric temperature of forested areas to shelter-height temperatures throughout the study showed the corrected HCMM temperatures to be accurate within plus or minus 2.0 to 3.0 °C for most images.

Atmospherically corrected temperatures were displayed using isotherm maps obtained from the Surface II mapping program (Sampson, 1975) and as color-coded temperature maps. Contour maps offer the advantage over color-coded temperature maps of being a smoothed representation of the data, and therefore easier to interpret on a general level. The maps were generated at a scale of 1:500,000, allowing them to be readily overlaid on available maps and Landsat MSS imagery.

The color-coded temperature maps were produced by assigning colors to ranges of temperatures obtained from the satellite imagery and corrected-temperature lookup tables. For day imagery each color represented approximately three DNs, or a range of approximately 0.7 to 0.9 °C. Night images, because of the decreased temperature range, were generally assigned two DNs (approximately 0.5 to 0.7 °C range) per color.

Greyscale HCMM IR images. Geometrically corrected greyscale HCMM and IR images allowed the most detailed analysis of surface temperature patterns in this study.
These data were used for statistical correlation analyses and visual interpretations. Correlations between DNs of the different dates were calculated for the entire study area (excluding the Atlantic Ocean and Gulf of Mexico) as well as for subsets of the study area. The results of the correlation analysis are given in Chapter 5.

The atmospherically uncorrected HCMM data were also examined visually to avoid the loss of detail that occurs when DNs are converted to temperatures and merged into color classes or displayed as isotherm maps. The data were enhanced using various linear and histogram equalization contrast stretches (Schowengerdt, 1983). These enhancements simply expand the limited range of image DNs to fully utilize the range of the display device.

**Image Analysis**

As stated above, the object of image analysis was to relate HCMM-derived surface temperatures to land cover and land use, soils and physiographic features in north-central Florida. A hierarchical approach to image analysis was used, proceeding from the interpretation of general to more specific temperature-surface feature relationships. First, geometrically and atmospherically corrected 1:500,000 HCMM isotherm maps were overlayed on Landsat MSS photographic images. This allowed the identification of general surface temperature patterns and comparison of the relative
complexity of these patterns for different parts of the study area.

In the second step, color-coded temperature maps and enhanced greyscale imagery were examined in conjunction with Landsat MSS, TM and black and white air photo mosaics. This allowed the interpretation of greater detail than that obtainable from isoline maps because actual pixels were visible in the data. These images were interactively displayed using the ELAS software, allowing various contrast stretches, enlargements and statistics to be generated. The ELAS DGTZ module was particularly useful at this stage of interpretation. This program allows the user to digitize areas on maps and highlight corresponding areas in the HCMM data. This capability was valuable for identifying the location of specific surface features in the relatively coarse scale HCMM data.

The final step involved the examination of land cover-temperature relationships for a subset of the HCMM data for which color-infrared NHAP aerial photographs were available. This area extends from Kingsley Lake in the north to the Oklawaha River in the south and from San Felasco Hammock in the west to the town of Interlachen in the east. Each of the 38 NHAP photos covering this area were examined along with the corresponding HCMM data. Individual DN values for various land covers were extracted from the HCMM data and converted to temperatures using the atmospherically
corrected lookup tables discussed previously. These data provided the most detailed information on surface temperature characteristics of the study areas.
CHAPTER V
IMAGE INTERPRETATION RESULTS

Temperature patterns for each imaging date are described separately below, first addressing the day and then the night data. For each date the meteorological conditions under which the data were obtained are given as well as a description of temperature patterns. A common format for the description of the data is based on the fact that the study area can be subdivided into several relatively homogeneous regions, which often correspond with surface features. These thermal regions will be discussed first, followed by a discussion of the individual imaging dates.

Thermal Regions

Seven thermal regions are discernable in all of the day images (Fig. 6). The Gulf Coast Region includes all or parts of Taylor, Lafayette, Dixie and Levy counties. Daytime temperatures in this region are generally low relative to those found over less heavily vegetated regions. The eastern boundary of this region closely follows that between the Central Florida Ridge and North Florida Flatwoods Soils (see Figure 2 in Chapter 4). Soils within the Gulf Coast Region include Tidal Marsh and Tidal Swamp,
Centenary-Leon-Plummer, Plummer-Rutledge and Itchetucknee-Chaires-Chiefland associations. All are poorly drained soils. Vegetation is primarily pine flatwoods with numerous cypress stands and marshes. Hardwood swamp forests are found along lakes and rivers and the Gulf coast is bordered by salt marshes.

The Suwannee Agricultural Region runs north and south the length of the study area, with daytime temperatures in this region among the warmest in the study area. The area is dominated by agricultural land covers, with Suwannee and Gilchrist counties having more than 50% of their land in farms, and Alachua, Levy and Marion having more than 30% in farms (U. S. Department of Commerce, 1981). Common crops include corn, sorghum, wheat, peanuts, soybeans and various hay and silage crops. Cultivated fields and pastures are interspersed with smaller forested areas consisting of mixed hardwoods, planted pine or longleaf pine-turkey oak communities. The boundaries of the Suwannee Agricultural Region closely follow those of the soils of the Central Florida Ridge. Included are the Alpin-Blanton-Chipley, Blanton-Susquehanna-Fuquay, Astatula, Jonesville-Pedro and Candler-Apopka-Astatula associations. All of these associations contain well drained sandy soils.

The Interlachen Karst Region extends from Kingsley Lake in Bradford county south to the Oklawaha River in northern Marion county, and from Lake Santa Fe eastward into Putnam
Figure 6: Thermal Regions.
Lighter tones indicate warmer temperatures.
county. This region of elevated temperatures includes soils from all three major soil groups, but little correspondence is found between soils found on the 1982 general soils map (Caldwell and Johnson, 1982) and temperature patterns observable in the HCMM imagery. One exception occurs in the south where the excessively drained Candler-Apopka-Astatula association is found. Also located in the region are the Pomona-Wauchula-Placid, Istokpoga-Samsula, and Leon-Pelham-Mascotte associations. The soils included in these associations are all poorly drained. It should be noted that an earlier soil map (Beckenbach and Hammett, 1962) shows a greater percentage of the Interlachen Karst Region to contain well drained soils, and surface temperature patterns correspond well with this map. The vegetation in this region includes pine flatwoods in the north, longleaf pine-turkey oak on well drained sand hills, and marsh and cypress in karst depressions. The region is notable for the large number of small karst-related lakes and sinkholes.

East of the St. Johns River in Flagler, Putnam and St. Johns counties is the Hastings Agricultural Region. Common crops are potatoes, vegetables, cabbage and various hay crops. This region falls entirely within the Soils of the Central and South Florida Flatwoods and includes only the poorly drained soils of the Pomona-Wauchula-Placid association. The eastern edge of this region is bounded for the most part by the Riviera-Winder association. Other than
this boundary, no clear relationship between temperature patterns and soil associations can be identified in the region.

The Lake George Region is a region of slightly warmer temperatures bordered on the north and west by the Oklawaha River and extends to the southern edge of the study area and east to Crescent Lake. The boundaries of the Lake George Region correspond closely to two soil associations of the Central Florida Ridge, the Candler-Apopka-Astatula and Astatula associations. These associations are composed of well drained sandy soils. West of Lake George in the Ocala National Forest the primary vegetation communities are sand pine and longleaf pine-turkey oak forest. Sand pine forests are actively logged within the national forest. Between Lake George and Crescent Lake pine flatwoods and longleaf pine-turkey oak are the dominant forest communities, though numerous small agricultural holdings are common. Hardwood swamp forests are found around Lake George and along the Oklawaha and St. Johns Rivers.

The Atlantic Coastal Region is an area of cooler temperatures extending from the Florida-Georgia border to the southern end of the study area and inland 20-25 km. The region includes soils from the North Florida Flatwoods and South and Central Florida Flatwoods. In Duval and Nassau counties these include Tidal Marsh and Swamp, Coastal Beach and Dunes, Chipley-Kureb-Lakeland, Plummer-Rutledge and
Leon-Pelham-Mascotte associations. All but the Coastal Beach and Dunes and Chipley-Kureb-Lakeland associations are poorly drained soils. South of Duval county are the Riviera-Winder, Coastal Beach and Dunes, Pomona-Wachula-Placid, Istokpoga-Samsula and Tidal Marsh and Tidal Swamp associations. All except the Coastal Beach and Dunes association are poorly drained. No distinct relationship between soil associations and surface temperature patterns is evident in the Atlantic Coast Region. Vegetation communities include coastal strand, salt marsh, pine flatwoods, longleaf pine-turkey oak and hardwood swamp forests.

The last region, the Central Region, includes the portion of the study area between the Suwannee Agricultural Region in the west and the St. Johns River in the east, excluding the Interlachen Karst and Lake George Regions. The western and southern boundaries of the Central Region correspond closely to those of the well drained Central Florida Ridge soils. The northern section includes the Leon-Pelham-Mascotte and Plummer-Rutledge associations, both comprised poorly drained soils. The southern section in Alachua, Putnam and Marion counties includes the Adamsville-Lochloosa-Sparr, Pomona-Wauchula-Placid, Istokpoga-Samsula and Bushnell-Boca associations. All are comprised of poorly drained sandy soils. The primary vegetation community in the region is pine flatwoods, with longleaf pine-turkey oak
forests found on well drained uplands in Nassau, Clay, Putnam and Alachua counties. Pine forests are subject to intensive lumbering throughout the region. Hardwood and cypress forests are present along river valleys, in wetter areas around lakes and rivers and in the Okefenokee Swamp near the Florida-Georgia border. Extensive freshwater marshes are found in Alachua county.

Night temperature patterns for the dates used in this study do not correspond to the above thermal regions as well as do the day data. Some of this lack of correspondence is because of the overall poor quality of the available night imagery. In spite of this lack of correspondence the thermal regions will be used to describe nighttime temperature patterns. This is done for two reasons. First, the daytime patterns appear to follow land cover and land use patterns in the study area relatively closely, providing a physical basis for the use of these regions for discussion purposes. Second, the use of the thermal regions allows a uniform format for discussing temperature patterns.

**Daytime Surface Temperature Patterns**

**November 5, 1978**

**Meteorological conditions.** The November 5, 1978 HCMM data are cloud-free and of good quality (Fig. 7 and Table 4). The 0700 EST surface weather map shows that the area was under the influence of a high pressure cell centered
over Tennessee and the barometric pressure was rising. Windspeeds at the time of imaging were low and from an easterly direction. No rainfall was recorded in the study area on the day of the satellite overpass. Only three stations within the study area measured any rainfall within five days prior to imaging, Fernandina Beach, St. Augustine and Daytona Beach, all below 0.18 cm. October 1978 was drier than normal for most of the study area, with 1.3 to 9.1 cm of rainfall. Daytona had anomalously high rainfall, with 21.0 cm for the month.

**Gulf Coast Region.** Temperatures in the Gulf Coast Region range from 25.2 to 26.0 °C for coastal marshes and wetlands to greater than 35.9 °C over interior agricultural areas. Most of the region has temperatures between 26.3 °C and 29.4 °C. Temperatures in the region correspond closely to vegetative land covers. Coastal marshes are among the coolest land covers, though these wetlands are poorly delimited for most of the Gulf Coast Region, tending to blend in with many of the wetter forests. This is particularly evident along the Suwannee River where temperatures of 25.2 to 26.0 °C extend several kilometers upstream of the salt marshes.

A close correspondence between surface temperature and forest type as found on the 1972 1:250,000 USGS Land Use and Land Cover Map may be observed in the image. Cooler areas (25.2 to 27.1 °C) correspond closely to the forested wetland
Figure 7: November 5, 1978 HCWM IR image.
TABLE 4

November 5, 1978 meteorological conditions.

