Remote Sensing of Thermal Radiation from an Aircraft — An Analysis and Evaluation of Crop-Freeze Protection Methods

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ABSTRACT

Thermal images from an aircraft-mounted scanner are used to evaluate the effectiveness of crop-freeze protection devices. Data from flights made while using fuel oil heaters, a wind machine and an undercanopy irrigation system are compared. Results show that the overall protection provided by irrigation (~2°C) is comparable to the less energy-efficient heater-wind machine combination. Protection provided by the wind machine alone (~1°C) was found to decrease linearly with distance from the machine by ~1°C (100 m) ~1. The flights were made over a 1.5 hectare citrus grove at an altitude of 450 m with an 8–14 μm detector. General meteorological conditions during the experiments, conducted during the nighttime, were cold (~ -6°C) and calm with clear skies.

1. Introduction

Heaters, wind machines and irrigation have long been used in the agriculture industry as a means of artificial freeze protection. Methods used and mechanisms involved are reviewed elsewhere (Bagdonas et al., 1978; Businger, 1965; Crawford, 1965; Turrell, 1973). Wind machines derive their effectiveness by transferring heat from higher to lower levels via turbulent mixing and work best during calm periods with a strong thermal inversion. Heaters function by transferring both sensible and radiant heat, losing most, however, to the upper atmosphere (Martsolf, 1976; Martsolf and Panofsky, 1975; Perry et al., 1977). With irrigation, the crop is either continuously sprinkled, maintaining temperature at the freezing point (Gerber and Harrison, 1964) or the grove is flooded prior to an expected freeze, increasing the heat capacity of the subsurface. Research in this area of micrometeorology has gained interest in recent years because of the undesirable effect of heaters upon the atmosphere and because of their inefficient consumption of (fossil fuel) energy. Viable options are being sought by the food and agricultural industry.

It has been difficult in the past to determine quantitatively the effectiveness of various measures taken to prevent freeze damage to crops. This difficulty is caused in part by the necessity to limit temperature measurements to a few discrete points. The degree of protection is usually small and on the order of, or even less than, natural temperature variations within the crop canopy. This makes placement and calibration of sensors quite critical. Very often, the effect to be measured is lost in this experimental noise. Historically, evaluations of various methods have often been made after a severe freeze by observation of actual damage (Wallis, 1963).

In recent years, however, infrared technology has advanced to the point where remote sensing of agricultural areas in the 8–14 μm “thermal” radiation region has become a reliable and practical research tool (Bartholic et al., 1972; Nixon and Hales, 1975; Sutherland and Bartholic, 1974). This provides a new perspective on evaluating methods because measurements can be made from a scanner aboard an aircraft giving a spatially continuous overview of surface radiation patterns of a relatively large area. The full impact of the technology lies in the fact that the magnitude of the emitted radiation under most conditions is directly related to the surface (or crop) temperature (Sutherland and Bartholic, 1977). The data, when properly reduced, give a temperature “picture” of an entire area as opposed to the more conventional ground measurements of a few discrete points. A major purpose of this paper is to demonstrate the utility of the remote sensing technique to micrometeorological problems in general. Also, our irrigation experiment is carried out by applying undercanopy sprinkling during freeze conditions and thus constitutes a novel approach to freeze protection.

Results of experiments conducted on the night of
22–23 February 1978 using both conventional ground measurements and aircraft thermal data are reported in this paper.

2. Description of apparatus and test site

The test site was an experimental citrus grove located in north central Florida (−29.5°N, 53 mASL). An aerial photograph of the grove is shown in Fig. 1. Trees in the northern two-thirds of the grove are ~4 m in height; those in the remainder, ~3 m. Tree spacings are 3.05 m east–west and 4.88 m north–south. The grove is homogeneous in the east–west direction except for a few missing trees; hence, comparisons will later be made by treating the west half of the grove as the control and the east half as the experimental portion. The grove is located on flat terrain of Kanapaha fine sand, approximately square, and 1.5 hectares in area.

The heaters, commonly known as Spots and Scheu, and the wind machine were purchased commercially and are types commonly employed in the industry (Bagdonas et al., 1978). The heaters were placed along every row (Spot-Scheu on alternate rows), at every other tree along rows, and were operated at fuel consumption rates of 1.63 and 2.89 L h⁻¹, respectively. The wind machine, located in the southwest corner of the grove, is ~10 m in height with a 4.7 m single propeller, driven by a gasoline engine and rotates about a vertical axis once every 5 min delivering approximately 500 Ns of thrust at a propeller angular velocity of 500 rpm.

