Table 1. Total citrus acreage in freeze damaged counties which were not enumerated independently during 1984 census.

County	1966	1968	1970	1972	1974	1976	1978	1980	1982	1984	1985
Citrus	1,831	2,343	2,222	1,536	1,447	1,379	1,280	1,260	1,256	*	35
Hernando	9,242	9,360	9,150	6,998	6,604	6,717	6,554	6,765	6,471	*	126
Hillsborough	59,276	60,729	59,727	42,912	40,397	39,750	38,163	37,976	37,631	*	24,111
Lake	139,868	143,153	142,796	132,674	129,570	126,016	123,246	122,777	117,730	*	12,183
Marion	14,436	14,342	13,988	11,784	11,223	11,327	11,272	11,484	11,396	*	198
Orange	65,817	68,005	65,961	60,567	56,320	54,007	51,174	50,672	48,547	*	16,670
Pasco	40,420	42,701	42,331	36,785	35,940	34,286	33,367	33,314	33,425	*	2,949
Putnam	5,113	4,944	4,709	3,440	3,329	3,041	2,692	2,631	2,464	*	4
Seminole	12,835	13,418	12,067	10,969	9,120	8,276	7,635	7,202	6,823	*	1,360
Sumter	2,413	2,443	2,379	1,771	1,677	1,760	1,760	1,772	1,593	*	62
Volusia	12,521	12,850	12,324	11,682	11,171	10,728	10,227	10,143	9,810	*	1,275
Others 1/	477	571	541	484	481	474	426	398	390	*	0
Above Totals	364,249	374,859	368,195	321,602	307,279	297,761	287,796	286,394	277,536	177,482	58,973

1. Combined data for Alachua, Flagler, and St. Johns counties.

able at best and may be abandoned when visited during the 1985-86 tree census survey.

Lake County, by far, suffered the greatest acreage loss of all counties in Florida. There were 143,153 acres of all types of citrus in 1968 and now there are just 12,183 acres of trees in commercial production with a 1983 or older plant date.

The smallest percentage loss of acreage occurred in Hillsborough County, the southernmost of the 14 counties included in this survey. Most of this county's loss was concentrated in the northern and northwestern area. As of July 1985, there were 24,111 acres of all citrus in that county. That is a 60% decrease from the 60,729 acres reported in 1968.

In the 1968 record year, Alachua, Flagler, and St. Johns counties collectively totaled 571 acres, only 0.06% of the State's citrus acreage. As of the 1985 survey, these three northern counties showed a complete loss of all commercial citrus.

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SATELLITE THERMAL IMAGERY ESTIMATION OF AIR TEMPERATURE IN GROVES DURING ADVECTIVE FREEZES

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Abstract. **Four major freezes have occurred in Florida during the last 5 winters. The 2 most recent freezes, Dec. 1983 and Jan. 1985, were advective freezes and are frequently referred to as the worst freezes of this century. Thermal maps developed during and following these freezes from infrared sensings made by GOES were used extensively to document the relative severity of these freezes. The satellite thermal maps indicated higher temperatures than those measured by thermometers in groves. The mechanism responsible for this difference is termed thermal inertia (TI, which also indicates temperature increase). In Lake and Orange Counties, TI values for the 1983 and 1985 advective freezes averaged from 2.4 to 7.8°F. Satellite-sensed and grove temperature observations were compared to indicate the areas in which the 1985 freeze was colder than the 1983 freeze, and the magnitude of these differences. A simple model is suggested for estimating the magnitude of TI and using such procedures in programs designed to automatically estimate grove temperature from satellite during future advective freezes.**

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The term "thermal inertia" (TI) was introduced recently as an explanation for the tendency for temperatures sensed by the GOES satellite to be higher than ground temperatures in citrus groves during the Dec. 1983 freeze (6,7,14). Prior to this freeze, excellent agreement between satellite-sensed temperatures and those measured by conventional instruments had been reported during clear, cool, nocturnal conditions in Florida (1,2,3). County extension citrus specialists acquired satellite data in real time and documented the agreement of such data with grove thermometer data during the frosts and freezes of 1981 and 1982 (9,13,15). These data were disseminated as black and white symbols maps (9,13), color prints of the TV images (6,9,10), and as color TV displays on the Satellite Frost Forecast System (SFFS) (7,11,12). Prior to the 1983 freeze, satellite thermal maps of Florida were considered to be very accurate documentation of the temperature distributions and they provided greater detail than had been possible before the 1977 freeze. However, thermal map interpretation of the advective freeze of 1983 presented problems due to both TI and cloud cover (6,7,14).