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Daily air temperatures: Maximum of 28.9 at Live Oak
(sheelter height) Minimum of 23.8 at Jacksonville
Average of 26.1

Soil temperatures: Maximum 25.6 at Monticello
(10.2 cm depth) Maximum 21.6 at Gainesville

All temperatures are given in degrees C, windspeeds in km/hr, wind direction in tens of degrees counterclockwise from north, relative humidity in percent and pressure in millibars. Temperature, wind speed, wind direction and relative humidity for Jacksonville, Tallahassee, Orlando and Tampa were taken at 1300 EST. Pressure was obtained from the 0700 EST surface weather map.
category while warmer areas (27.6 to 29.4 °C) match the evergreen forest land category. Evergreen forests are dominated by pines interspersed with cypress domes and are subject to intensive logging. Logging of the pine forests leads to a wide variety of stand ages and heights within the region, ranging from recent clearcuts to mature pine forests. Forested wetlands also contain pines, but frequently have a higher number of cypress and hardwood species. These areas are subject to less intensive logging.

Within the Gulf Coast Region are areas of notably higher temperatures. Warmer temperatures (in excess of 34.1 °C) around Old Town and Fanning Springs in Levy and Dixie counties correspond to agricultural land covers. Several smaller areas can be identified with forests that have been recently clearcut or are in various stages of regrowth. Examples of such areas can be found in northern Lafayette county, southern Lafayette county approximately 20 km west of the junction of Santa Fe and Suwannee Rivers, just northeast of the mouth of the Suwannee River, 15-20 km northeast of Cedar Key and north of Waccasassa Bay. Temperatures are from 2.3 to 8.7 °C higher than those of nearby pine flatwoods and higher by another 1.0 to 2.0 °C over nearby forested wetlands.

**Suwannee Agricultural Region.** Temperatures are higher in the Suwannee Agricultural Region than in dominantly forested regions; the mean temperature in the region is 33.5 °C as
compared to 27.6 C in the Gulf Coastal Region. Temperature patterns are complex in the Suwannee Agricultural Region because of the mix of bare soil, grass, crops and forest in the area. Minimum temperatures of 27.6 C are found along the Suwannee River and over forested areas; maximums exceed 39.0 C over agricultural lands.

Vegetation density appears to be the primary factor controlling surface temperatures in the Suwannee Agricultural Region. Hardwood forests along the Santa Fe and Suwannee Rivers have temperatures between 27.6 and 27.9 C, with planted pine forests generally 2.0 C or more warmer. Temperature differences within pine forests, and between pine forests and nearby agricultural lands are also evident. A planted pine forest located on well to moderately drained soils has temperature differences of 1.0 to 1.5 C between the most densely forested and less heavily forested sections. The pine forests are 6.0 to 8.0 C cooler than adjacent agricultural fields. Similar temperature differences are found in comparisons between planted pines around the Deerhaven Power Plant north of Gainesville and nearby agricultural lands. The sparse longleaf pine-turkey oak forests found in Gilchrist and Levy counties are 1.5 to 2.0 C warmer than dense pine forests and experience temperatures similar to those of young planted pine forests.

Agricultural areas with minimal vegetation cover experience the highest temperatures in the region. By early
November vegetation cover over agricultural lands is minimal because most crops have been harvested. These sparsely vegetated agricultural areas have temperatures greater than 32.0 C, with extensive areas greater than 35.3 C. Maximum temperatures in the region exceed 39.0 C in western Marion county.

Within or bordering the Suwannee Agricultural Region are three urban or industrial features influencing surface temperature patterns; they are the open-pit phosphate mine in Hamilton county and the cities of Lake City and Ocala. Examination of the isotherm map shows that the phosphate mine causes the 29.0 C degree contour to extend eastward to include the mine, with temperatures approximately 1.0 to 2.0 C higher than surrounding forested areas. More pronounced are the urban heat islands of Lake City and Ocala. Lake City has a maximum temperature difference of 10.0 C over nearby pine forests. Ocala has a less pronounced heat island, with temperatures 2.0 to 4.0 C above surrounding agricultural lands.

**Interlachen Karst Region.** Minimum temperatures in the Interlachen Karst Region are 26.3 to 27.1 C for pixels influenced by lakes, while maximums exceed 37.0 C over agricultural lands. The majority of the region exhibits temperatures greater than 29.7 C and large areas are warmer than 33.0 C.
High temperatures in the region are related to the sparse vegetation and well drained soils found there. The dominant vegetation community, longleaf pine-turkey oak forest, generally has an open canopy and minimal understory. This means that a greater percentage of the higher-temperature soils will be visible to the satellite sensor, resulting in elevated surface temperature measurements. The potential for high temperatures in these areas is further increased by clearing of the already sparse forests for housing developments. An example of this is found in a region of longleaf pine-turkey oak forests east of Lake Geneva where temperatures exceed 34.1 C. Similar temperatures are located around the Interlachen area and south of Kingsley Lake over Camp Blanding. Comparison to pine flatwoods adjacent to the Interlachen Karst Region show longleaf pine-turkey oak forests to be 5.0 C or more warmer.

Highest temperatures (37.0 C) in the region are located over agricultural areas where maximum soil exposure is found. Temperatures over an open-pit heavy mineral mine southeast of Kingsley Lake reach 36.3 C, only slightly lower than those found over agricultural areas.

Hastings Agricultural Region. As in the Suwannee Agricultural Region, lowest temperatures (25.2 to 26.0 C) are associated with forested inliers. In the Hastings Agricultural Region these are primarily hardwood swamp forests along the St. Johns River and its tributaries.
Temperatures over forested areas are between 25.2 and 27.1 C, and pastures are mostly 1.0 to 2.0 C warmer. Temperatures greater than 35.3 C are common in cultivated areas, with a significant amount of the region exhibiting temperatures greater than 36.3 C. In spite of the poorly drained soils in the region surface temperatures are similar to those found over more well drained agricultural areas elsewhere.

Lake George Region. Lowest temperatures, 25.2 to 26.0 C, in the Lake George Region are found over swamp forests and maximum temperatures exceed 34.8 C for an agricultural area approximately 15 km north of Lake George. The majority of the land surface in the region lies between 27.6 and 33.8 C.

Highest surface temperatures are found over three land covers, sparsely vegetated longleaf pine-turkey oak forests, logged areas and agricultural sites. Elevated surface temperatures, up to 31.6 C, occur over an area of longleaf pine-turkey oak forest south of Lake Kerr. An adjacent clearcut area has temperatures between 33.0 and 33.8 C. Another area of longleaf-pine turkey oak south of Rodman Reservoir has temperatures from 30.9 to 31.6 C.

Temperatures in the northeast corner of the Ocala National Forest range from 28.3 to 33.8 C with most between 29.7 and 30.9 C. This area is covered by a relatively dense sand pine forest that has been extensively logged, therefore high surface temperatures would be expected. Because
temperatures are for the most part lower than found over clearcuts elsewhere in region it is plausible that temperatures in the area are being masked by the relatively coarse resolution of the HCMM sensor. The logged areas are generally small, below 0.3 km² and irregularly shaped. Overlaying of a template representing the original 600-by-600-m HCMM temperature measurements onto NHAP air photos shows that pixels seldom fall entirely on clearcuts, thus the temperatures measured will commonly include both clearcut and forest. The resulting mixed pixels will lead to increased temperatures for forests and decreased measurements for clearcuts.

High surface temperatures are found over agricultural lands and pastures between Lake George and Crescent Lake. Surface temperatures here are generally between 30.9 and 35.9 C. Temperatures between 26.3 and 28.6 C are found over forested areas and around small lakes.

**Atlantic Coastal Region.** In the Atlantic Coast Region minimum temperatures are 23.7 to 24.9 C along the Atlantic coast and for salt marsh and lagoon areas. Maximum temperatures of 30.9 to 31.6 C are associated with urban and interior agricultural areas. The majority of the region lies between 25.2 and 27.1 C.

As in the Gulf Coast Region, temperature differences can best be explained by vegetation cover and surface moisture, with wetlands being cooler than dry forests. Agricultural
and logged areas tend to exhibit higher temperatures (by 1.0 to 2.0 C) than do forested areas. Because of their influence on the vegetation distribution in the Atlantic Coast Region Pleistocene beach ridges are visible in some portions of the region. The lack of definition of these features is probably caused by the coarse resolution of the HCMM thermal data.

Urban areas exhibit a notable influence on surface temperatures in the Atlantic Coast Region. Eastern Jacksonville is approximately 2.0 to 4.5 C warmer than rural areas and a slight heat island can be seen on Jacksonville Beach. Daytona Beach has a maximum urban-rural temperature difference of approximately 7.0 C.

Central Region. Minimum temperatures (excepting water bodies) in the Central Region are 25.2 to 26.0 C and are found over freshwater marshes and hardwood swamp forests. Maximum temperatures exceed 37.0 C over agricultural areas and at the heavy mineral mine northeast of Starke. The majority of the region exhibits temperatures between 26.3 and 31.6 C.

As elsewhere, temperature differences can be related to variations in vegetation covers. Coolest temperatures are associated with wetlands. Wetland forests north of Lake Santa Fe and north of Newnans Lake are between 26.0 and 26.8 C. Similar temperatures are found north of Ocean Pond and in the Okefenokee Swamp. Freshwater marshes in Paynes
Prairie, Lake Levy and around Orange Lake have roughly equivalent temperatures, between 26.0 and 26.8°C. Temperatures over pine flatwoods range from 26.3°C in the wettest areas to approximately 29.0°C in drier areas. Mixed pine-cypress forests north of Gainesville have temperatures as low as 26.3°C while those around Lake Sampson and in Austin Cary Forest north of Newnans Lake are between 27.6 and 28.9°C. Drier pine forests northeast of Kingsley Lake are slightly warmer, between 28.3 to 28.9°C. Temperatures over dominantly hardwood forests in San Felasco Hammock are between 27.6 to 27.9°C, roughly equivalent to the coolest pine forests.

As in the Gulf Coast Region, comparisons with air photos and Landsat imagery show a close correspondence between areas approximately 2.0 to 7.0°C warmer than surrounding forests, recently logged or regrowth sites. A clearcut in Austin Cary Forest is up to 5.0°C warmer than surrounding forests. Another clearcut north of Lochloosa Lake is similarly warmer than surrounding forests.

Urban and industrial areas exert important local controls on surface temperatures in parts of the Central Region. The northern heavy mineral mine east of Starke has temperatures greater than 37.0°C, making it one of the warmest areas in the region. The urban area of Jacksonville has a well-developed heat island, with downtown temperatures approximately 6.0°C above surrounding rural areas. Also
evident are the heat islands of Orange Park and Palatka. Gainesville has maximum temperatures of 36.6 °C, approximately 9.0 °C greater than nearby forests and more than 10.0 °C greater than nearby wetlands.

It is interesting to note that airports are consistently some of the warmest cultural land covers, often warmer even than downtown urban areas. Jacksonville and Cecil Field Naval Air Stations Naval Air Stations both have temperatures between 34.1 and 34.8 °C, and Jacksonville International Airport has temperatures up to 31.6 °C. Even smaller airports at Gainesville and the abandoned Green Coves Springs military base display temperatures approximately 4.0 °C warmer than adjacent rural regions.

December 17, 1978

Meteorological conditions. The December 17, 1978 HCMM data are the lowest quality day imagery used in this study (Fig. 8 and Table 5). The 0700 EST surface weather map shows a cold front running from Jacksonville to Cedar Key. This front appears to have stalled and is visible over the northern part of the study area. Clouds are evident northeast of Jacksonville and light cloud cover influences temperature measurements over much of the study area north and east of the Suwannee River. A north-south temperature gradient is noticeable in the imagery, with regions north of a line running from Jacksonville to Steinhatchee notably
cooler than areas south of that line. Advection of cool air from the Atlantic Ocean also appears to have lowered temperatures along the east coast. The front was dry, with no rainfall recorded in the study area on the imaging date or five days prior. Most of the study area received more than 6.5 cm of precipitation in the first twelve days of the month. November 1978 was drier than normal, receiving 0.3 to 8.1 cm of rainfall.