Undertree irrigation sprinkler heads are in every row, centered in the row and under alternate trees along the row. The irrigation system is powered with a 20 kW electric motor and pumps well water (~21°C) from a depth of ~30 m. The pump valve was adjusted to give a deposition rate of 0.02 cm min⁻¹.

Ground based temperatures were sensed with copper-constantan 32 gauge thermocouples. Signals were referenced against a zero point cold junction and collected with a computerized data acquisition system. Signals were further referenced against a thermocouple buried ~5 m in the subsurface. Overall accuracy of the system is approximately ±0.25°C.

Aircraft flightlines were from south to north, scanning an area perpendicular to the flightline ~1 km wide. The aircraft altitude was 450 m for all data reported herein, however, flights were also made at 900 m on most occasions as a check of atmospheric interference. The spacial resolution of the aircraft scanner when flying at 450 m is ~1.25 m². The data, recorded on magnetic tape aboard the aircraft, was later digitized at a rate which preserved this resolution. The term pixel (picture-element) will be used in referencing this resolution area. A fourth power law was used to convert scanner signal to surface temperature and emissivities were approximated as unity. Errors due to these approximations for the situations encountered in this experiment are small (Sutherland et al., 1979; Sutherland and Bartholic, 1977). A more complete description of the aircraft and scanner can be found elsewhere (Sutherland and Bartholic, 1975).

3. Results

a. Ground-based measurements

The night of the experiments was characterized by low temperatures, calm winds and low humidity. Wind speeds were below the threshold of measurement (i.e., <0.50 m s⁻¹), although a drift of vapor from north to south was observed when the irrigation system was initially turned on. No clouds were visible during the course of the experiments and dewpoint measurements at the ground were from −18 to −9°C as determined with a sling psychrometer.

Plots of upper canopy leaf temperatures for both the west (control) and east (experimental) halves of the grove are shown in Fig. 2. Data represent samples taken every 30 s and averaged over 5 min intervals. The singly cross-hatched time regions at the top denote the times the wind machine was operating. The doubly cross-hatched and dotted intervals indicate heating and irrigation, respectively, which was done in the east half only. Circled symbols refer to times of thermal images that will follow (Fig. 3) showing simultaneous scanner data. It should help the reader to know that because lethal temperatures were being approached, certain actions were taken which complicated the experiment somewhat but were necessary to protect the
grove and surrounding crops. Also, malfunctions due to the cold forced certain actions. The degree of effectiveness of the wind machine, according to the observations near midnight, is on the order of 2°C in the west half (nearest the wind machine) and ~1°C in the east half (Fig. 2). The heaters in the east half appear to add ~1°C of protection at 0600 when used in combination with the wind machine.

A less conspicuous observation is seen between 0300 and 0430 LT when the east portion was being irrigated. Temperature in the east half increased markedly more than that in the west half. Contrasting this with the earlier observation near midnight, we assume the increased effectiveness in the east half is due to the irrigation. This initial effect could be due to the vapor cloud that was formed upon beginning the irrigation. This cloud was visible at first but had diffused away before the thermal flight near 0400. Another subtle observation of Fig. 2 is that in the east half, the temperature remained at the elevated level even after the wind machine was turned off and did not decrease until irrigation ceased near 0400. The decrease near 0400 did not, however, return the grove to the temperature observed prior to the irrigation but instead remained on the order of 1°C higher.

Data of Fig. 2, although interesting, would be difficult to use for authoritative statements concerning the relative effectiveness of the various freeze protection devices. A major purpose of this paper is to emphasize this point with the aid of the scanner data presented in the following subsection.

b. Aircraft thermal data

Thermal images (reproduced electronically from the original digitized data) obtained simultaneously with ground truth at the times labeled in Fig. 2 are shown in Fig. 3. Darker tones are the colder and lighter tones are the warmer, with a total span from approximately -6 to 0°C. Although, limitations of the photographic process do not allow direct comparison between images, the qualitative aspects of the experiments are immediately evident. In Fig. 3b, which is a thermal scan made early in the evening before any of the protection devices were started, it is immediately clear that the grove, although nearly homogeneous in vegetative cover, cannot be identified by a single temperature. In general, the soil surface between rows is considerably warmer than the trees. This was also verified with ground-based data (not shown) and has often been observed with conventional instruments in groves during similar conditions (Bartholic and Wiegand, 1969). Some caution is necessary here because of the error caused by the lower emissivity of sand as compared to vegetation (Sutherland, 1979). The error, however, is <0.5°C with the particular tree height to spacing ratios of the grove.