The purpose of this paper is to document the necessity of making a TI correction in the thermal maps from the Jan. 1985 freeze and to suggest ways that TI corrections may be estimated for future advective freezes.

Materials and Methods

The materials consist primarily of abstracts from 2 data sets. The first data set is satellite temperature observations acquired via SFFS. The other is a combination of grove thermometer observations acquired by the third author from growers in Lake and Orange Counties, plus those routinely collected through the Federal-State Frost Warning Service thermograph network.

Satellite data. Since Feb. 1982, infrared thermal data arrays from the geostationary weather satellite, known as GOES-East, have been directly downlinked by an antenna located at the University of Florida in Gainesville (8,12). A thermal view of the Florida peninsula is routinely captured in one minute every half hour as a sector of scene consuming at least 7 minutes. However, on 29 July 1984 the second (redundant) optical encoder lamp on GOES-East failed, disrupting the infrared and visible imagery from its location at 75W longitude (16). The imagery from GOES-West, the only geostationary satellite that still has operational imaging capability, continued to flow through GOES-East so it was unnecessary to reposition the antenna (12). GOES-West was maneuvered eastward to approximately 100W during the hurricane season. It was then moved about 10 degrees West to 110W. This covered the most important portion of the area previously scanned by the 2 satellites when one was positioned at 75W and the other at 135W (16). The satellite data documenting the 1985 freeze was sensed by GOES-West, repositioned at about 108W, while GOES-East documented the Christmas 1983 freeze at 75W. Infrared data from 4 different satellites during the 1978-1981 period revealed no detectable difference in temperature. However, it makes overlaying the data for comparison purposes more difficult.

Grove data collection. Air temperature refers to the minimum temperature observations from sheltered liquid-in-glass thermometers and/or thermographs. These data were handled in the same manner described in the 1983 freeze case (14) and reported in the 1984 Cold Protection Notebook and in its 1985 revision (7). The analyses were confined to the same stations used in the 1983 Freeze study (14), with the result that from 4 to 6 stations were missing in the second case. The addition of the Holly Hills site counteracted the decrease in number of observation sites.

Data analysis. The methods were the same as for the 1983 case (14), except that the view of Florida from GOES-West placed Florida so near the ENE horizon that it was more difficult to locate the particular satellite pixel corresponding to the surface grove temperature observation. The method consists of transferring a two-dimensional array of the satellite data into a spread sheet program on a personal computer and then manipulating the column width and the font size. The resulting array overlays a map on which lakes, rivers, township lines, highways, and other geographical features are drawn. These aid in lining up the satellite data with surface features which are expected to show up in the temperature data. When GOES-East failed, the view from GOES-West became the only data source to SFFS. The N-S axis of Florida was so canted to the NW that one pixel was removed from the beginning of every 4th scan line and the line shifted to its left to effect a relative straightening of the state. Even with this "correlation" the alignment of the satellite data with the location of the surface temperature observations was a manual operation and subjective in nature.

A similar problem existed in attempts to subtract the satellite maps for the 2 freezes to produce a "difference" map. For the 1981 and 1982 freezes, this subtraction was accomplished by computer and the programs retained so that it could be quickly and easily accomplished every time there was interest in comparing 2 freezes. Attempts to revise this software so that it would compute a difference map when the views were from 2 different locations in space failed. Consequently, the difference map was developed manually by a method very similar to the one described for navigating the individual pixels to locations on a geographical map (Fig. 1).