**Gulf Coast Region.** Temperatures in the Gulf Coast Region range from below 16.8 C to greater than 25.2 C, with a north-south temperature gradient evident in the region. Comparison with the November 5, 1978 data shows that temperature patterns are similar, though not as well defined.

As in the November data, temperatures follow vegetation patterns. Pine flatwoods south of the cold front have temperatures between 20.2 and 22.0 C and forested wetlands between 18.0 and 19.8 C. North of the cold front such differentiations are difficult to make. The majority of the lumbered areas found in the November 3, 1978 data are found in the December 17, 1978 image. Temperature differences between logged and nearby forested areas are smaller in the December image, ranging from 2.2 to 5.8 C. Warm temperatures associated with lumbered areas are more evident south of the cold front and are for the most part less extensive than those found in the November 5, 1978 data.
Figure 8: December 17, 1978 HCMN IR image.
TABLE 5

December 17, 1978 meteorological conditions.

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<th>Station</th>
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Daily air temperatures: Maximum of 25.5 at Hastings (shelter-height) Minimum of 15.5 at Fernandina Average of 21.3

Soil temperatures: Maximum of 20.0 at Monticello (10.2 cm depth) Maximum of 18.0 at Gainesville

See Table 4 for explanation.
Suwannee Agricultural Region. Minimum temperatures in the Suwannee Agricultural Region are 17.6°C over forested areas in the north; maximum temperatures are found over agricultural land covers in northwest Levy county and exceed 29.4°C. The north-south temperature gradient visible elsewhere in the imagery is also evident in the Suwannee Agricultural Region. North of the Santa Fe River temperatures below 22.0°C are common, while south of the river most agricultural areas are greater than 22.3°C.

As in the November 3, 1978 data, temperatures are largely controlled by the presence or absence of vegetation, particularly south of the cold front. North of the Suwannee River forested sites generally exhibit temperatures 1.0 to 3.0°C cooler than the warmest agricultural areas, though in some areas a temperature difference is not readily identified.

South of the river the influence of vegetation on surface temperatures is better defined. A planted pine area southeast of Archer has temperatures from 22.0°C over the densest parts to 23.8°C over younger, more open sections. Forest-agriculture temperature differences are relatively small, with the pine forest being only 2.0 to 3.5°C cooler than surrounding agricultural lands. A sparse pine forest east of Lake Kanapaha has temperatures between 23.0 and 23.8°C, and similar temperatures are found over young pines elsewhere. Temperatures over mixed pine-cypress forests
around the Deerhaven Power Plant are cooler, at approximately 20.5 C, possibly reflecting wetter conditions and a more complete crown cover. These temperatures are similar to those found for mixed pine-hardwood forests in northern Marion county. Bottomland hardwoods along the Santa Fe and Suwannee Rivers are the coolest land covers, with temperatures as low as 19.1 to 19.8 C.

The open-pit phosphate mine in Hamilton county is obscured by clouds, but Lake City exhibits temperatures up to 24.5 C, which are between 2.5 to 6.5 C higher than surrounding rural areas. No heat island is evident for Ocala.

Interlachen Karst Region. Minimum temperatures in the Interlachen Karst Region are 19.1 to 19.8 C for pixels including lakes and adjacent wetlands. The maximum temperature is 27.9 C for agricultural sites in the region. No north-south temperature gradient is evident in this region because of its position south of the stalled cold front.

As in the November 5, 1978 imagery, sparsely vegetated sections display higher temperatures than do forested sections. Temperatures for longleaf pine-turkey oak forests east of Lake Geneva and around Interlachen are between 24.2 and 26.2 C. The Camp Blanding area displays temperatures between 25.2 to 25.5 C. These temperatures are 3.0 to 4.0 C warmer than pine flatwoods south of Kingsley Lake and east of the open-pit heavy mineral mine.
Agricultural fields in the eastern part of the region are again the warmest areas with temperatures up to 27.9 C. The heavy mineral mine east of Kingsley Lake has temperatures between 22.3 and 23.4 C -- warmer than pine flatwoods of the adjacent Central Region, but similar to or cooler than longleaf pine-turkey oak forests in the Interlachen Karst Region.

**Hastings Agricultural Region.** Minimum temperatures in the Hastings Agricultural Region are 19.1 to 19.8 C over forested sections; maximums of 26.6 to 27.3 C are found for an isolated agricultural area. The majority of the region lies between 20.2 and 24.2 C. Temperature patterns visible in the November 5, 1978 data are evident in the December data, though these patterns are subdued and exhibit a decreased range of temperatures. Temperatures in the region appear to be influenced by advection of cooler air from the Atlantic Ocean, with the eastern boundary somewhat less well defined than in the November 5, 1978 data.

**Lake George Region.** Minimum temperatures in the Lake George Region are 18.0 to 18.7 C for wetlands; maximums of 26.6 to 27.3 C are found over an agricultural area north of Lake George. The majority of the land surface has temperatures between 20.2 to 24.4 C.

As in the November 5, 1978 data, a close correspondence between temperature and vegetation patterns is evident. The
area of longleaf-pine turkey oak south of Lake Kerr displays temperatures approximately 2.0 C warmer than nearby forested areas; an adjacent clearcut is 3.0 to 5.0 C warmer. Similar temperatures are found for the longleaf pine-turkey oak forest south of Rodman Reservoir. Temperatures over heavily logged sand pine forests range from 21.3 to 25.8 C and again the small size of individual clearings appears to decrease their influence on temperatures in the area.

Agricultural areas between Lake George and Crescent Lake are again relatively high, with temperatures between 23.4 and 27.3 C. Forested areas between the two lakes are between 20.2 and 22.0 C. Wetland forests along the St. Johns River are 18.0 to 19.8 C.

**Atlantic Coast Region.** Temperatures in the Atlantic Coast Region appear to be influenced by the advection of cool air from the adjacent waters of the Atlantic Ocean. This influence significantly reduces surface temperature contrasts in the region. Minimum temperatures are below 16.8 C and are found over the coastal barrier islands, lagoons, marshes and inland wetlands. Maximum temperatures of 23.3 to 24.2 are found over the Jacksonville urban area east of the St. Johns River and over the city of Daytona Beach.

In spite of the lack of temperature contrast in the data, similarities between the December 17, 1978 and November 5, 1978 temperature patterns are evident. Examination of
contrast-enhanced greyscale imagery shows that slight temperature differences exist between agricultural and forested lands, with forested land being slightly cooler. Marshes and other wetlands are slightly cooler than forested areas.

Urban areas exert an important local influence on temperature patterns, with eastern Jacksonville approximately 2.0 to 4.0 C warmer than nearby rural areas. The community of Palm Bay is visible, with temperatures between 3.0 to 4.0 C warmer than surrounding rural areas. Daytona Beach is 2.5 to 4.5 C warmer than nearby forests.

Central Region. Temperatures in the central region below 16.8 C are found north of the cold front over wetlands. Maximum temperatures of 27.3 C are found over an agricultural area northeast of Ocala. Elsewhere in the imagery a north-south temperature gradient is visible, with temperatures north of the Santa Fe River cooler than those to the south. North of the front surface temperatures are mostly between 16.8 C and 19.8 C, and south of the front temperatures of 20.2 to 22.0 are common.

Overlaying the December 17, 1978 and November 5, 1978 imagery shows that a close correspondence exists between temperature patterns for the two dates. This correspondence is evident even in the northern section, where cloud cover partially obscures the surface. As in the November data, temperature patterns correspond to vegetation and land use
patterns. North of the cold front temperature differences are subdued, though over two non-forested areas temperatures of 22.3 to 23.0 C are found, approximately 3.0 to 5.0 C warmer than surrounding land covers. Coolest temperatures north of the front are associated with wetlands, with temperatures slightly warmer over pine flatwoods.

South of the cold front temperature-land use relationships are much easier to recognize. Wetlands again are among the coolest land covers, with temperatures over marshes in Paynes Prairie as low as 18.4 C over the wettest areas, those around Orange Lake are between 19.4 and 19.8 C. Wetland forests in the Santa Fe Swamp have temperatures as low as 19.1 C, while those around Lake Sampson are between 18.4 and 19.4 C.

Mixed pine-cypress forests north of Gainesville are between 20.2 and 20.5 C; in the Austin Cary Forest temperatures are slightly higher, between 21.7 to 22.7 C. Logged areas in Austin Cary Forest are 3.5 to 5.0 C warmer than forested areas, and similar temperature differences are found over a clearcut north of Lochloosa Lake. Temperature differences between different forest types are particularly evident in San Felasco Hammock State Preserve, a forested area northwest of Gainesville. Temperatures are between 20.2 and 21.0 C for predominantly hardwood forests, between 21.3 and 22.0 C for upland pine forests and between 19.1 and 19.8 for marshes and swamp forests.
Urban areas are among the warmest features in the December data. Maximum temperatures for downtown Jacksonville are approximately 4.0 C warmer than adjacent rural areas. Orange Park and Palatka have temperatures approximately 3.0 C higher than nearby forested areas, and downtown Gainesville is 5.5 C higher than nearby forested areas. As in the November 5, 1978 data, Cecil Field and Jacksonville Naval Air Stations, Jacksonville International, Green Cove Springs and Gainesville airports are all characterized by relatively high temperatures. The northern end of the heavy mineral mine northeast of Starke also is warmer than surrounding forested areas.

March 28, 1979

Meteorological conditions. The March 28, 1979 imagery were obtained under virtually cloud-free conditions and are of good quality (Fig. 9 and Table 6). The only cloud cover over the study area consists of intermittent cumulus clouds east of Jacksonville and extending southward to the southern end of the Interlachen Karst Region. No rainfall was recorded in the study area on the day of the HCMM overpass, and less than 1.2 cm fell five days prior to imaging over most of the study area. Total rainfall for the month (all prior to the 28th) ranged from 1.8 to 10.2 cm with coastal stations recording the highest amounts.
Figure 9: March 28, 1979 HCM IR image.
### TABLE 6

March 28, 1979 meteorological conditions.

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Daily air temperatures: Maximum of 28.8 at Live Oak and Perry (shelter-height) Minimum of 21.1 at Steinhatchee Average of 25.5

Soil temperatures: Maximum of 26.6 at Monticello (10.2 cm depth) Maximum of 20.0 at Gainesville

See Table 4 for explanation.
**Gulf Coast Region.** Minimum temperatures in the Gulf Coast Region are 22.9 to 23.6 C over coastal marshes and adjacent wetlands and maximum temperatures exceed 38.7 C over non-forested areas. The majority of the region has temperatures between 27.3 and 32.9 C.

Surface temperatures again are relatable to vegetation patterns and land use in the region. Coolest temperatures (22.9 to 23.6 C) are found along coastal marshes, and a noticeable temperature gradient is evident along most of the Gulf coast. Forested wetlands are again separable from drier pine forests. Temperatures over forested wetlands range from 22.9 to 27.0 C, with most pine flatwoods at 27.3 to 29.4 C. Logged areas visible in the November 5, 1978 and the December 17, 1978 data are again recognizable in the March data. Temperature differences between forested and non-forested sites range from 1.1 to 8.6 C, slightly lower than those found in the November 5, 1978 data.

**Suwannee Agricultural Region.** Minimum temperatures in the Suwannee Agricultural Region are 26.5 to 27.0 C over small sections of the Suwannee River valley. Maximum temperatures exceed 40.0 C and are found over agricultural land in western Marion and Suwannee counties. The majority of the region is between 34.5 to 39.8 C.

Temperatures between 27.3 and 28.2 C are found for bottomland hardwood forests along the Suwannee and Santa Fe Rivers. Temperatures over dense planted pine forests are
between 28.5 and 29.4 C, and less dense pine forests are approximately 1.0 to 2.5 C warmer. Longleaf pine-turkey oak forests in Gilchrist county are between 33.4 to 35.7 C. Highest temperatures are found over agricultural lands, most of which in late March would have been recently planted and have minimal vegetation cover. Temperatures in excess of 37.6 are common over bare agricultural fields, while pastures in Marion county are between 33.4 and 37.2 C.

