Spray Irrigation Effects on Surface-Layer Stability in an Experimental Citrus Orchard during Winter Freezes

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ABSTRACT

Observations taken by two surface radiation and energy budget stations deployed in the University of Florida/Institute for Food and Agricultural Service experimental citrus orchard in Gainesville, Florida, have been analyzed to identify the effects of sprayer irrigation on thermal stability and circulation processes within the orchard during three 1992 winter freeze episodes. Lapse rates of temperature observed from a micrometeorological tower near the center of the orchard were also recorded during periods of irrigation for incorporation into the analysis. Comparisons of the near-surface temperature lapse rates observed with the two energy budget stations show consistency between the two sites and with the tower-based lapse rates taken over a vertical layer from 1.5 to 15 m above ground level. A theoretical framework was developed that demonstrates that turbulent-scale processes originating within the canopy, driven by latent heat release associated with condensation and freezing processes from water vapor and liquid water released from sprayer nozzles, can destabilize lapse rates and promote warm air mixing above the orchard canopy. The orchard data were then analyzed in the context of the theory for evidence of local overturning and displacement of surface-layer air, with warmer air from aloft driven by locally buoyant plumes generated by water vapor injected into the orchard during the irrigation periods. It was found that surface-layer lapse rates were lower during irrigation periods than under similar conditions when irrigation was not occurring, indicating a greater degree of vertical mixing of surface-layer air with air from above treetops, as a result of local convective overturning induced by the condensation heating of water vapor released at the nozzles of the sprinklers. This provides an additional explanation to the well-accepted heat of fusion release effect, of how undertree irrigation of a citrus orchard during a freeze period helps protect crops against frost damage.

1. Introduction

Irrigation (also referred to as sprinkling) is a popular method of protecting orchards from frost damage (see Gerber and Harrison 1964; Barfield et al. 1990). This is true, in part, because such irrigation systems are needed for drought abatement and are available for frost control at little additional cost (Martsolf 1992a). The release of latent heat of the fusion mechanism, through which protection is provided, has been modeled with some success. In the study of Barfield et al. (1990), heat delivered to a leaf (treated as a flat plate) or blossom (treated as a sphere) was calculated from the process of the fusion of liquid water to ice, which covers the plant elements. The energy budget of the sprinkled leaves is then a balance between the heat provided by fusion minus that lost by evaporation, or by convection and advection into the surrounding environmental air (see Businger l965). However, since evaporation consumes 7.5 times the amount of energy per unit mass as is liberated by the fusion for a unit mass, an increase in the advection of dry air into the orchard can change the heating system into a cooling system. This occurred in many Florida citrus groves during the advective freeze of 1962 (Wallis 1963; Martsolf 1990) and has since discouraged citrus producers from using overtree sprinkler systems that deliver precipitation rates of less than 2.5 mm h^{-1} for frost control (Barfield et al. 1990; Kalma et al. 1992).

Since 1962, undertree irrigation systems have replaced the overtree systems in most citrus orchards. The cold protection effect of these systems has been greater than that predicted by models (Barfield et al. 1990). It would seem, therefore, that other processes are at work in addition to that involving the release of the latent heat of fusion. One such process may involve condensation of water vapor evaporated near and advected away from the sprinkler

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orifice. Water vapor introduced in this manner would lead to injected plumes of elevated water vapor mixing ratios within the orchard, a process observed many times in the experimental citrus orchard at the University of Florida in Gainsville, Florida (Martsolf 1992b, 1993). The plumes of high-mixing-ratio air become visible as the vapor condenses into fog droplets, appearing to bubble upward through the tree canopy and spreading out over the upper canopy. This kind of mechanism may explain the fact that protection from freezes in orchards using undertree irrigation systems has achieved greater success than expected (Oswalt and Parsons 1981).

If this kind of mechanism could be shown to be important in the protection of citrus groves during freeze events, much effort could be avoided, that is otherwise expended by trial and error, to find the best location and number of sprinklers per tree. Under the heat of fusion assumption, placement of sprayers is critical for uniform distribution of the latent heating effect [see Sutherland et al. (1981) and Perry et al. (1980) for discussions on deployment logistics]. Furthermore, under the generally stable conditions of a strong nocturnal inversion during radiation frosts when irrigation is most effective (Kalma and Fuchs 1975), injected vapor plumes would tend to mix warmer air downward into the near-surface layers. This alleviates severe cold and contributes to a windbreaking effect above the tree tops (by mixing down high-momentum air into the canopy). This study explores the possibility that such processes take place in the Institute For Food and Agricultural Sciences (IFAS) citrus orchard by examining data collected during freeze events when the irrigation systems were turned on.