Results and Discussion

Differences between satellite-sensed and air temperature. The expectation that thermal maps from satellite data closely represent the temperatures measured by conventional methods in groves developed from reported comparisons during frost conditions prior to the 1983 advective freeze (1,2,3,8,9,10,11,13,15). Actually, the close agreement between the satellite pixel temperature and a grove minimum temperature should be considered fortuitous since there are major differences between the 2 methods of sensing temperature. Major differences are reviewed in the following paragraphs.

Grove minimum temperatures are generally sensed with an alcohol-in-glass thermometer containing a small black marker which sticks at the minimum point that the column attains after a previous resetting. These thermometers are commonly used to calibrate thermograph records, which provide records over time of durations of temperatures below particular thresholds. Both temperature sensing methods describe the temperature of a relatively small element that is shielded to restrict response to air temperature. These air temperature sensings are generally made about 5 ft above the soil surface. Procedures and equipment are standardized to permit comparisons from place to place with assurance. In summary, the conventional temperature sensings represent only a very small area in close proximity to the sensors and include any errors that may be introduced by the characteristics of the site and the calibration of the instruments.

The pixel temperatures sensed through the satellite's infrared telescope represent a much larger area, approximately 20 square miles when GOES-East is the sensing instrument and closer to 25 square miles when GOES-West is stationed at approximately 100W. On an area basis, the expectation that thermometer and satellite temperatures would be equal depends on whether the thermometer is located at a site that represented the particular satellite pixel at that particular time. Since the satellite scans vary slightly in space, the pixels end up at different locations in different scans or maps. The possibility always exists that a given thermometer and satellite pixel temperature will fail to agree simply because of the area they represent. Notice in Table 1 that the difference between the air temperature and the satellite temperature *for the site* called

Table 1. Comparison of minimum temperatures observed by traditional thermometry with associated satellite pixel temperatures for 21-22 Jan. 1985 at 7:30 AM.

	Temperature (°F)					
	21 Jan.			22 Jan.		
STATION	Minimum[z]	Pixel[y]	Difference	Minimum[z]	Pixel[y]	Difference
Weirsdale 1	16	20.9	4.9	18	23.6	5.6
Weirsdale 2	16	20.9	4.9	19	25.4	6.4
Lady Lake 1	15	23.6	8.6	15	25.4	10.4
Lady Lake 2	15	26.3	11.3	17	26.3	9.3
Fruitland Park	14	20.9	6.9	16	23.6	7.6
Umatilla	16	23.6	7.6	18	26.3	8.3
Tavares	16	36.2	20.2	19	29.0	10.0
Leesburg ARC	14	23.6	9.6	16	28.1	12.1
Tangerine	17	25.4	8.4	20	25.4	5.4
Howey	18	23.6	5.6	18	25.4	8.4
Plymouth	16	20.9	4.9	18	23.6	5.6
Mascotte	16	23.6	7.6			
Pinehills	18	25.4	8.4	20	26.3	6.3
Apopka ARC	14	30.8	16.8	19	28.1	9.1
IMG	16	23.6	7.6	18	28.1	10.1
Groveland	16	16.4	0.4	19	25.4	6.4
Montverde	16	28.1	12.1	19	28.1	9.1
Avalon	18	25.4	8.4	19	28.1	9.1
Lake Ingram	18	25.4	7.4	20	28.1	8.1
Hartzog Rd	19	25.4	6.4	19	26.3	7.3
USDA Foundation Farm	18	23.6	5.6	19	26.3	7.3
Tilden Barn	22	25.4	3.4	22	28.1	6.1
Hi-Acres Barn	20	26.3	6.3	23	26.3	3.3
Holly Hills	17	23.6	6.6	18	25.4	7.4
Clermont	17	20.0	3.0	18	23.6	5.6
Oviedo	14	25.4	11.4			
Stanford	18	23.6	5.6	19	25.4	6.4
Mean	16.7	24.37	7.77	18.6	26.23	7.63
Standard Deviation	1.90	3.65	4.05	1.70	1.64	1.99

[z]Minimum temperature by traditional thermometry.
[y]Satellite pixel temperature.