The open-pit phosphate mine exhibits temperatures approximately 2.0 to 4.0 C warmer than adjacent forested areas. Lake City has a noticeable heat island, with maximum temperatures of 38.3 C, or approximately 10.0 C warmer than forested areas east of the city. No heat island is evident for Ocala because the city is surrounded by high-temperature agricultural lands that masks any warming associated with urbanization.

**Interlachen Karst Region.** Cumulus clouds obscure a small part of the Interlachen Karst Region, locally affecting satellite-derived surface temperatures. Minimum surface temperatures in the Interlachen Karst Area are 26.5 to 27.0 C and are associated with water bodies. Maximum temperatures exceed 38.7 C over sparsely vegetated areas. Again longleaf pine-turkey oak forests are among the warmest land covers with temperatures in excess of 36.0 C. These temperatures are approximately 5.0 to 8.0 C higher than those of nearby pine forests. Temperatures between
34.8 and 37.2 °C are found over Camp Blanding, which are 3.5 to 5.5 °C warmer than pine flatwoods. Agricultural areas have temperatures up to 39.9 °C, and the heavy mineral mine east of Kingsley Lake has temperatures as high as 37.2 °C.

**Hastings Agricultural Region.** Minimum surface temperatures are 24.1 to 24.9 °C for forested wetlands; maximum temperatures of 34.8 to 35.7 °C are found over agricultural sites. The majority of the region has temperatures from 27.7 to 31.3 °C. The lower surface temperatures in this region as compared to other agricultural areas are probably caused by evaporation from the poorly drained soils in the region.

**Lake George Region.** Minimum temperatures in the Lake George Region are 22.9 to 23.6 °C over wetlands; maximum temperatures exceed 37.6 °C over clearcuts and agricultural land. Temperatures over most of the region are between 29.7 and 33.4 °C. Warmest areas in the Ocala National Forest are associated with clearcuts and longleaf pine-turkey oak forests. As in the November 5, 1978 and December 17, 1978 data, elevated temperatures are found over the longleaf pine-turkey oak forest (33.4 to 35.5 °C) and the adjacent clearcut (36.0 to 38.7 °C) south of Lake Kerr. An area of similar temperatures is located over a longleaf pine-turkey oak forest south of Rodman Reservoir. Temperatures over sand pine forests range from 27.3 to 38.0, with highest
temperatures found over extensively logged areas. These temperatures can be compared to 27.3 to 28.2°C for pine flatwoods to the west across the Oklawaha River. The agricultural region north of Lake George is again the largest area of high temperatures, with most of the area over 37.6°C. Wetland forests along the St. Johns River are between 24.1 and 26.1°C.

**Atlantic Coastal Region.** Minimum temperatures in the Atlantic Coast Region are 22.9 to 23.6°C over lagoonal salt marshes with maximums of 36.0 to 37.2°C for urban areas. The majority of the region has temperatures between 25.3 and 29.4°C. Temperature patterns again closely follow land cover patterns. Striping suggestive of the Pleistocene beach ridges found along the coast is more prominent in the March data than in any of the other images. Warmer temperatures (27.5 to 29.4°C) are found over agricultural land and logged areas, with cooler temperatures (24.1 to 27.0°C) over forests.

As in the November 5, 1978 and December 17, 1978 data, urban areas are seen to exert a considerable local influence on local temperature patterns. Eastern Jacksonville has temperatures up to 37.2°C, which are 5.0 to 10.0°C warmer than nearby rural areas. The heat island of Jacksonville Beach is well developed, with maximum temperatures of 33.4 to 34.5°C. The city of St. Augustine is visible, with temperatures 1.0 to 2.0°C higher than surrounding rural
areas. The community of Palm Bay is again warmer than surrounding areas by 2.0 to 3.0 C. Daytona has highs of 33.4 to 34.5 C, approximately 5.0 to 7.0 C warmer than nearby forests and more than 9.0 C higher than lagoonal temperatures.

Central Region. Minimum temperatures in the Central Region are 22.9 to 23.6 C over wetlands (excluding water bodies); maximums exceed 38.7 C over isolated agricultural areas. The majority of the region lies between 27.3 and 36.0 C. Cumulus clouds affect some of the satellite-derived surface temperatures in the region.

Temperature patterns in the region correspond well to those from the other dates and to vegetation and land use patterns. Marshes around Orange Lake, Lochloosa Lake and Paynes Prairie are between 24.1 and 26.1 C. Wetland forests have the coolest temperatures, with areas in the Okefenokee Swamp between 24.1 and 26.1 C. Temperatures over forested wetlands in the Santa Fe Swamp are between 25.3 and 26.5 C, while around Lake Sampson they are from 26.1 to 26.5 C. Hardwood forests in San Felasco Hammock are between 27.7 and 28.5 C. Mixed pine-cypress forests north of Gainesville are 27.3 to 28.5 C, with pine forests in Austin Cary Forest between 29.0 and 29.4 C.

Clearcuts in Austin Cary Forest are up to 6.0 C warmer than forests, although north of Lochloosa Lake temperatures of a clearcut are only 3.0 C higher, possibly reflecting
wetter conditions and greater ground cover. Other logged areas also display high surface temperatures. Examples are found 5 km southwest of Ocean Pond, east of the open-pit phosphate mine, around the town of Macclenny and in Clay and Putnam counties near the St. Johns River.

As in the Atlantic Coast Region, urban areas are influential on local temperature patterns. Downtown Jacksonville has temperatures as high as 38.3°C, with most of the urban area above 34.8°C (3.0 to 10.0°C warmer than nearby rural areas). Temperatures for Orange Park and Palatka are approximately 3.0 to 5.0°C above rural temperatures. Temperatures for Gainesville are between 33.8 and 37.2°C, which are up to 10.0°C warmer than those found in San Felasco Hammock. As in the November and December data, Cecil and Jacksonville Naval Air Stations, Jacksonville International, Green Cove Springs and Gainesville airports are notably warmer than nearby forested areas. The heavy mineral mine northeast of Starke again is warmer than forested areas. On this date temperatures were approximately 6.0 to 10.0°C warmer.

October 7, 1979

**Meteorological conditions.** The October 7, 1979 HCMM data were cloud-free and of good quality, though unfortunately complete coverage of the study area was not available (Fig. 10 and Table 7). No image data are available for the
Hastings Agricultural or Lake George Regions and therefore they will not be discussed below. The 0700 EST surface weather map shows that the region was under the influence of a high pressure cell situated in the Gulf of Mexico and air pressure was rising. No rainfall was recorded on the day of the satellite overpass and only five stations recorded rainfall five days prior to imaging, all less than 0.3 cm. Rainfall for September was above normal and ranged from 14.4 cm to 60.6 cm throughout the study area. Maximum precipitation was measured at east coast stations, with Fernandina Beach receiving the most rainfall. Central and southern stations received significantly less rainfall, most between 17.0 and 25.0 cm.

Gulf Coast Region. Minimum temperatures of 23.3 to 24.4 C are found over wetlands; maximums of 31.7 to 32.3 C are found over isolated clearings. The majority of the region lies between 24.8 and 29.9 C. The image does not cover the Gulf Coast Region south of the Suwannee River.

The limited range of the data relative to the other three day images makes it difficult to identify relationships between land cover and temperature patterns from the color-coded temperature or isotherm maps. Examination of the contrast-stretched greyscale image allows such comparisons to be more easily made. As in the other daytime images, coolest temperatures are associated with saltwater marsh, with forested wetlands slightly warmer. Pine forests are
Figure 10: October 7, 1979 HCM IR image.
TABLE 7
October 7, 1979 meteorological conditions.

<table>
<thead>
<tr>
<th>Station</th>
<th>Temperature</th>
<th>Wind Speed</th>
<th>Wind Direction</th>
<th>Relative Pressure</th>
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</table>

Daily air temperatures: Maximum of 30.6 at Usher Tower (shelter height) Minimum of 26.6 at Steinhatchee Average of 28.1

Soil temperatures: Maximum 29.4 at Monticello (10.2 cm depth) Maximum 25.5 at Gainesville

See Table 4 for explanation.
approximately 1.0 to 2.0 C warmer than forested wetlands. Logged areas are again among the warmest areas, though temperature differences with adjacent forests are low, most not exceeding 3.0 C. The maximum difference in the October data is 6.2 C. These small temperature differences may be caused by wet surface conditions since rainfall was above normal prior to the imaging time. It is also expected that ground cover in clearings and regrowth areas would be more complete in early October than in November and December after leaf loss by deciduous plants or in March before leaf area has increased greatly.

Suwannee Agricultural Region. Minimum temperatures in the Suwannee Agricultural Region are 26.3 to 27.1 C; maximums exceed 35.5 C over some agricultural areas. The majority of the region lies between 27.7 and 34.8 C. The image does not provide coverage for areas south of the town of Archer.

Temperatures in this region are not as high relative to other regions as is found in the other daytime data. The lower temperature differences are probably related to two factors. Vegetation cover in October is likely to be greater than in November or March, reducing warming of soils and allowing increased ET. It is also likely that soil moisture was greater in the October data because of the wetter than normal conditions prior to imaging.
Coolest temperatures (25.8 to 26.6 C) are associated with forested areas along the Santa Fe and Suwannee Rivers. Temperatures are from 27.1 to 27.7 C for the densest pine forests and 1.5 to 2.0 C higher for less dense forests. Agricultural land is generally between 30.2 to 34.5 C, with temperatures exceeding 34.8 C for several areas. Lake City has a well defined heat island, with maximum temperatures approximately 6.0 C above those of nearby forested areas. The open-pit phosphate mine does not appear to have the warming influence in the October image found in the other images. This may be caused by wet conditions related to the higher-than-normal rainfall received prior to imaging.

Interlachen Karst Region. Minimum surface temperatures are 26.3 to 27.1 C around lakes and wetlands; maximums of 34.8 to 35.5 C are found east of Lake Geneva. Most of the region lies between 30.2 to 33.4 C. The southern portion of the region is not included in the October image.

As in the other daytime images, longleaf pine-turkey oak forests experience the highest surface temperatures. The sparsely forested area east of Lake Geneva is the warmest section of the region with temperatures from 34.5 to 35.5 C, or 4.0 to 5.0 C higher than nearby pine flatwoods. Temperatures over Camp Blanding are cooler, between 31.0 and 33.4 C. The heavy mineral mine west of Kingsley Lake is also visible, with maximum temperatures of 33.7 C. Agricultural areas are not covered in this image.
Atlantic Coast Region. Minimum temperatures are 24.8 to 25.8 C over lagoons and wetlands; maximums are 33.7 to 34.5 C over eastern Jacksonville. Most of the region has temperatures between 26.3 and 29.9 C. Temperature patterns are similar to those found in the other day images and again reflect vegetation and land use patterns. Forested areas and wetlands are the coolest land covers, with agricultural and logged areas 1.0 to 3.0 C warmer. Slight evidence of the striping related to Pleistocene beach ridges is visible, though data are not available for the southern portion of the region where this striping is most pronounced in other daytime images. Eastern Jacksonville has a well-developed heat island with maximum urban-rural temperature differences greater that 8.0 C. Jacksonville Beach is also 2.0 to 3.0 C warmer than surrounding rural areas.

Central Region. Minimum temperatures of 24.8 to 25.8 C are found over wetlands; maximum temperatures exceed 35.5 C over eastern Jacksonville. The majority of the region lies between 25.8 and 29.1 C. Overlaying of the October imagery with other daytime data sets shows that temperature patterns are similar despite the reduced range of the data. Wetlands are the coolest land covers, with wetland forests in the Okefenokee Swamp between 24.8 and 25.8 C. Wetland forests in the Santa Fe Swamp are from 26.3 to 27.1 C, and around Lake Sampson they are between 26.3 and 26.6 C. Mixed pine-cypress forests north of Gainesville are between 26.3 and
28.8 C, while in Austin Cary Forest temperatures are 27.7 to 28.8 C.