2. Data collection

Two surface radiation and energy budget systems (SREBS) were deployed in open areas between two blocks of trees at the northern and southern ends of the University of Florida (UF)/IFAS experimental citrus orchard in Gainesville during the January and February 1992 period. During this time, three freeze events occurred. The stations measured all directional solar and infrared radiative flux components, meteorological parameters (wind, pressure, temperature, relative humidity, and precipitation), soil temperature and moisture at various depths, vertical gradients of temperature and mixing ratio within the surface layer, and sensible, latent, and soil heat fluxes. (Moisture quantities can only be measured accurately above freezing conditions.) A detailed description of the station design can be found in Smith et al. (1992). For purposes of this study, the temperature gradients in the surface layer were the principal focus. Near-surface temperature is the primary information used in freeze protection management in the Florida citrus groves, and such data obtained from both in situ sensors and satellites have been used for many years to help understand and predict freeze conditions along the Florida peninsula (Chen et al. 1983).

Both stations were well exposed, both to downwelling radiation and to northerly flow. The northern station (station 1) was deployed completely in the open, whereas the southern station (station 2) was shielded from southerly flow by nearby packing sheds and laboratory buildings located directly south of the orchard. A tower used for monitoring inversion strength is located near the center of the orchard. The orchard itself is based on a squared plantation frame design, or, in more basic terms, a two-dimensional simple-squared lattice [see Gilabert et al. (1994) for discussion of orchard geometries]. The orchard consists of 459 orange trees of three varieties. Each is equipped with a spray nozzle, in which some nine different types of nozzle heads are used. Figure 1 provides a schematic diagram of the orchard, the locations of the measuring systems, the layout of the different varieties of orange trees, and the placement of the different types of sprayer nozzles. Figure 2 provides a schematic diagram of a SREBS system along with a photograph of its deployment in the IFAS orchard.

Temperature sensors (consisting of standard copper–constantan thermocouples) were mounted at 1.5 and 15 m above ground level on the inversion tower. Fine wire thermocouples for obtaining near-surface temperature gradients were mounted on the two arms of each SREBS station, the lower arm at 1.5 m above ground level, the upper at 2.5 m. Inversion tower data were recorded every minute during two of the freeze events, while the SREBS data were recorded every 6 min continuously from 19 January to 28 February.

The first freeze event occurred during the nights of 24–26 January, the second during 8–9 February, and the third during the night of 27–28 February. The latter event was, in actuality, a near freeze. The inversion tower was operated during the January and late February events, but not during the 8–9 February event. In the following analysis, tower lapse rates are always represented in gradient form. That is, vertical temperature gradients from the tower refer to differences obtained over the 13.5-m interval between the 1.5- and 15-m levels. This facilitates simultaneous graphical presentation of the gradients measured at the surface stations and the tower.

Moisture measurements were not made on the tower nor at the SREBS sites during periods below freezing since the cooled mirror dewpoint hygrometers used by the SREBS cannot function whenever the dewpoints fall below 0°C. As a result, no mixing ratio measurements or latent heat fluxes were obtained during the freeze periods themselves, and conservative thermodynamic variables such as moist static energy or equivalent potential temperatures could not be calculated. Under such conditions, the best measure of vertical mixing in the surface layer is the change in temperature lapse rates or temperature gradients.

3. Theory

The energy budget of orchard leaves has previously been calculated by balancing the heat of fusion of frozen