Tavares is 20° F the first morning and 10° F the second. Tavares is situated between 2 large lakes and it is impossible to choose a pixel which is not representative of mostly lake in its view. The portion of the pixel that is lake makes a significant difference in the pixel temperature when there are large temperature differences between the land and the lake surfaces. A similar situation exists in the case of Apopka Agr. Res. Center.

Previous experience has indicated that under typical frost conditions the differential between the temperatures sensed by these 2 methods is very consistent. Therefore, there must be some compensating mechanisms under these conditions.

While a thermometer depends upon a convective coupling to air temperature, the satellite senses temperature by sampling the energy emitted by radiating surfaces. Thus, the satellite sensor is not responding to air temperature but rather to surface temperature. During radiant frost situations, the surface cools by radiant energy loss to space, and this radiant loss is the major cooling mechanism. Air temperature lags behind surface temperature during cooling, so surfaces are cooler than the air. During advective freezes, the major cooling mechanism is the advection of cold air into the region. Surfaces are cooled by convective transfer of heat to the cold air that moves over them. Therefore, surface temperatures lag behind air temperatures during the advective cooling process. Certain surface conditions affect the amount of lag, e.g., heat capacity and the conductivity of the material near the surface. A surface with a high heat capacity and the ability to lose that heat rapidly by its transport to the surface would be expected to have the greatest lag in temperature behind the air temperature fall. A well-insulated surface, i.e. one that has a low heat conductivity, will have a temperature very near the well-mixed air during an advective freeze. The major variable in the heat capacity of a natural surface is its moisture condition. Moist surfaces and full lakes mean high heat-storage capability and the greatest lags of surface temperature behind air temperature as advection takes place. Conditions prior to both advective freezes were moist.

Comparison of the 1983 and 1985 Freezes. Fig. 1 is a comparison of the satellite maps in which the 1985 freeze is shown to be colder than the 1983 freeze in most areas. The comparison was made using data printed with no attempt to correct for the difference in TI which amounts to 2.3° F on the average for the Lake-Orange Counties area (Table 2). Table 3 contains minimum temperature summaries indicating that the first morning of the 1985 freeze was 3.6° F colder for the average station in Lake and Orange Counties. So it is likely that the difference in TI between the 2 freezes masks a major portion of the difference between the air temperatures. The areas marked "C" in Fig. 1 are likely to be underestimated, i.e. lower than they would be if the satellite was sensing air temperature instead of surface temperature. However, since the trees respond to both the radiant and convective exchanges, the comparison between the 2 freezes from the standpoint of the tree is likely to be somewhere between the 2 temperatures.