As in the Gulf Coast Region, logged and agricultural lands do not display large temperature differences relative to forested areas as is found in the November and March data. These small temperature differences are likely related to wet surface conditions and a greater percentage of ground cover in clearings. This is particularly evident in the northern part of the Central Region where clearcuts are only 1.0 to 2.0 C warmer than forests. Temperature differences between clearings and forest in Austin Cary Forest are approximately 4.5 C. Similar temperature differences between clearcuts and pine flatwoods are seen in Putnam and Clay county.

Urban and industrial land covers again are notable in the imagery. Jacksonville has a well-developed heat island with downtown temperatures of 38.2 C -- up to 10.0 C higher than nearby rural areas. Orange Park is approximately 6.0 C warmer than nearby rural areas, and though only northern Gainesville is covered by the image temperatures are 4.0 to 5.0 C higher over the city than for surrounding forests. Airports are again readily seen, with Cecil Field and Jacksonville Naval Air Stations, Jacksonville International, Green Cove Springs and Gainesville airports displaying temperatures from 2.0 to 7.0 C greater than nearby rural areas. The heavy mineral mine northeast of Starke has temperatures 2.0 to 3.0 C higher than nearby forests.
Nighttime Surface Temperature Patterns

May 21, 1978

Meteorological conditions. Parts of the study area experienced fog on the night of May 21st and therefore interpretation of the underlying surface temperatures is difficult in many areas (Fig. 11 and Table 8). Heavy fog is found over parts of the Interlachen Karst, Central and Atlantic Coast Regions, with surface temperatures being completely obscured in these areas. Fog also seems to have been present over the Suwannee River valley along the border between Lafayette and Suwannee counties, obscuring the river in this area. Other areas influenced by fog may exist, but it is difficult to determine the exact extent of such areas.

No rainfall was recorded at the time of the satellite overpass. Several stations recorded between 1.2 and 2.5 cm of precipitation five days prior to May 21. Rainfall for the month of May was above normal for most of the region, with maximum precipitation occurring within the first five days of the month.

Gulf Coast Region. Minimum temperatures in the Gulf Coast Region are below 16.1 C and are found in agricultural and clearcut areas. Maximum temperatures of 21.7 to 22.2 C scattered throughout the study area are related to wetlands and small lakes. The majority of the region lies between 17.1 to 20.4 C. Fog appears to influence the temperatures in some portions of the region.
Figure 11: May 21, 1978 HCMR IR image.
TABLE 8
May 21, 1978 meteorological conditions.

<table>
<thead>
<tr>
<th>Station</th>
<th>Temperature</th>
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<th>Wind Direction</th>
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</table>

Daily air temperatures: Maximum of 19.4 at Jacksonville
(shelter height) Minimum of 14.4 at Several stations
Average of 15.9

Soil temperatures:
Maximum 21.1 at Monticello
(10.2 cm depth) Maximum 23.9 at Gainesville

All temperatures are given in degrees C, windspeeds in km/hr, wind direction in tens of degrees counterclockwise from north, relative humidity in percent and pressure in millibars. Temperature, wind speed, wind direction and relative humidity for Jacksonville, Tallahassee, Orlando and Tampa were taken at 0100 EST. Pressure was obtained from the 0700 EST surface weather map.
It is more difficult to relate nighttime temperature patterns to land use and land covers than it is for the daytime data. A weak inverse relationship between day and night temperature patterns is evident in some parts of the study area; surface materials with the highest day temperatures tend to be the coolest at night. A correspondence between lower temperatures and agricultural and logged areas is evident in parts of the region. Logged areas that have an inverse relationship to day temperature patterns can be found west of the junction of the Santa Fe and Suwannee rivers, in northern Lafayette county and northeast of Cedar Key. These areas are typically 1.0 to 2.0°C cooler than nearby forested areas. Not all lumbered areas appear cool in the data. Areas near the coast in Dixie county are warmer by 1.0 to 2.0°C than surrounding forests, most likely because of wet conditions at these sites.

The coolest areas in the day images, which are wetlands and water bodies, are generally the warmest areas in the night data. Small lakes not visible in the daytime data are readily seen in the night image. The lower Suwannee River and adjacent forested wetlands are readily identified by their warm signatures, as are coastal marshes and wetlands. Temperatures 0.5 to 2.5°C warmer than nearby pine forests and up to 4.5°C warmer than agricultural and logged areas are common for wetlands.
Suwannee Agricultural Region. Minimum temperatures in the Suwannee Agricultural Region are below 16.1 °C; maximums are 21.7 to 22.2 °C. The region is not as well defined as in daytime images, particularly north of the Santa Fe River. The Suwannee Agricultural Region can be divided into two thermal subregions in this (May 21, 1978) image. The first is an area of cooler temperatures located in Suwannee, Levy and Gilchrist counties around the intersection of the Suwannee and Santa Fe rivers and extending northward into Hamilton county. Most of this section is between 16.1 and 17.5 °C, with little temperature difference between agricultural and forested sites. Warmer temperatures are found along rivers and around lakes where the warming influence of water is dominant.

The second subregion is for the most part 0.5 to 2.5 °C warmer and is non-contiguous. Included are agricultural areas in Lafayette, western Suwannee, Marion, Alachua and southern Levy counties. The areas in Lafayette and Suwannee county are primarily agricultural, with warmest temperatures over forested areas along the Suwannee. Warm temperatures in these counties are most likely caused by the presence of fog because the otherwise clearly visible Suwannee River is obscured. In Marion and Alachua counties the Suwannee Agricultural Region boundaries are fairly well defined. Warmest temperatures here are 18.9 to 20.4 °C in eastern Levy county for an area of mixed pasture, pine and hardwood
forest. South of Levy Lake similar temperatures are found over a similar area of mixed pasture and pine and hardwood forest. Coolest areas (16.1 to 16.6°C) are found over pastures.

Urban areas exert little influence on surface temperature patterns in the Suwannee Agricultural Region. No heat islands are evident for either Lake City or Ocala. The open-pit phosphate mine is readily identified in the imagery, primarily because of associated settling ponds. Temperatures associated with the mine range from 18.9 to 23.5°C.

Interlachen Karst Region. Much of the Interlachen Karst Region is under the influence of fog and therefore it is difficult to obtain reliable temperatures in the region. Two observations however can be made about the region. First, because of the large thermal contrast between land and water, lakes are better defined in the nighttime images than in the daytime images. Several of the smaller lakes are identifiable either individually or as warm spots representing clusters of lakes. Second, an agricultural area south of George's Lake in the eastern part of the region shows up as a cool (16.1 to 16.6°C) site as would be expected of a sparsely vegetated surface with well drained soils.
Hastings Agricultural Region. The majority of the Hastings Agricultural Region is affected by fog cover. The southern portion east of Palatka appears to the least affected, and here low surface temperatures (16.1 to 16.6 C) are associated with agricultural lands.

Lake George Region. The Lake George region does not appear to be under the influence of fog. Minimum temperatures are below 16.1 C and maximums exceed 23.9 C for water bodies. The majority of the region has temperatures from 16.1 to 18.4 C. The generally low temperatures are expected because the relatively open forests and well drained soils found in the region would allow a relatively high rate of radiative cooling. The large number of small clearcuts within the forest would also tend to increase radiative cooling in the area. Relationships between temperature and forest type are difficult to find, but it appears that longleaf pine turkey-oak forests are 0.5 to 2.0 C warmer than sand pine forests. Examples can be found south of Rodman Reservoir and Lake Kerr. Both areas are notable for increased temperatures in the day images. Beckenbach and Hammet (1962) show the longleaf pine-turkey oak areas to be underlain by well to moderately well drained soils and the sand pine forests to be in areas of excessively drained soils. The correspondence of surface temperatures with soil drainage characteristics suggests that soils are important in determining nighttime
temperatures in the area. Warmest temperatures east of Lake George are associated with the numerous small lakes in that area. Forested areas between Lake George and Crescent Lake are mostly cooler than agricultural areas.

Atlantic Coast Region. The northern portion of the Atlantic Coast Region is heavily influenced by fog, with only coastal marshes easily identifiable in this section. South of St. Augustine the fog appears to be less influential. Minimum temperatures here are 16.1 to 16.6 C; maximums are in excess of 23.9 C over lagoonal areas. Though temperature patterns are difficult to relate to land covers because of the limited range of temperatures, it appears that forested areas are approximately 0.5 to 1.0 C cooler than agricultural areas. A slight striping is visible in the image, following the direction of the Pleistocene beach ridges found in the area. Lagoonal areas are easily identified by their warmer signatures. Daytona Beach has a well-defined heat island with temperatures from 18.9 to 20.4 C, which are approximately 2.0 to 4.5 C higher than nearby urban areas. No other heat islands are visible in the region.

Central Region. The majority of the Central Region east of Palestine Lake in Union county and north of Lake Santa Fe in Alachua county is severely affected by fog, with most surface temperatures completely obscured. Scattered fog
also affects temperatures elsewhere in the region. Pine forests in the northwest section of the region have temperatures from 16.1 to 16.6 C, with clearings below 16.1 C. Mixed pine and cypress forests around Gainesville are between 17.1 and 18.4 C, with clearings below 16.6 C. The dominantly hardwood forests in San Felasco Hammock display similar temperatures. Pastures around Paynes Prairie have temperatures below 16.6 C.

Particularly notable in the region is the prominence of wetlands. Paynes Prairie, south of Gainesville, is exceptionally well defined in the image, with temperatures approximately 2.0 to 5.0 C greater than surrounding areas. Visible in the prairie is open water in the northeast, with dry pastures along the northern and southern edges slightly warmer. A region of dry prairie between U. S. 441 and Interstate-95 displays the highest temperatures. Levy Lake, another prairie in southern Alachua county, displays similar temperature patterns, as do wetlands surrounding Orange Lake and Lochloosa Lake. Wetlands north of Ocean Pond are visible and cypress swamps in the Okefenokee Swamp in the northern portion of the study are well defined.

The urban areas of Jacksonville and Gainesville influence local surface temperature patterns. In spite of being under fog cover, downtown Jacksonville is visible, with temperatures from 20.7 to 22.2 C. Comparisons with other local temperatures are not possible because of the shrouding
fog. Gainesville has a particularly well defined-heat island. The downtown area has temperatures from 20.7 to 21.3 C, with most of the city between 18.9 C and 20.4 C. Maximum urban-rural temperature differences here exceed 5.0 C.

November 3, 1978

Meteorological conditions. The November 3, 1978 data were acquired during the passage of a cold front (Fig. 12 and Table 9). Cloud cover related to the front can be seen over the eastern coast of the study area and just west of the St. Johns River, obscuring surface temperatures in these areas. High wind speeds ahead of the front produce considerable wind smear from water bodies south of a line running from Jacksonville to Waccasassa Bay. Because of this problem, the Interlachen Karst, Atlantic Coast, Hastings Agricultural and Lake George Regions will not be discussed below. North of this line wind speeds are lower and skies are clear. The front was dry, with only trace precipitation recorded at one station in the study area. Several stations recorded small amounts of rainfall within five days prior to imaging, though only three recorded more than 0.7 cm. The month of October 1978 was drier than normal for most of the study area, with 1.3-9.1 cm of rainfall. For October 1978 Daytona had anomalously high rainfall, with 21.0 cm.
Figure 12: November 3, 1978 HCMM IR image.
### TABLE 9

November 3, 1978 meteorological conditions.