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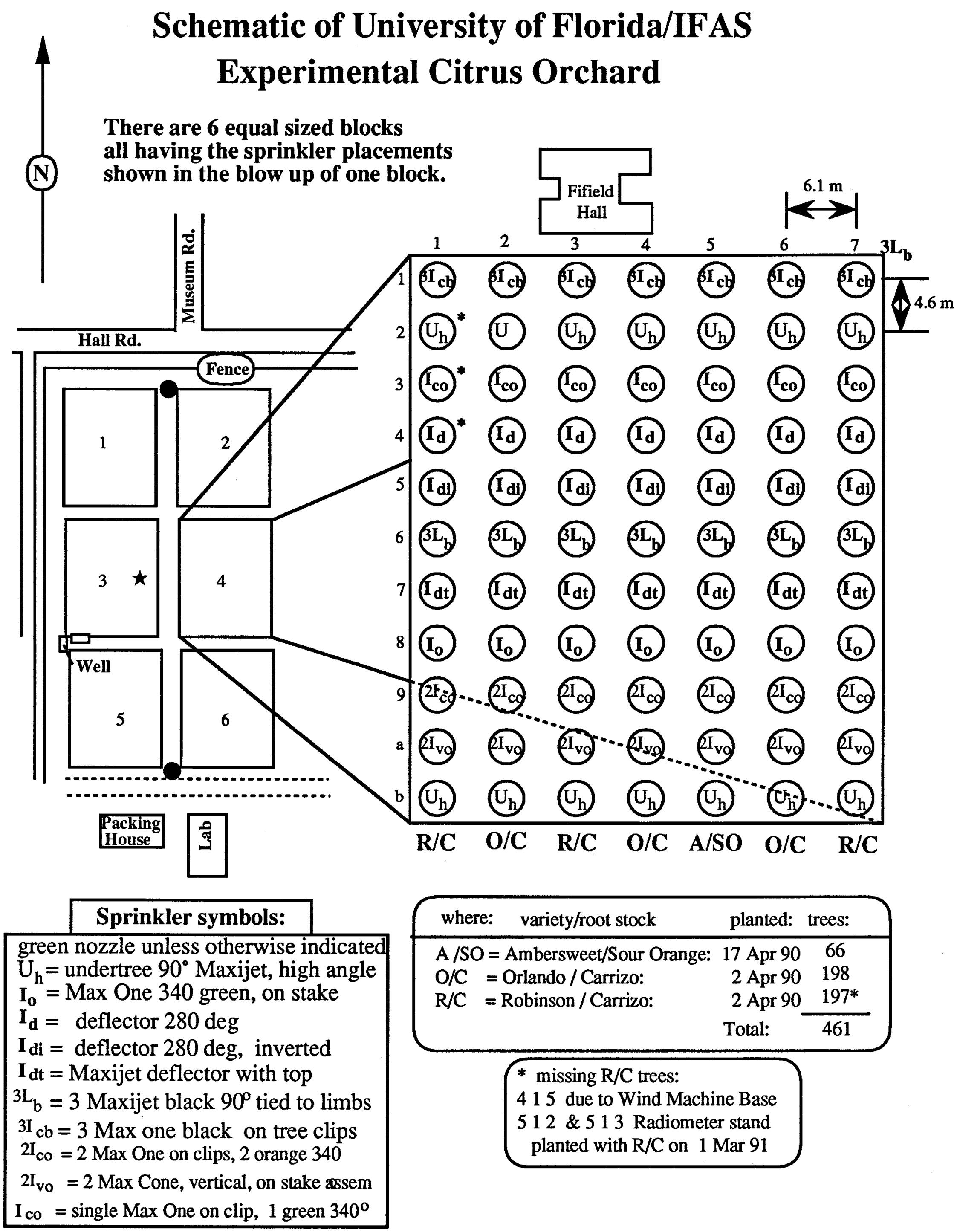

FIG. 1. Schematic layout of the IFAS experimental citrus orchard at the University of Florida in Gainesville. The map inset shows the locations of the two SREBS stations (black circles) and the inversion tower (black star). The types of sprayers used on the trees and the different varieties of trees are indicated.

irrigation water against evaporative losses and advection to the surrounding atmosphere. Because of the dominant effects of evaporation cooling during advection freezes, sprinklers were moved under the tree canopies so that the effect of advective evaporative losses would be minimized. During undertree irrigation, it is postulated that in-canopy air becomes buoyant relative to the air above the canopy. This has been observed and becomes visible

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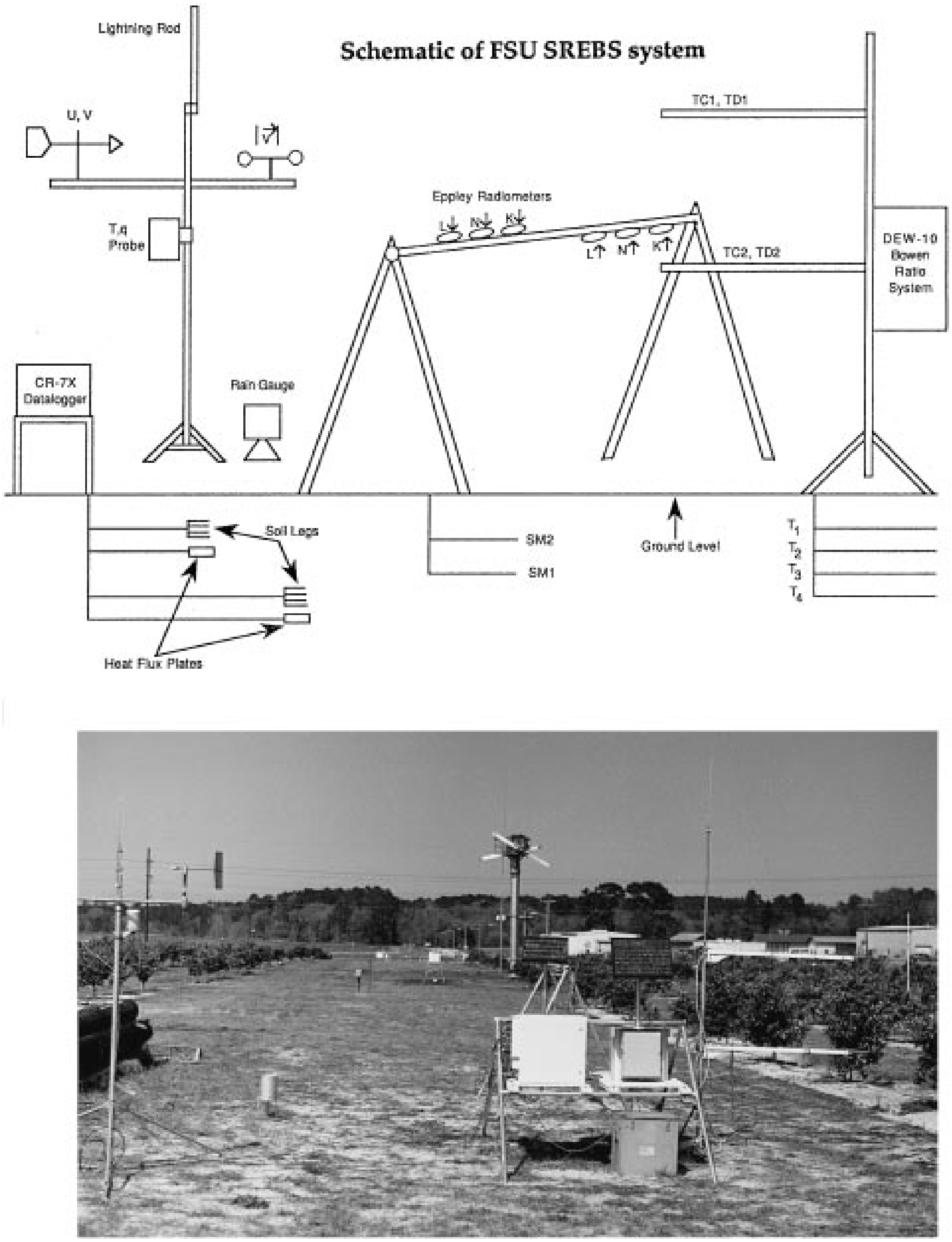