Fig. 3c is a thermal image of the grove with the wind machine on. The machine itself shows up as a
Fig. 3. Images of the test grove: (a) visible photograph, (b)–(f) thermal images.

warm spot in the southwest corner of the grove. The small dark areas at the center of the north edge of the grove and at the southeast corner of the grove are the fuel oil tanks and data acquisition facility, respectively. Temperature of the area in general had dropped significantly in the 2 h between flights but this will not be apparent from the thermal images as reproduced here but was verified from the original digitized signal and ground measurements. The image of Fig. 3c shows that the effect of the wind machine was to change the temperature pattern of the grove, causing higher tempera-
tures in the area nearest the wind machine. A relaxation back to the earlier temperature pattern 2 h later is readily discernable in Fig. 3d. The image of Fig. 3e shows the effect of the undetree sprinklers which were used in the east half only. The difference between the two halves is immediately apparent. The "missing dark row" in the east portion of the grove was being used for other unrelated experiments and the undetree sprinklers were not operated along this row.

At this juncture, it is informative to compare Fig. 3e with Fig. 3f which is a thermal scan made 2 h later when half of the grove was heated. There appears to be no detectable difference in protection provided between grove irrigation and grove heating and this will later be shown essentially true. However, caution is needed at this point because the lighter tones in Figs. 3e and 3f are due to the water or heaters between the rows which are at elevated temperatures. The very lightest tone in fact represents temperatures beyond the upper range of the scanner (~0°C) and are unusable. This problem will be addressed and circumvented in the following section.

4. Analysis

It was pointed out above that the thermal images as presented should only be used in a qualitative manner. The reason for this lies in the photographic reproduction process and does not by any means reflect the precision of the original data. For the analysis to follow, the original digitized data are analyzed on a pixel-by-pixel basis giving on the order of 16,000 pixels for the entire grove. This is one of the major advantages of the remote sensing technique which provides information unattainable with conventional ground measurements.

a. Wind machine

Plots of pixel density as a function of temperature (T) for the control and wind experiment are shown in Fig. 4. The y coordinate of the plots (commonly called histograms) represents the percentage of pixels in the grove with temperature between \( T - \Delta T \) and \( T + \Delta T \), where \( \Delta T = 0.15°C \). A direct comparison of the averages shows the effect of the wind machine to be \(-1°C\), discounting the overall decrease (0.25–0.50°C) that occurred in the 2 h between flights. Both plots show a slight skew toward the lower temperatures which might be indicative of the fact that about 80% of the grove is relatively cold vegetation. It was also borne out by curve fitting with a Gaussian function that the experimental plot is slightly narrower (~0.08°C) than the control. This difference reinforces the idea that the wind tends to mix air causing a better approximation to thermal equilibrium. The fits yielded a mean of \(-4.34°C\) for the control and \(-3.26\) for the wind protected grove.

To further analyze the wind machine results, the grove was sectored perpendicular to the southwest-northeast diagonal into four approximately equal areas and an analysis run on each sector. The average temperatures for the sectors plotted as a function of distance from the wind machine are shown in Fig. 5. The data fit well to the linear function which is also shown. The lower points were constructed from both the 2200 and 0200 images when the wind machine was off. These data were adjusted to account for nocturnal temperature fall along a smooth curve estimated from the
ground measurements of Fig. 2. These data also yielded a good linear fit. There appears to be no apparent explanation for the decrease with distance for the unprotected grove and this observation will simply be accepted.

The two linear functions were then subtracted to yield the following equation for temperature effectiveness as a function of distance \( d \) from the wind machine:

\[
\Delta T \, [{\degree C}] = 1.15 - 0.0105 \times d \, [m].
\]

This gives a temperature fall of \( \sim 1 \degree C \) per 100 m and an intercept of 109.5 m which corresponds to a "protected" area of 3.77 hectares which is in fair agreement with, but slightly less than, advisory information given to growers which range 4–7 hectares for a wind machine of this type (Bagdonas et al., 1978).

\[b. \text{Irrigation and heating}\]

Pixel density plots for the irrigation and heater plus wind experiments are shown in Fig. 6. The controls curves once again show the skew toward lower temperatures noted earlier. Also, the temperature difference based upon means is 0.62\degree C for the controls and is comparable to the earlier results if the estimate of 0.25–0.50\degree C for overall nocturnal temperature fall is assumed for the later experiments. The strength of the inversion as measured on the meteorological tower in the center of the grove was approximately 0.25\degree C m\(^{-1}\) for both cases.