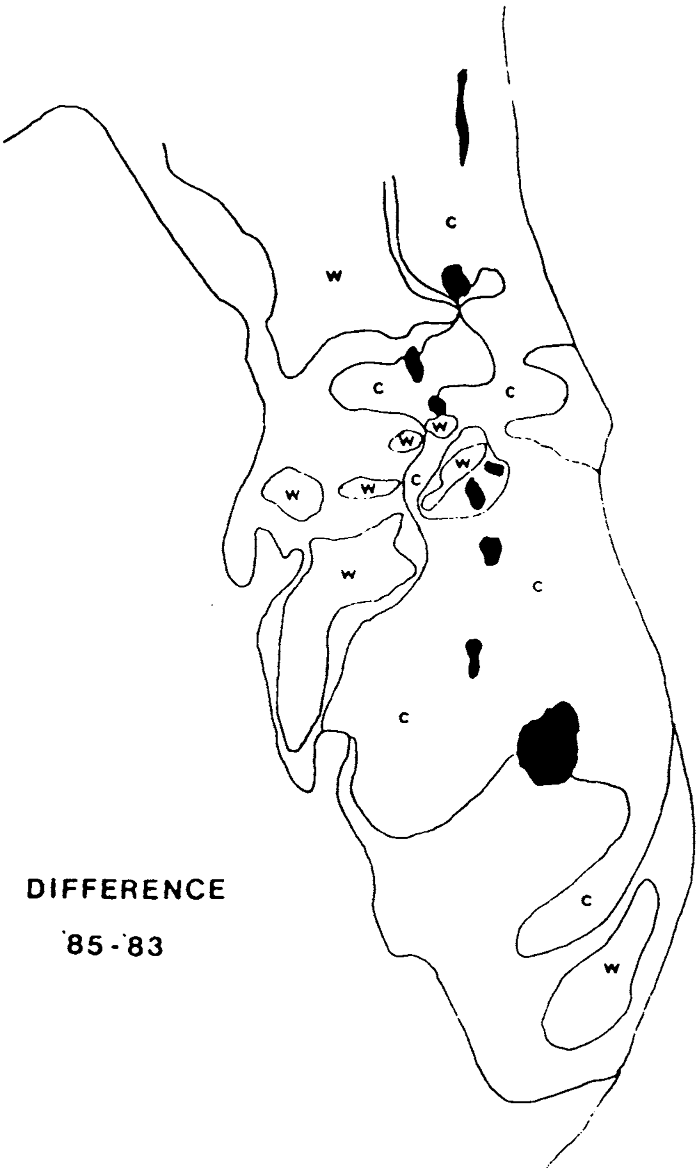

Fig. 1. Comparison of satellite maps for 7:30 AM EST 21 Jan. 1985 with 7:30 AM EST 25 Dec. 1983. The areas marked "c" for colder are areas in which temperatures were colder in the 1985 map than those indicated by the 1983 map, while those marked "w" were warmer. Areas between the marked areas are too close to the same temperature to designate.

Modeling the magnitude of thermal inertia. In order for the satellite thermal maps to be a good approximation of the absolute temperature as well as relative temperatures from location to location, an estimate of the magnitude of TI is required. If TI could be estimated in real time then it would be possible to simply subtract TI from the satellite data prior to displaying the maps. Fig. 2 describes the relationship between TI and the advective index. An advective index is a function of wind speed and moisture conditions of the surface upwind and could be determined ahead of time. The factors in the advective index would be weighted to minimize the departure of means shown in Table 2 from the one-to-one line, making the advective index essentially equal to the TI in magnitude. During the Jan. 1985 freeze with high wind speeds and relatively moist conditions, the thermal inertia did not exceed 8° F.

To illustrate the role of wind speed in TI, wind speeds from the Orlando Airport records are indicated in Fig. 3.

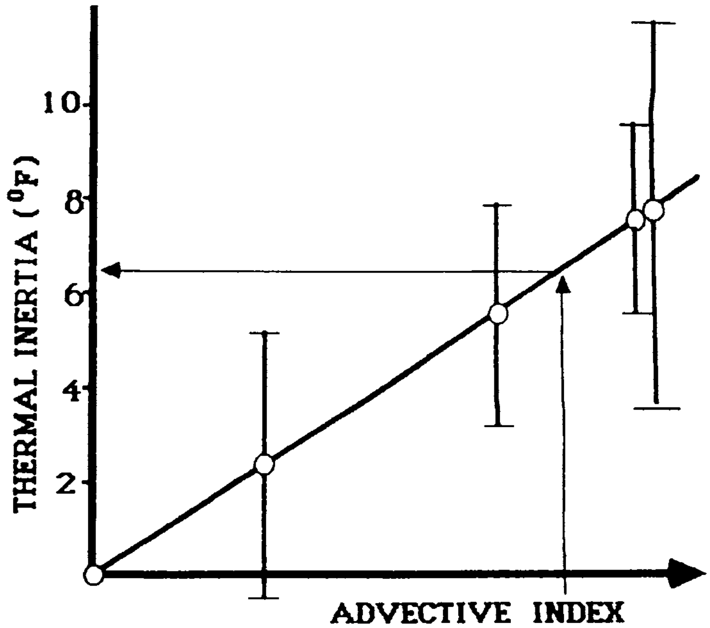

Fig. 2. The relationship between thermal inertia and advective index, for estimation of thermal inertia. The data points are from Table 2 with the standard deviations of the satellite data indicated as confidence intervals. The zero data point represents all the observations that have been made in radiative frosts in which the thermal inertia is assumed to average zero. If the scale for the advective index is chosen carefully, it could be equated to the thermal inertia scale, making the terms redundant.