FIG. 2. Top panel provides a schematic illustration of a SREBS system; the temperature measuring arms are placed at 1.5 and 2.5 m above the surface. Bottom panel provides a photograph of the two SREBS systems deployed in the IFAS experimental orchard. The station closest to the camera is the south station, while the north station is barely visible at the other end of the grove.

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as rising plumes of fog droplets. The effect of these plumes on temperature lapse rates over the orchard as a whole cannot be properly understood in terms of leaf energetics alone and must be treated in terms of convective turbulence on a space scale on the order of the entire orchard. In this section, we consider the two main processes that generate buoyancy—the increase of mixing ratios and warming by release of latent heat of fusion or condensation. The fraction of the irrigation water being injected as vapor is unknown. However, the release of latent heat of condensation per kilogram is an order of magnitude larger than that of fusion because of the differences in the phase change energy barriers. The main point in this section is to demonstrate that these mechanisms can produce buoyancies sufficient to generate a mean upward motion over the orchard capable of reducing lapse rates close to the ground.

During irrigation, two general types of overturning are possible, which operate at different scales. In the first type, mixing of stable air above the trees, in response to rising plumes from within the canopy emanating from localized latent heat release, causes warmer air to be mixed down to treetop height. In the second type, the areas over the trees contain active plumes, which become organized to the extent that air is drawn through the sides of the trees, with compensating subsidence taking place outside the orchard area. Differences in the two mechanisms are a matter of scale and organization, but both involve plumes and compensating subsidence as the dominant mechanisms and both produce warmer air over the orchard. Thus, this treatment of mixing in terms of general orchard-scale overturning is a parameterization of small-scale turbulent processes. We assume zero horizontal temperature and energy gradients outside the orchard and calm conditions. The ambient air is assumed to have a temperature of $T_o = 273.15$ K at the surface, with an arbitrary initial lapse rate of Γ. Injected water is assumed to immediately freeze, sensible and latent heat flux from the trees and ground surfaces are assumed to be small (zero), and radiation flux convergence effects are assumed to be negligible.

a. Effects of irrigation on buoyancy

It is assumed that energy from the irrigation pumping process is used to vaporize an unknown fraction of irrigation water (F_v) part of which then increases the mixing ratio of the in-canopy air at ambient temperature. The irrigation rate per tree (I) is therefore written as

$$I = F_v I + (1 - F_v)I. \tag{1}$$

Since the energy for vaporization comes from the pumping process, no heat is taken from the ambient air while the local mixing ratio increases, and therefore the rise in temperature associated with the condensation-deposition of vapor and the freezing of water represents a net gain of energy. The irrigation rate per tree for the IFAS orchard is 1.682×10^{-2} kg s^{-1} per tree (16 gal h^{-1}). Each tree in the orchard is assumed to be contained within an imaginary differential volume 4.572 m long (15 ft) by 6.096 m wide (20 ft) and 2 m deep, giving a volume per tree of 55.742 m^3.