<table>
<thead>
<tr>
<th>Station</th>
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Daily air temperatures: Maximum of 14.4 at Fernandina (shelter height) Minimum of 4.4 at Cross City Average of 8.5

Soil temperatures: Maximum 15.0 at Monticello (10.2 cm depth) Maximum 22.7 at Gainesville

See Table 8 for explanation.
Gulf Coast Region. Minimum temperatures in the Gulf Coast Region are below 7.9 °C over clearings and agricultural areas; maximums are 15.1 to 16.4 °C over coastal marshes, wetlands and water bodies. The majority of the region lies between 8.4 and 11.5 °C. Temperature patterns are similar to those found in the May 21, 1978 data.

Inspection of the greyscale imagery shows a close correspondence between sites displaying the coldest temperatures (below 7.9 °C) and areas that are sparsely vegetated. These areas also displayed the lowest temperatures in the May data. Examples can be found 15 to 20 km west of the junction of the Santa Fe and Suwannee Rivers and approximately the same distance west of the Suwannee River in Lafayette county. Cooler areas northeast of Cedar Key and just north of Waccasassa Bay correspond to logged areas that are generally warmer in the daytime imagery. Temperatures from 8.4 to 9.7 °C are found over most pine flatwoods, and areas between 10.1 and 11.5 °C are mostly associated with forested wetlands. These temperature-land cover relationships are readily seen around the logged area west of the junction of the Santa Fe and Suwannee Rivers.

Several warm areas along the border between the Gulf Coast and the Suwannee Agricultural Regions are related to lakes along this boundary. The Suwannee River valley is particularly well defined because of its relatively high temperature (mostly above 11.5 °C), as are coastal marshes.
Delineation of coastal marshes is more readily done using this November 3, 1978 night image than using any of the day images.

**Suwannee Agricultural Region.** The Suwannee Agricultural Region is slightly affected by wind smear in Alachua, Marion and southern Levy counties. North of these counties the data are of good quality. Minimum temperatures are below 7.9 C; maximums are greater than 12.8 C over water bodies.

Again the region appears to separate into two subregions, with the cooler temperatures in the north and warmer ones in the south. Most of the northern region is below 7.9 C, and the south is between 8.4 and 11.1 C. Warmest temperatures in the north are associated with water bodies and bottomland hardwood forests such as in the Lake City karst area and along the Suwannee and Santa Fe Rivers. Agricultural lands and pine forests exhibit similar temperatures and it is difficult to consistently differentiate between the two cover types. The open-pit phosphate mine is again notable for its high temperatures.

Temperatures in the southern section are mostly above 8.4 C, though some agricultural areas are cooler. The highest temperatures are associated with bottomland forests and lakes. Slightly warmer temperatures, between 10.1 and 11.5 C, are found over mixed pine and hardwood forests and most agricultural lands are between 8.2 to 9.7 C.
Central Region. Much of the Central Region is affected by cloud cover and high wind speeds, therefore only select portions of the region will be discussed. Minimum temperatures are below 7.0 C, with maximums of 12.8 to 13.3 C over urban areas (excluding water bodies). Pine forests in Hamilton and Columbia counties again display some of the lowest temperatures in the region (7.9 C and below). Temperatures over pine forests in the Gainesville area are between 8.4 and 9.7 C, with logged areas below 7.9 C. Similar temperatures are found over San Felasco Hammock. Wetlands again are important in influencing temperature patterns. Paynes Prairie and Levy Lake both have temperatures above 11.9 C, and wetlands around Ocean Pond and in the Okefenokee Swamp are also visible.

The Gainesville urban area also is well defined by higher temperatures. Downtown temperatures are up to 15.1 to 16.4 C, with most of the city between 11.9 and 13.3 C. Urban-rural temperatures differences range from approximately 1.0 to 8.0 C.

February 1, 1979

Meteorological conditions. Cloud cover obscures surface temperatures in some northern areas and advection of heat from Lake George and Crescent Lake is evident over land surfaces south of these water bodies (Fig. 13 and Table 10). Elsewhere meteorological conditions were adequate to allow
interpretation of surface temperature patterns. Shelter-height temperatures for most of the study area are below 0.0 C, making this the coldest imaging date. No rainfall was recorded in the study area on the day of the data collection though most stations recorded more than 1.2 cm on January 31. January of 1979 was wetter than normal, with all stations recording more than 13.8 cm of rainfall. Highest rainfalls were recorded at Usher Tower and High Springs, with 26.9 and 28.9 cm respectively.

Gulf Coast Region. Temperatures in the Gulf Coast Region range from less than 0.6 C over sparsely forested areas to over 5.7 C along the Suwannee River. The majority of the region has temperatures between 0.6 and 4.5 C. Cloud cover affects surface temperature measurements in Lafayette county.

The low range of temperatures makes land cover-temperature relationships difficult to ascertain. Sparsely vegetated areas again exhibit the lowest temperatures. The logged area west of the junction of the Suwannee and Santa Fe Rivers again is cool, with temperatures 1.0 to 2.0 C below nearby forested areas. Lumbered areas around Waccasassa Bay are also slightly cooler than nearby forested areas. Differences in temperatures between different forest types are small and often not detectable. Highest temperatures for surfaces other than water bodies are for forested wetlands near the Gulf coast in Dixie county where
Figure 13: February 1, 1979 ECMWF IR image.
TABLE 10
February 1, 1979 meteorological conditions.

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<tr>
<th>Station</th>
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<td>30</td>
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</tr>
<tr>
<td>Tampa</td>
<td>7.2</td>
<td>16.6</td>
<td>34</td>
<td>74</td>
</tr>
</tbody>
</table>

Daily air temperatures: Maximum of 2.2 at Jacksonville (shelter height)
Minimum of -5.5 at Starke
Average of -2.5

Soil temperatures: Maximum 2.7 at Monticello
Maximum 9.4 at Gainesville

See Table 8 for explanation.
temperatures are between 4.1 and 4.5 C. Similar temperatures can be found for some forested wetlands in Levy county. Wetlands and lakes are evident because of their warmer temperatures, with coastal marshes, the Suwannee River and lakes along the border between the Gulf Coast and Suwannee Agricultural Regions above 4.9 C.

Suwannee Agricultural Region. Temperatures in the Suwannee Agricultural Region range from less than 0.6 C over agricultural lands to greater than 4.9 C over water bodies. Temperatures for agricultural areas are 1.0 to 4.0 C cooler than those of forests. The region can again be divided into two sections -- the cooler north and warmer south. The northern portion of the region is partially obscured by clouds. Temperatures are mostly below 1.1 C, but temperatures between 1.5 and 2.7 C are found in wetter areas around Lake City and over some forested areas. The southern section is cloud free and mostly warmer than 1.5 C. The boundaries of the region are well defined below the Santa Fe River. Lowest temperatures are found over sparsely forested well drained areas along the western border of the region. Here temperatures below 1.9 C are common. The majority of the agricultural lands exhibit temperatures of 2.3 to 2.7 C, with the more heavily forested areas between 3.2 and 3.6 C.

Interlachen Karst Region. The Interlachen Karst Region is readily identified by cooler temperatures as would be
expected because of its well drained sandy soils. Minimum temperatures are 0.6 to 1.1 C, while maximums are greater than 4.9 C over lakes. The coldest areas are found over sparsely vegetated longleaf pine-turkey oak forest and over agricultural land. These areas are consistently the warmest in the day images also. Notable in the region is the large number of small lakes that are highly visible because of the high land-water temperature contrast in the data. The heavy mineral mine in the region does not have an important influence on temperatures.

Hastings Agricultural Region. The Hastings Agricultural Region is poorly defined in this February 1, 1979 image, but lower temperatures are evident in the area. Temperatures over agricultural lands are between 2.3 and 3.6 C while nearby forested areas are approximately 1.0 to 2.5 C warmer. The relatively warm temperatures found in the Hastings Agricultural Region as compared to other sparsely vegetated areas are probably related to the poorly drained soils in the area and possibly to a warming influence by the nearby St. Johns River.

Lake George Region. Low temperatures are found over the Lake George Region because of the well drained soils and sparse pine forests. Comparison with forested areas to the west in the Central Region and to the east in the Atlantic Coast Region show that the Ocala National Forest is
generally 1.0 to 2.5 C cooler. Lowest temperatures occur over agricultural land north of Lake George and over the heavily lumbered pine forests in the eastern part of the Ocala National Forest. Temperatures approximately 0.5 to 2.0 warmer are found over longleaf pine-turkey oak forests. Lakes and water bodies are easily identified by their higher temperatures and bottomland forests along the Oklawaha River are also clearly defined.

**Atlantic Coast Region.** Surface temperatures in the Atlantic Coast Region are relatively warm, with most areas above 4.1 C. A notable lack of contrast is found in the region, possibly because of the moderating influence of the Atlantic Ocean. This lack of contrast makes comparisons of surface temperatures with land cover difficult for most of the region.

Cooler temperatures in some areas can be related to agricultural or sparsely-forested lands. One such area is found just east of Crescent Lake, where temperatures are approximately 1.0 C cooler than in surrounding areas. A similar area is located east of the St. Johns River near Green Cove Springs. Warm temperatures south of St. Augustine are not readily related to land covers but probably are found over wetter areas. No urban heat islands are visible in the region.
Central Region. The northern portion of the Central Region is affected by cloud cover, with most of Hamilton, Baker and Nassau counties obscured. Minimum temperatures elsewhere are below 0.6 C; maximums exceed 4.9 C over water bodies and wetlands. Coldest temperatures are found over areas that have been extensively lumbered or are agricultural. Good examples of such areas can be found southwest of Cecil Field Naval Air Station where lumbered areas are 0.5 to 1.5 C cooler than nearby forests (forested areas have temperatures of 1.5 to 2.7 C). Similar temperatures are found for lumbered areas around Penney Farms, Green Cove Springs and north of Newnans Lake. Forests south of Gainesville and east of the Oklawaha River are slightly warmer than those to the north, having temperatures from 3.2 to 4.5 C. Examination of shelter-height temperatures shows that these temperature differences are more likely caused by a slight north-south temperature gradient than by differences in forest type or structure. Cooler sites within these southern forests that are identifiable as clearings have temperatures approximately 0.5 to 1.5 C cooler than well-vegetated areas. This difference is similar to that found in the cooler forests to the north where temperatures are lower overall.

Wetlands are again prominent in the region. Wetland forests in the Okefenokee Swamp are visible in spite of intermittent cloud cover. Areas around Ocean Pond and Lake
Santa Fe are not as well defined as in other images, but those associated with Orange Lake, Lochloosa Lake, Lake Levy and Paynes Prairie are all easily identified. Paynes Prairie is again particularly well defined, with noticeable temperature differences between water, wet prairie and dry prairie. No notable urban heat islands are found in the region.
CHAPTER VI
DISCUSSION AND COMPARISON TO PREVIOUS INVESTIGATIONS

Several general relationships between land cover and surface temperature can be derived from the detailed descriptions given in the previous chapter. These observations are discussed and compared to findings of other studies.

Consistency of Surface Temperature Patterns

Visual examination of the daytime imagery shows that daytime temperature patterns are similar in form, if not magnitude, in fall, winter and spring in north-central Florida. This correspondence between temperature patterns exists, though to a lesser degree, even under changing weather conditions such as found in the December 17, 1978 data. The degree of overall similarity between the different images is given by correlation coefficients (Table 11). Correlations between the different day images are high for both the entire study area and the individual thermal regions. Correlations are lowest for the December 17, 1978 data because of the poor meteorological conditions under which the data were collected.
TABLE 11

Correlation coefficients.

Correlation matrix calculated from DNs for the entire study area. (Atlantic Ocean and Gulf of Mexico excluded).

<table>
<thead>
<tr>
<th></th>
<th>11-05-78</th>
<th>12-17-78</th>
<th>03-28-79</th>
</tr>
</thead>
<tbody>
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<td>11-05-78</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>12-17-78</td>
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<td>1.00</td>
<td></td>
</tr>
<tr>
<td>03-28-79</td>
<td>0.88</td>
<td>0.63</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Correlation matrix calculated from DNs for a subset of the data based on area covered by October 7, 1979, (Fig. 10, Atlantic Ocean and Gulf of Mexico excluded).