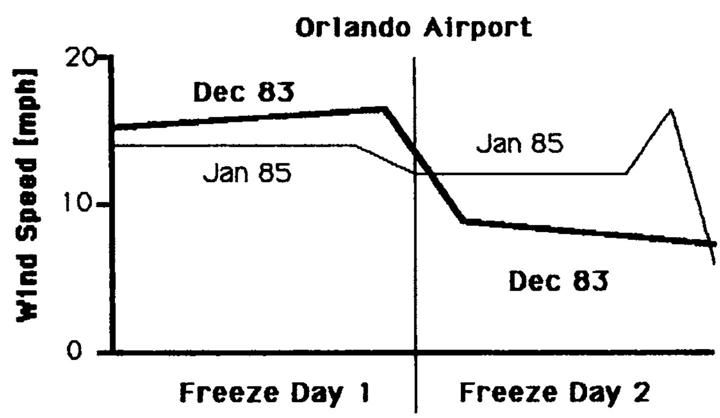

Fig. 3. A highly smoothed presentation of wind speed observations from the Orlando Airport, acquired automatically from the National Weather Service AFOS by SFFS. The wind in the Jan. 1985 freeze is shown to continue at a high level through the second day of the freeze while the wind subsided noticeably in the 1983 freeze on the second day.

Table 2. Comparison of the temperature (°F) differentials between satellite and grove minimum observations for 2 mornings during advective freezes.

	Dec. 1983		Jan. 1985	
Method	25	26	21	22
Satellite temp.	26.0±2.3	22.0±3.2	24.4±3.7	26.2±1.6
Grove temp.	20.5	19.6	16.7	18.6
Temp. differential	5.5	2.4	7.8	7.6

Table 3. Grove minimum temperature of the first and second days of the Dec. 1983 and Jan. 1985 advective freezes.

	Day 1			Day 2		
	1983 25 Dec.	1985 21 Jan.	Difference	1983 26 Dec.	1985 22 Jan.	Difference
	Temperature (°F)					
Mean	20.3	16.7	3.6	19.4	18.7	0.7
SD	1.5	1.4	1.3	1.4	1.3	1.2
Observations	27	27	27	25	25	25

Notice that the wind speed in the Dec. 1983 freeze decreased more the second day of the freeze than it did during the 1985 Freeze. This seems to provide a partial explanation for the greater temperature differential between satellite and ground temperatures for second day of the 1985 freeze than the 1983 freeze (Table 3). Moisture also is an important factor determining the magnitude of thermal inertia, but no satellite data exists for an advective freeze when lakes are low and land surfaces are very dry. However, if such a freeze event were to occur, then the thermal inertial would probably be less than the 7 to 8° F experienced in the 1985 advective freeze.

Conclusions

Thermal inertia is a term used to describe the average temperature lag that can be expected during advective freezes when satellite thermal maps are compared with minimum temperatures observed by ground instruments. Thermal maps published as documentation of the 1983 and 1985 advective freezes show from 2.4° F to 7.8° F thermal inertia on the average for the Lake-Orange Counties area (6). Consideration of the heat transfer mechanisms involved suggest that thermal inertia is dependent upon wind speed and soil moisture. The higher the wind speed and the more moist the soil, the higher the thermal inertia. The value of 7.8° F computed for the morning of 21 Jan. 1985 is likely to be the highest value that should be expected. A model is proposed for estimation of thermal inertia for freezes of lower wind speeds and less moisture. Satellite thermal maps remain valuable means of comparing one location with another. They can be expected to provide estimates of temperatures very close to those measured in groves under frost conditions, and even under advective conditions with an appropriate correction for thermal inertia.

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