The mixing ratio after injection is given by

$$q_p(p, T_o) = q_o(p, T_o) + \Delta q + (1 - \delta)\frac{\Delta t F_v I}{M_t}, \tag{2}$$

where q_o is the mixing ratio before injection, q_p is the mixing ratio after the vapor is pumped into the trees, p is the surface pressure, T_o is the ambient temperature, M_t is the total mass of air in the volume, Δt is a representative time step, Δq is the saturation mixing ratio deficit, and δ is the Dirac delta function. The parameters Δq and δ are evaluated by first defining q_{so} as the saturation mixing ratio before injection, meaning the air can take up a differential amount of vapor $dq_{so} = q_{so} - q_o$ due to irrigation pumping, after which saturation occurs. Then $\Delta q = \delta dq_{so}$, where δ is given by the following.

$$\text{If} \quad \frac{\Delta t F_v I}{M_t} \geq dq_{so}, \quad \text{then } \delta = 1, \tag{3a}$$

$$\text{or if} \quad \frac{\Delta t F_v I}{M_t} < dq_{so}, \quad \text{then } \delta = 0. \tag{3b}$$

Then, if condition (3a) holds,

$$q_p(p, T_o) = q_o(p, T_o) + dq_{so},$$

or equivalently,

$$q_p(p, T_o) = q_{so}(p, T_o). \tag{4a}$$

Otherwise, condition (3b) holds, and

$$q_p(p, T_o) = q_o(p, T_o) + \frac{\Delta t F_v I}{M_t}. \tag{4b}$$

We introduce Δq so that we can separate the injected vapor into the portion that increases the mixing ratio and the excess greater than saturation, which undergoes condensation and/or deposition. Accordingly, the irrigation rate is rewritten as

$$I = \Delta q F_v I + (1 - \Delta q)F_v I + (1 - F_v)I. \tag{5}$$

Of course, as long as the quantity of vapor injected ($\Delta t F_v I/M_t$) is less than the difference between the saturation mixing ratio and the preinjection mixing ratio, none of the injected vapor will be left for condensation or deposition.

Due to the excess water vapor undergoing condensation and/or deposition and the remaining irrigation water undergoing freezing, diabatic heating takes place, due to the release of latent heat, at the rate

$$c_p \Delta T = \frac{\delta \Delta t(L_f + L_v)(1 - \Delta q)F_v I}{M_t} + \frac{\Delta t L_f (1 - F_v)I}{M_t}, \tag{6}$$

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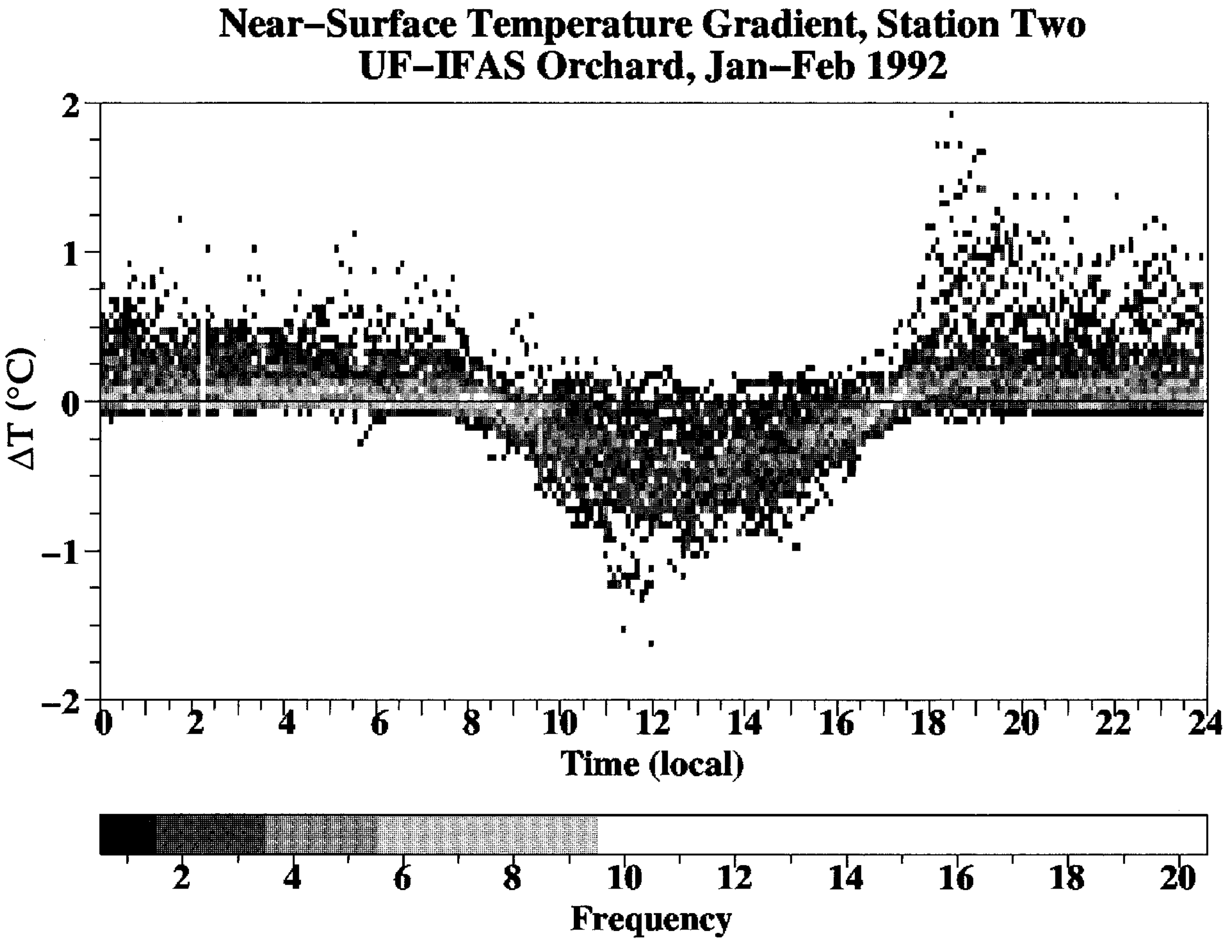