<table>
<thead>
<tr>
<th></th>
<th>11-05-78</th>
<th>12-17-78</th>
<th>03-28-79</th>
<th>10-07-79</th>
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<td>12-17-78</td>
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<td>1.00</td>
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<td>0.81</td>
<td>0.73</td>
<td>0.83</td>
<td>1.00</td>
</tr>
</tbody>
</table>

All correlation coefficients are significant at the 0.01 confidence level.
Visual inspection of the imagery shows that a correspondence also exists between the different nighttime images. The correspondence between the different night images is not as strong as that found between the day images, partially because of the poor quality of the nighttime data. Statistical correlations were not calculated for the night data because of the poor quality of the images. Night surface temperature patterns observed in this study are similar to those described in other studies of north-central Florida nocturnal temperature patterns (Chen et al., 1982; Allen et al., 1983).

A weak inverse relationship exists between daytime and nighttime surface temperature patterns, particularly over well drained agricultural lands and wetlands. This inverse relationship has been noted also by Chen et al. (1979) and Allen et al. (1983) for peninsular Florida, and by Kalma et al. (1983) for areas around Melbourne, Australia. The inverse relationship between day and night temperatures of well drained soils is the result of the low thermal inertias of these soils, allowing large diurnal temperature fluctuations. In clearcuts this relationship points to the importance of radiative warming and cooling in the absence of vegetation that otherwise would block incoming solar radiation from the surface and prevent its escape at night.
Surface Temperatures and Natural Land Covers

Daytime surface temperature patterns in north-central Florida are more strongly affected by land cover patterns than are nighttime temperature patterns. Similar findings have been noted by Carlson et al. (1981), Vukovich (1983) and Kalma et al. (1983). This lack of differentiation between land covers in the night data is partly a function of the constant sensitivity (approximately 0.3 to 0.4 C per DN) of the HCMM radiometer and the smaller range of temperatures typically found at night. Radiometers with increased radiometric resolution can be adjusted to provide a greater number of DN's by decreasing the upper and lower temperatures ranges for nighttime sensing while simultaneously increasing the sensitivity of the sensor to 0.2 C or less per DN. The improved differentiation of land covers in the day data is also caused by the fact that surface temperature differences are commonly found at or near the early afternoon time of the HCMM overpass (Price, 1977).

The much weaker influence of land cover and land use on nighttime temperature patterns is particularly evident where relatively small-scale land cover variations are found. This is notable for planted pine forests within the Suwannee Agricultural Region where nighttime cooling leads to relatively homogeneous temperature patterns. Forested areas covering less than 0.19 km² are identifiable in daytime HCMM
images, while some covering 18.5 km² are not readily seen in the night data.

Carlson et al. (1981) and Goward (1981) state that surface moisture availability is the dominant controlling factor in surface temperatures for urban areas. The results of this study suggest that this is also one of the, if not the most, important factor controlling daytime surface temperatures in north-central Florida. The availability of moisture allows a larger portion of incoming solar radiation to be partitioned to latent rather than sensible heat fluxes, resulting in reduced surface temperatures. These latent heat fluxes can occur as the result of evaporation over open water bodies or soils, or from ET over vegetated surfaces.

Canopy density appears to be the other dominant factor affecting surface temperatures. Sader (in press) found that forests with a more closed canopy exhibit lower temperatures than do younger, less dense forests. Soils will generally reach temperatures that are much higher than the overlying vegetation canopy (Kimes, 1980; Kimes et al., 1980). A dense vegetation cover intercepts the majority of the incoming solar radiation (Monteith, 1973), therefore minimizing the warming of the soil surface. Likewise, the amount of soil visible to the sensor is a function of canopy density, thereby influencing surface temperature measurements (Kimes et al., 1980; 1983). At night a more
open canopy will allow a greater amount of energy to be lost to radiative cooling, resulting in lower surface temperatures (Geiger, 1966; Oke, 1978).

The daytime gradation of natural land covers from coolest to warmest reflects the importance of surface moisture and vegetation density in determining daytime surface temperatures in north-central Florida. Lowest temperatures are found over open water bodies where evaporative cooling and the high thermal inertia of water would keep temperatures low.

A precise daytime gradation of vegetation types from coolest to warmest is difficult to find because of overlapping temperatures of different land covers. In spite of this, a general pattern can be seen that reflects the importance of surface moisture availability and vegetation cover. Coastal marshes are commonly the coolest land cover, with adjacent wetland forests slightly warmer. Freshwater marshes such as found in Paynes Prairie, and cypress swamps similar to those in Santa Fe Swamp, have temperatures similar to or slightly warmer than those found in coastal wetland forests. The wettest pine-cypress flatwoods and riverine hardwoods are next in the gradation, being slightly warmer. Dominantly hardwood forests such as those found in San Felasco Hammock and dense pine forests have temperatures slightly above mixed pine-cypress flatwoods. Planted pines on well drained soils are slightly warmer, with temperatures
increasing as canopy closure decreases. Sand pine and longleaf pine-turkey oak forests are the warmest natural vegetation covers.

Seasonal variations related to leaf-off or full-leaf conditions of deciduous vegetation are difficult to find for most areas. The one exception is found in dominantly hardwood forests in San Felasco Hammock. Here hardwoods in full-leaf in the October images are 0.5 to 1.0 C cooler than dense pine forests, while in the November, December and March images no such difference can be found.

Consistent relationships between nighttime surface temperatures and vegetation cover are more difficult to find than those in day images, mainly because of the low-temperature ranges and poor quality of the night data. Lakes and marshes are usually well defined in night data by their warm signatures and are often easier to identify than in the day data. Wetter forests, particularly those along rivers and around lakes are also relatively easy to identify.

It has been stated by several authors that forests typically exhibit warmer temperatures than do agricultural or cleared lands (Sabins, 1978; Balick and Wilson, 1980; Fritschen et al., 1982; Kalma et al., 1983). This pattern is visible in some areas, particularly in the Gulf Coast Region where differences between clearcuts and adjacent forests are evident, and in the southern part of the February 1, 1979 data.
This pattern is not as well defined in the northern Suwannee Agricultural and Central Regions. Higher temperatures are found over some hardwood and mixed hardwood-pine forests, particularly in low-lying areas. Pine forests, on the other hand, often have temperatures that are similar to those found over agricultural lands. In some areas these low temperatures can be related to clearing of the forest cover or to the location of the forests on well drained soils, while in others such an explanation cannot be found.

Where these temperature similarities cannot be explained by land cover or soil type, meteorological conditions may provide an explanation. The presence of fog and antecedent scattered thunderstorm activity in the May 21, 1978 image complicates interpretation of that image, making accurate determinations of surface temperature difficult. Warm temperature over agricultural lands may be related to fog or moisture from thunderstorms. Low temperatures in the northern pine flatwoods in the February 1, 1979 data may be the result of the north-south temperature gradient and overall low temperatures as well as the cloud cover visible in the data.

The November 3, 1978 image data were collected either under high wind speeds (18.5 km/h measured at 0100 EST at Orlando) as in the southern portion of the data, or shortly after the occurrence of high wind speeds as northern portion
High winds tend to homogenize surface temperatures via advection of sensible heat. Temperature decreases at the top of the canopy (the active radiating surface of a dense forest) would be expected, because wind speeds would be higher than within the canopy (Geiger, 1966). In sparse stands, such as young planted pines, winds speeds may be adequate to reduce temperatures even in the trunk area.

Longleaf pine-turkey oak communities and sand pine forests are among the coolest forest covers because their location on excessively-drained sandy soils and minimal crown closure makes them effective radiators at night.

Surface Temperature and Cultural Land Covers

Modifications of natural vegetation covers greatly influence surface temperature patterns in the study area. The four primary modifications of natural land covers are the clearing of forests for agricultural lands, clearcut logging, urbanization and industry.

Agricultural Land Covers

By virtue of their areal extent as well as high surface temperatures, agricultural lands exert the greatest influence on temperature patterns in north-central Florida. This is particularly true in the Suwannee Agricultural and Hastings Agricultural Regions, where temperature differences
relative to forested areas often exceed 10.0 C for the November and October data.

Daytime surface temperatures over agricultural lands approach or exceed 40.0 C in the November 5, 1978 and October 7, 1979 dates. Surface temperatures of this magnitude are not unreasonable for sparsely-vegetated agricultural lands, with temperatures often exceeding this value (Pinter et al., 1979; Kimes et al., 1980; Kimes; 1980; Byrne et al., 1981). Temperatures cited here probably do not reflect the maximum surface temperatures found over agricultural land in the study area since the large field of view of the sensor will typically not contain only agricultural lands.

Lower surface temperatures for agricultural land covers are found in the December 17, 1978 data because of the overall low temperatures on that date. Relatively low surface temperatures in the October 7, 1979 data are most likely caused by high surface moisture since wetter than normal conditions prevailed prior to imaging, and more complete ground cover likely to be found on the November, December or March imaging dates. Temperature differences between agricultural and forest land covers are low for these two, on the order of 5.0 C or less.

Nighttime surface temperatures are generally low over bare agricultural areas because trapping of outgoing longwave radiation is minimal. This is particularly notable in the February data.
Forestry Practices

The practice of clearcutting is known to modify the local climate of forests because the removal of vegetation affects radiation, hydrological, soil temperature and mass transfer regimes (Geiger, 1966; Lee, 1978). Increases in surface temperatures also have been measured for clearcuts and young timber stands. Temperature relative to mature forest in the Pacific Northwest measured using 30-m aircraft scanner data were 8.0-9.0°C for 0-12 year old stands and 2.5°C for 25-33 year old stands (Sader, in press).

In north-central Florida, logging practices exert a considerable influence on regional temperature patterns because of the extent of lumbering activity in the region. Approximately seventy percent of the land in north-central Florida is used for commercial forestry (Sheffield, 1980). Day temperature differences between logged sites and mature forests are highest in the November and March data, ranging from less than 2.0°C to greater than 8.6°C. The lower temperature differences cited here compared to those in the Pacific Northwest can be attributed to several factors. These include the coarse resolution of the HCMM satellite that increases the number of mixed pixels and the wet conditions often found in pine flatwoods in north-central Florida. Rapid regrowth of herbaceous species in clearcuts would also be important by reducing the amount of exposed soil that would tend to have high temperatures (Conde et al., 1983a; 1983b).
The influence of logging practices on night temperatures is less evident than that seen in day images. Clearcuts identified in the nighttime images are generally cooler than surrounding forests. These lower temperatures are the result of the lack of an extensive vegetation canopy that allows increased radiative cooling of the surface (Geiger, 1966). Not all cleared areas exhibit low temperatures; wet clearcuts, such as those found near Cedar Key, will typically have temperatures above those of adjacent forests. These areas exhibit a thermal behavior similar to wetlands and flooded agricultural lands (Chen et al., 1982).

Urban and Industrial Land Covers

Increased surface temperatures of urban areas have been noted in several studies and have been attributed to thermal characteristics of typical urban materials, decreased moisture availability over sparsely vegetated surfaces, low albedos of urban areas and the structure of the urban canopy (Pease et al., 1976; Oke, 1978; Carlson et al., 1981; Goward, 1981; Vukovich, 1983).

Several urban areas exhibit notably higher surface temperatures than do surrounding rural areas. Strongest day urban-rural temperature differences are found over Jacksonville, Daytona, Lake City, Palatka and Gainesville. Other notable urban areas are Ocala, St. Augustine, Orange Park and Palm Bay. Urban-rural temperature differences
range from less than 4.0 to greater than 10.8°C, and as noted by Vukovich (1983), are smaller in the winter. Urban-rural temperature differences found in north-central Florida are less than summer maximums cited by Price (1979) for several New England cities, but similar to those cited by Matson et al. (1978) for the midwest and northeast U.S., and by Carlson et al. (1981) and Vukovich (1983) for St. Louis and Los Angeles.