The nearly identical results for the irrigation and heater-wind machine experiment is once again observed in the plots of Fig. 6. An evaluation based upon mean temperatures show the heated grove to be colder (0.02\degree C) than the irrigated grove although the difference is certainly insignificant. The bimodal distribution giving a second peak at the extreme upper end of the temperature range in both is obviously due to pixels containing water or heaters. This causes some uncertainty in making direct comparisons between experiment and control by use of mean temperatures only. It seems more meaningful to examine the lower temperature extreme to see the effect on the colder pixels. This is quite practical since the vegetation represented by the colder pixels is the commodity which we desire to protect, not the (warmer) sand, water and heaters between rows.

The fact that the colder pixels are the ones of interest suggest that the results be presented in a manner that clearly shows the effect upon the lower temperature pixels. It is fortuitous that the warmest pixels in the irrigation and heating experiment are artifacts for which we have no direct interest.

Direct comparisons of all methods are shown in Fig. 7. The \( y \) coordinate represents the percentage of pixels \( P(<T) \) below the temperature \( T \). For example, 78% of the pixels in the grove were below 4\degree C for the control but only 45% were below 4\degree C for the wind experiment, etc. In this case, results of the wind experiment were shifted by 0.45\degree C to adjust for overall nocturnal cooling.

The wind and control plots of Fig. 7 simply demonstrate the previous observation that the effect of the wind is mostly to shift all pixels by about the same amount. The two lower curves show that the irrigation and heater-wind machine methods are much more effective than the wind machine alone. The sudden upswing for the lower curves between \(-1\) and 0\degree C are caused by water or heaters and data in this region should simply be ignored. Comparison between the irrigation and heater-wind
machine methods is difficult. It appears that the heater-wind machine combination is slightly more efficient at transferring heat to the coldest pixels; however, irrigation appears to be the most effective overall for the intermediate temperatures. It is unlikely that the data of Fig. 7 show either to be superior and the observations should be viewed as showing no detectable difference in protection provided by the two methods.

5. Conclusions and discussion

When used with appropriate digital data reduction procedures the remote sensing technique can be an extremely useful tool in studying micro-meteorological effects. Perhaps hidden in the quantitative focus of this paper is the fact that the method might be practical for real-time decision-making processes in industry. Thermal images such as those demonstrated in Fig. 3 would certainly be more useful than single air temperature measurements which are often the basis of very critical decisions. These images, coupled with cumulative histograms showing the relative percentage of a grove that is below a certain critical temperature, would be an objective observation much superior to present observations which are somewhat subjective.

Undercanopy irrigation can be a very effective means of freeze protection equalling that of the more expensive heaters. This is very significant to industry since the cost of irrigation is nearly 20 times less than that of heating with present fuel costs.

Some caution is given to the fact that our experiments were carried out during calm and dry conditions and it is not certain that the same results would apply under different meteorological conditions. In a crude manner of thinking, the irrigation experiment can be viewed as simply pumping heat to the grove in the form of internal heat energy (water at 21°C) and as latent heat (586 cal g⁻¹). The mechanism by which this heat energy is transferred from the water to the crop canopy is quite important in extrapolating the results to more general conditions. A radiative process, for example, would be expected to be insensitive to wind speed whereas an evaporation-condensation mechanism would not. An elementary calculation accounting for the decrease in water temperature to 0°C yields an equivalent heat flux of 0.42 ly min⁻¹ for a given water deposition rate of 0.02 cm min⁻¹. This increased flux which is directed away from the water and into the air and then presumably to the crop canopy is certainly large enough to account for the marked increase in temperature (Sutherland, 1980). The radiative flux assuming a surface elevated by 21°C would be ~0.04 ly min⁻¹ of which ~85% would be received by the canopy. Although significant this radiative flux is over an order of magnitude smaller than the total available indicating that the dominant mechanism is due to evaporation at the water surface, then condensation at the crop canopy.
surface. If this explanation is accepted, then it is logical to expect that winds might diminish the effect by causing more rapid re-evaporation at the leaf surfaces. On the other hand, another effect of the irrigation is to increase the heat capacity and dew point of the surrounding air through the increased vapor content. This would essentially arrest cooling of the air and thus reduce heat transfer (loss) from the leaf. More experiments would be required to determine quantitatively how the efficiency of these two mechanisms are affected by wind.

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REFERENCES