FIG. 3a. The distribution of temperature gradients at station 1 as a function of time of day. The shaded gray scale indicates the number of occurrences at each point in the ΔT time plane. The gradients are negative during daytime and positive at night, with the largest positive gradients in the early evening and the most negative gradients just after midday. During the evening and nighttime hours, the greatest frequencies lie between $-0.25°C$ and $+0.25°C$. The figure includes all surface-layer gradients measured every 6 min between 18 January and 28 February, a total of 9004 observations.

where c_p is the specific heat of air at constant pressure, L_f and L_v are the latent heats of freezing and condensation, and ΔT is the resulting temperature change of an air parcel in the canopy due to diabatic heating. The parcel temperature T_p is then

$$T_p = T_o + \frac{\delta \Delta t(L_f + L_v)(1 - \Delta q)F_v I}{c_p M_t} + \frac{\Delta t L_f(1 - F_v)I}{c_p M_t}. \quad (7)$$

Note that the mass and volume fractions of injected vapor and liquid water are small enough that we may safely neglect the effect of mechanical mixing and conduction on the temperature of the air in the canopy.

The virtual temperatures of air at T_o–q_o and T_p–q_p are now defined as

$$T_{vo} = T_o[1.0 + 0.61q_o(p, T_o)] \quad (8a)$$

$$T_{vp} = T_p[1.0 + 0.61q_p(p, T_p)]. \quad (8b)$$

Finally, the buoyancy B of the modified parcels is given by

$$B = \frac{(T_{vp} - T_{vo})g}{T_{vo}}, \quad (9)$$

where g is the acceleration due to gravity.

b. Parcel vertical velocities

Laboratory experiments (see Ludlam 1980; Batchelor 1970) show that the rise rate w for a plume can be written as

$$w^2 = C^2 rB, \quad (10)$$

where $C^2 = 1.2$ is a Froude number and r is the radius of the plume at its widest extent. The parameter r can be approximated by $z = nr$, where z is the distance from the plume cap to its point of origin, and from experiments n = 4. Some of the sprinklers were on the ground spraying upward into the trees, others were placed near the treetops

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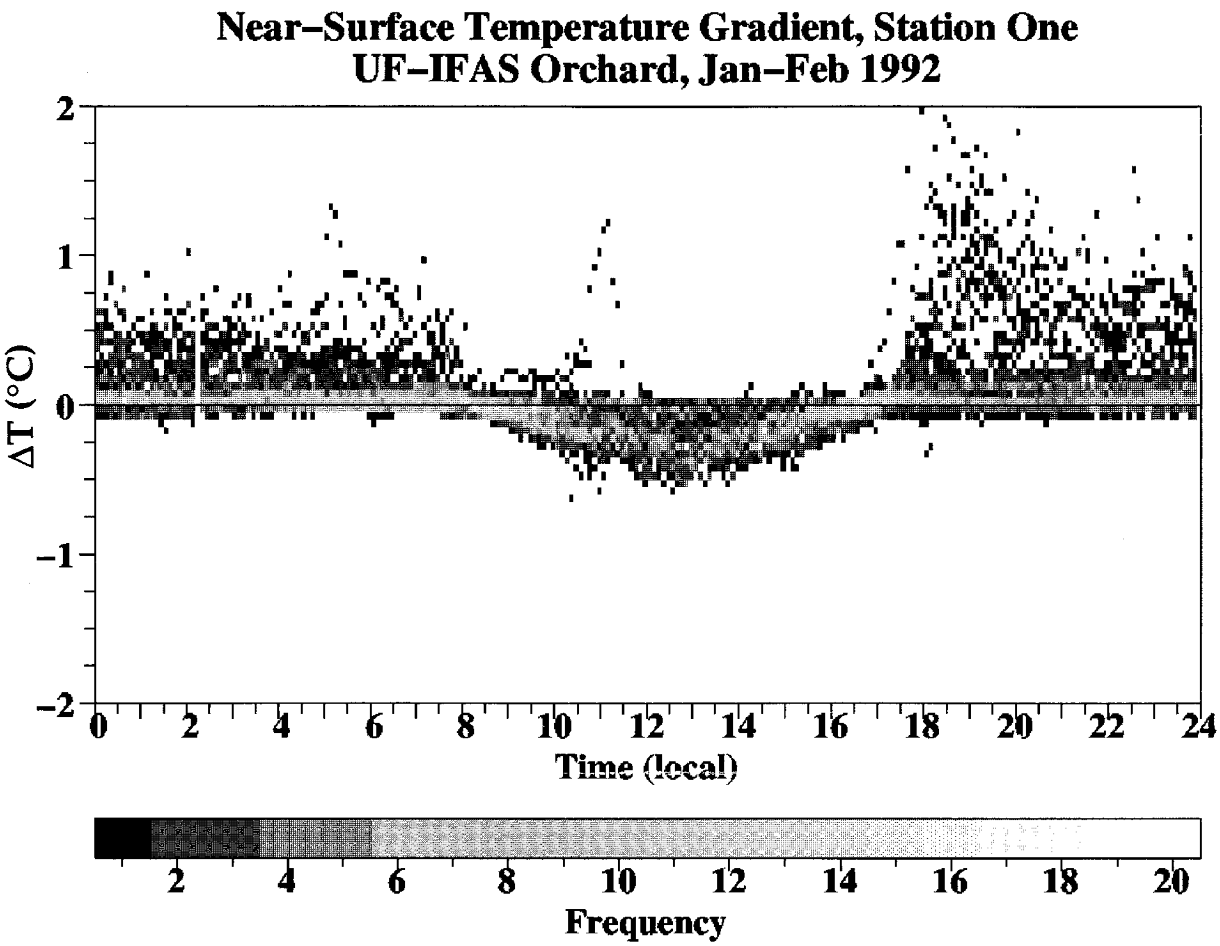