The importance of night urban heat islands is difficult to assess from the HCMM images because of the poor quality of the data. Gainesville has a noticeable heat island in two of the night images, with urban-rural temperature differences from 3.3 to 4.3°C for the May 21, 1978 data, and up to 5.4°C in the November 5, 1978 data. Daytona Beach is up to 4.5°C warmer than nearby rural areas in the May image. These are similar to those cited by Matson et al. (1978) for several midwestern and northeastern cities, and slightly warmer than those given by Vukovich (1983) for St. Louis.

It is important to note that the above urban-rural temperatures differences were made by comparing maximum urban surface temperatures with those of nearby forested areas. When comparisons are made between urban areas and clearcuts, agricultural lands or longleaf pine-turkey oak forests, these temperature differences disappear or reverse themselves. Given the relatively large extent of agricultural, deforested or naturally vegetated land covers
in north-central Florida, the relative significance of urban heat islands is somewhat diminished. This is particularly true for the towns of Lake City, Gainesville, Palatka and Ocala, all of which border agricultural areas.

Airports are notable for their high daytime temperatures. This is particularly true of Cecil Field and Jacksonville Naval Air Stations. Smaller airports or those with greater amounts of vegetation typically have lower surface temperatures. Airports are not notable in the night data.

Three surface mines in the study area, the two heavy mineral mines near Starke and the phosphate mine in Hamilton county, generally are warmer than nearby forests. Higher temperatures in these areas are most likely caused by the large amount of exposed soil at these sites. The heavy mineral mines are not notable in the night imagery. The phosphate mine is highly visible at night because of the warm temperatures of settling ponds.

**Influence of Soils on Surface Temperatures**

Daytime surface temperature patterns conform to the soil drainage classes found on general soils maps of the study area, with well drained soils displaying higher temperatures than poorly drained soils. Chen et al. (1982) found that nighttime surface temperatures also correspond to soil drainage classes, with well drained soils exhibiting the lowest temperatures. In spite of the poor quality of the
night data, a similar relationship is evident in the images used in this study.

The correspondence between surface temperature and soil type appears to be as much the result of the lack of dense vegetation on well drained soils as it is on soil characteristics themselves. Because soil moisture is the primary determinant of soil temperature (Myers, 1983), well drained soils tend to exhibit higher surface temperatures than do poorly drained ones. Well-drained soils are also dominated by land covers (agricultural lands, longleaf pine-turkey oak and sand pine forests) that have relatively open canopies for much of the year, allowing increased daytime warming and nighttime cooling. The dependence of surface temperature on vegetation cover can complicate the mapping of even general soil drainage classes. An area where this problem is notable is in the Hastings Agricultural Region, where poorly drained soils exhibit high temperatures because of artificial drainage and lack of vegetation cover. Clearcut areas in the poorly drained pine flatwoods also exhibit high surface temperatures.

Other disagreements with published soils maps can be cited. High surface temperatures in the Interlachen Karst Region coincide with areas mapped as poorly drained soils of the Pomona-Wachula-Placid and Leon-Pelham-Mascotte association. Better agreement is obtained when comparisons are made to an earlier soils map by Beckenbach and Hammett
(1962) that maps these as well drained soils, indicating a possible error in the 1982 map.

**Physiography and Surface Temperatures**

The use of remotely-sensed data for physiographic studies in Florida is complicated by the lack of relief and the well vegetated land surface that obscures the geology and landforms of the state. Low relief landforms will not display the thermal shadowing effect noted by Offield (1975) and Schneider et al. (1979), and spectral identification of soil and rock is not possible because of vegetative cover. Instead, subtle vegetation differences may provide clues to landforms; in other areas distributions of water bodies and wetlands provide the primary source of information available from remotely-sensed data. Because of this, thermal data are only of value where they can be used to identify such vegetation or moisture distributions.

The relatively coarse scale of the HCMM imagery makes it suitable only for broad, regional geomorphologic studies. Large physiographic features such as the 17 m scarp in Levy and Gilchrist counties are identifiable because of vegetation, soil and land use changes in the area, while landforms such as the Pleistocene beach ridges along the Atlantic coast are noticeable only in the most general way in the HCMM data. With this in mind, the thermal data were examined to determine what information they might offer that
is not readily obtainable from other types of commonly available remotely-sensed data.

Sabins (1969) found that for a sparsely vegetated area in California, thermal data provided greater contrast than did standard panchromatic black and white aerial photographs. Similar results were obtained over the largely vegetated north-central Florida study area. Comparison of HCMM thermal data to individual Landsat MSS bands, HCMM DAYVIS and black and white aerial photographs indicate that the HCMM thermal data provide equal or better land cover differentiation than do many single band or broad band data sources. Not unexpectedly, individual thermal bands do not offer the amount of information obtainable from a multispectral approach using a combination of visible and reflective infrared wavelengths.

Because of the sensitivity of thermal data to surface moisture, the data can be of use where surface moisture differences provide important clues for identifying landforms. Such uses might include mapping ridge-and-swale systems associated with old shorelines that are identified by alternating wetlands and uplands, or the mapping of shallow karst depressions.

Though used by Schneider et al. (1979) for physiographic mapping in the Great Plains, nighttime thermal data appear to be somewhat limited by the low range of temperatures found in such data. This problem would be partially solved
by the use of data collected by a more sensitive sensor than the HCMM radiometer. As with the day thermal data, the primary value of the night data appears to be its sensitivity to moisture differences and surface water. Nighttime thermal data can be used for mapping drainage patterns that can provide clues to the physiography of an area. The easy identification of the Suwannee and Santa Fe Rivers in the night data point to the usefulness of thermal data for mapping of rivers. Cantrell (1964) suggested that night thermal data might be used to map water bodies and streams covered by overhanging vegetation. The water should warm the overhanging vegetation, allowing the identification of the stream channel. The coarse resolution of the HCMM data do not allow this to be tested here, but the sensitivity of thermal data to vegetated marshes appears to support this suggestion.
Summary and Conclusions

Relationships between satellite-derived surface temperatures and land cover, land use, soils and physiography in north-central Florida were examined using HCMM thermal data. Subsets of four day HCMM scenes were selected providing fall, winter and spring daytime coverage. Three additional subscenes provided fall, winter and spring night coverage. No summer cloud free day or night data were available.

The data were first registered to a UTM projection and corrected for atmospheric attenuation and radiation using a radiative transfer model. In addition, the November 5, 1978 HCMM data were registered to Landsat MSS data for the same date. Isotherm and color-coded temperature maps and enhanced greyscale and RGB images were generated from the data and used in conjunction with black and white and color infrared air photos, Landsat MSS and TM images, and soils, physiographic, land use and topographic maps to relate surface temperatures to land use and surface features.

Visual examination and correlation coefficients show day temperature patterns to be consistent throughout fall,
winter and spring. The poor quality of the night data precluded calculation of correlation coefficients, but visual comparison of the night imagery, as well as comparison to previous studies, show these temperature patterns also to be consistent through time.

Land use and land cover have a much greater influence on day than night temperatures. The dominant factors controlling daytime surface temperatures are moisture availability and vegetation density. Temperatures of natural land covers closely reflect the influence of these factors, with marshes and wetland forests displaying the lowest temperatures. Upland pine and hardwood forests exhibit slightly higher temperatures, with sparsely vegetated young pine forests and longleaf pine-turkey oak forests having the highest surface temperatures.

Removal of the natural vegetation in the study area generally results in increased day surface temperatures. Agricultural lands, both because of their extent and high temperatures, produce the most notable influence on surface temperature patterns. Clearing of forests for lumber and pulpwood is the second most important factor in increasing surface temperatures. Urban areas and surface mines locally influence temperature patterns by increasing surface temperatures.

Land cover and land use patterns are for the most part poorly defined in the night data. This appears to be the
result of both the poor quality of the data and the limited range of temperatures typically occurring at night. Vegetation cover and the distribution of water again control surface temperatures patterns. Agricultural lands and logged areas are among the coolest land covers at night because of the high rates of radiative cooling of these surfaces. Some pine forests, particularly those with extensive clearcutting, exhibit temperatures similar to agricultural lands. The distribution of surface water is important in controlling night temperatures, with water bodies and wetlands consistently exhibiting the highest surface temperatures. Possibly because of the low thermal inertias of well drained sandy soils, areas with these soils also exhibit low temperatures, even when covered with forests. A good example of this can be found in the low night temperatures found in the Ocala National Forest. Some urban areas are also warmer than surrounding localities, while surface mines in the area exert a minimal influence on surface temperatures except where they include large areas of open water.

Soil drainage classes correspond fairly well with surface temperatures, with well drained soils displaying the highest daytime and lowest nighttime temperatures. This correspondence is related to both soil characteristics and land uses and covers typically occurring on well drained soils. This correspondence is weakest in areas where clearcutting or artificial drainage has occurred.
Thermal data offer information that could be of use to the study of coastal plain landforms. The sensitivity of thermal data to moisture variability is perhaps its most valuable feature. Daytime thermal data also exhibit greater contrast between land covers than do many other data sources, making them useful for mapping vegetation patterns that can be relatable to physiographic features.

**Future Research**

Several potential applications of remotely-sensed thermal data can be found in the literature; this study dealt with only a few: land cover, soil and physiographic mapping and climate modification studies. Recommendations for future research given here will only deal with these topics.

Difficulties encountered during the course of this study were similar to those found by other HCMM investigators (Short and Stuart, 1982) and include the limited temporal resolution, coarse spatial resolution and poorly understood calibration of the HCMM radiometer. The 0.4 C NETD of the HCMM radiometer is adequate for many uses, but increased radiometric resolution would improve night image contrast. Additionally, the fact that the HCMM data are historical data makes the collection of field data, particularly meteorological data, difficult. Improved meteorological data would be particularly valuable for any modelling efforts.
The problem of low temporal resolution can be partially solved if coarse resolution data are satisfactory. For regional studies, the daily crossover of the NOAA AVHRR sensor increases the chance of cloud-free data, though the 1.1 km data precludes its use in detailed studies. Such data would be useful for examining climate modification in areas of large-scale land use change such as currently occurring in tropical forests.

The influence of vegetation type and density on surface temperatures was demonstrated in this study. Future studies of vegetation-temperature relationships would benefit from the use of data with higher spatial and spectral resolution such as that provided by the Landsat TM or aircraft scanner data. The 120-m TM thermal data, though they are collected near the morning thermal crossover time of many materials and may be poorly calibrated (Schott and Volchok, 1985), have the benefit of being collected simultaneously with several visible and reflective infrared bands that have well-documented vegetation monitoring abilities. Examination of the IR data in conjunction with these bands would provide an improved means of relating surface temperatures to vegetative land covers. This would be particularly valuable for relating surface temperatures to stand density and age in actively logged forests as done by Sader (in press).
Application of thermal data to soils and physiographic mapping is difficult in Florida because of the low relief and relatively dense vegetation cover of the state. Physiographic mapping would be improved by the use of data with a higher spatial resolution than currently available from satellite thermal radiometers. For many areas even the 120-m resolution of the Landsat TM may not be adequate, and therefore aircraft scanner data would be preferable. Both soils and physiographic mapping would benefit from more detailed information on relationships between vegetation characteristics and remotely-sensed surface temperature than is currently available.
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BIOGRAPHICAL SKETCH

Steven E. Dicks was born in 1957 in Stuart, Florida. His first 18 years of life were spent in several southern Florida cities. He entered the University of Florida in 1975 and received a Bachelor of Arts degree in history and a Master of Science degree in geography. He expects to receive the degree of Doctor of Philosophy in geography from the same institution in May 1986.
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

James A. Henry
James A. Henry, Chairman
Associate Professor of Geography

Cesar Caviedes
Professor of Geography

Robert Marcus
Professor of Geography

Robert Lindquist
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