FIG. 3b. Same as Fig. 3a except for station 2, with a total of 9595 observations.

spraying downward (see Fig. 1). We therefore assume that, in the mean, the plumes originate halfway between the ground and the tops of the trees (approximately 2 m). Under such conditions, $z = 1$ m and $r = 0.25$ m represent the dimensions of a typical plume. The turbulent-scale vertical velocities can then be expressed by

$$w = (1.2 \times 0.25 \times B)^{1/2}. \qquad (11)$$

The moist static energy at constant height within the differential volume is given by $h_p = C_pT_p + L_vq_p$. (Note that at constant height we can ignore the gz term.) Energy balance requires that

$$\frac{\partial h_p}{\partial t} = -w\frac{\partial h_p}{\partial z} - \frac{\partial(\rho w' h'_p)}{\partial z} + S_{oh} - S_{ih}, \qquad (12)$$

where w is the vertical wind velocity, ρ is the density of air in the differential volume, S_{oh} is the source of energy (the irrigation), S_{ih} is the energy sink, and the second term on the right-hand side represents the eddy flux divergence of h_p, generated by buoyant plumes originating within the volume. Inside the volume, it is assumed that $\partial h_p/\partial z = 0$ (i.e., there is thorough mixing of properties during injection), and there are no internal sinks of energy other than conduction paths to the ground and vegetation, which are assumed to be small (i.e., $S_{ih} = 0$). Furthermore, the eddy fluxes only have meaning at the top and bottom of the volume, since horizontal gradients are assumed to be zero. Since the vertical velocity at the bottom of the volume (w_b) is zero, and designating w_t as the velocity at the top, $\rho w_b h_p = 0$ and the energy flux through the top of the volume is $\rho w_t h_p$. Thus, there is net energy flux divergence from the ground to the top.

For a period of time, the flux divergence offsets the phase changes in the volume, which generates local buoyant eddies by releasing latent heat and increasing mixing ratios. The buoyant eddies then maintain an equilibrium state between the source of energy (the irrigation) and the losses (the buoyant plumes). During this period of equilibrium, freezing ambient temperatures are maintained for the process to continue. Then (12) is rewritten as

$$\rho w'_t h'_p \Delta A_t = (\delta L_f + L_v)(1 - \Delta q)F_v I + L_f(1 - F_v)I, \qquad (13)$$

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where ΔA_t is the area of the top and the bottom of the volume.

The irrigation water is pumped from a well 25 m below the surface, using a 5-hp motor. The temperature of the well water is consistently at 20.5°C, and we estimate an environmental relative humidity of 20%. To calculate conservative estimates of buoyancy effects in the orchard, we consider only the effect of freezing the injected water and ignore the heating due to the injection of warm water and the condensation of injected water vapor. This latter term may be large because the latent heat of condensation is an order of magnitude greater than the latent heat of fusion. The actual fractional water vapor injection rate is unknown, so we consider two values of F_v an order of magnitude apart. If $F_v = 0.01$, the temperature of the buoyant plumes as calculated from (7) is found to be 273.228 K, and the mixing ratio from (4b) is 0.7662×10^{-3} kg kg^{-1}. Using $F_v = 0.1$, the temperature is 273.2209 K, and the mixing ratio is 0.7875×10^{-3} kg kg^{-1}. The virtual temperature with $F_v = 0.01$ is therefore 273.3557 K, while for $F_v = 0.1$ it is 273.3521 K, which is slightly lower. Thus the buoyancy effects using the smaller value of F_v are slightly greater since of the release of greater amounts of latent heat of fusion offsets loss of buoyancy due to a lower mixing ratio. Therefore, in the sense of generating lower buoyancy, the value of $F_v = 0.1$ is a conservative value.

Using $F_v = 0.1$, since saturation vapor pressure at T_o is $q_{so} = 3.819 \times 10^{-3}$ kg kg^{-1} and $q_o = 0.7638 \times 10^{-3}$ kg kg^{-1}, $dq_{so} = 3.0552 \times 10^{-3}$ kg kg^{-1}, which is the capacity of the volume for these conditions. This means that $\Delta t F_v I/M_t = 2.3667 \times 10^{-5}$ kg kg^{-1} per unit time step of 1 s. Therefore, $\Delta t F_v I/M_t < dq_{so}$, which means $\delta = 0$. Under such conditions, the buoyancy acceleration is calculated from (9) to be 0.0073 m s^{-2}, which from (11) gives a rise rate of 0.0467 m s^{-1}. The temperature of the buoyant plume is calculated from (7) to be 273.2209 K, with a mixing ratio of 0.7875×10^{-3} kg kg^{-1}. This gives a moist static energy for the parcels of $h_p = 276.2826 \times 10^3$ J kg^{-1}, with a density of 1.2747 kg m^{-3}. If it is assumed that the flux through the top of the unit volume of area $A_t = 27.8709$ m^2 is unimpeded, then the net buoyant eddy energy transport through the trees would be 4.583×10^5 J s^{-1}, which is greater than the energy source allows, because in this case the total energy available from irrigation, $E = L_v F_v I + L_f(1 - F_v)I = 9.2622 \times 10^3$ J s^{-1}. This is not surprising since no allowance has been made for turbulent dissipation through the trees and the presence of the trees themselves has been ignored. In addition, the loss of energy by the combined effect of nocturnal net infrared radiative exchange from canopy and ground, and heat flow in the soil has been ignored so far. This must be balanced in the surface energy budget equation by combined sensible and latent heat exchange with the surface (F_S). Examination of the net IR and soil flux measurements for the three freezes from the period 1800–0800 LT, when irrigation was taking place, reveals an average available heating of -29 W m^{-2}, or an energy loss rate from the canopy level of $F_S = 0.82 \times 10^3$ J s^{-1} per tree, due to the combined effects of sensible and latent heat transfer. Notably, this term is small so that the surface energy budget plays a minor role in buoyancy generation at night.

The effect of turbulent dissipation and the surface energy budget is parameterized by forcing energy balance between the flux generated by the plumes and the actual rate of energy production by the irrigation minus the sensible and latent heat losses. The dissipation factor F_t is used to correct the vertical velocity as $\overline{w} = wF_t$ and is given by

$$F_t = \frac{E - F_S}{\rho_p w h_p \Delta A_t}, \qquad (14)$$

where $\overline{w}$ is the mean vertical velocity over the orchard necessary to maintain energy balance. With the above conditions, $\overline{w} = 8.604 \times 10^{-4}$ m s^{-1}. Finally, mass balance requires horizontal divergence (div$_h$) into the orchard of -4.303×10^{-4} s^{-1}, and since the equation of continuity requires

$$\mathrm{div}_h = -\frac{\partial w}{\partial z}, \qquad (15)$$

we can estimate vertical velocities at the 1.5- and 2.5-m levels of the SREBS stations to be 3.23×10^{-4} and 5.38×10^{-4} m s^{-1}, respectively.

c. Modification of lapse rate

Now, the rate of change of the lapse rate is given by

$$\frac{d\Gamma}{dt} = \frac{d}{dt}\frac{[T(z_2) - T(z_1)]}{\Delta z}, \qquad (16)$$

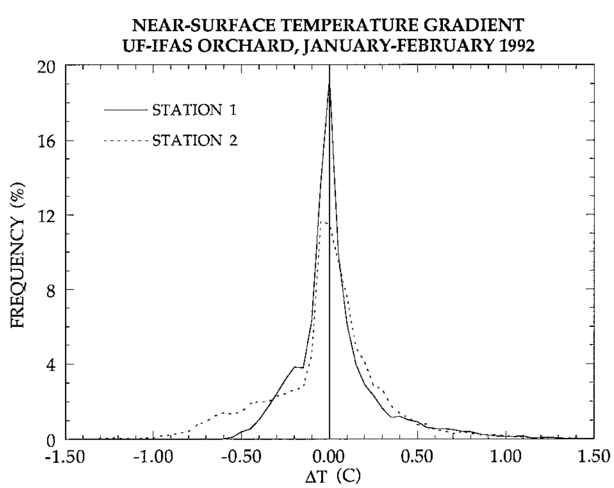

FIG. 4. Frequency distributions of temperature gradient magnitudes observed at station 1 and station 2 during the entire experiment period. While station 2 shows higher frequencies of larger negative gradients (occurring during daytime hours), the frequency distributions are nearly identical for the positive gradients occurring at night.

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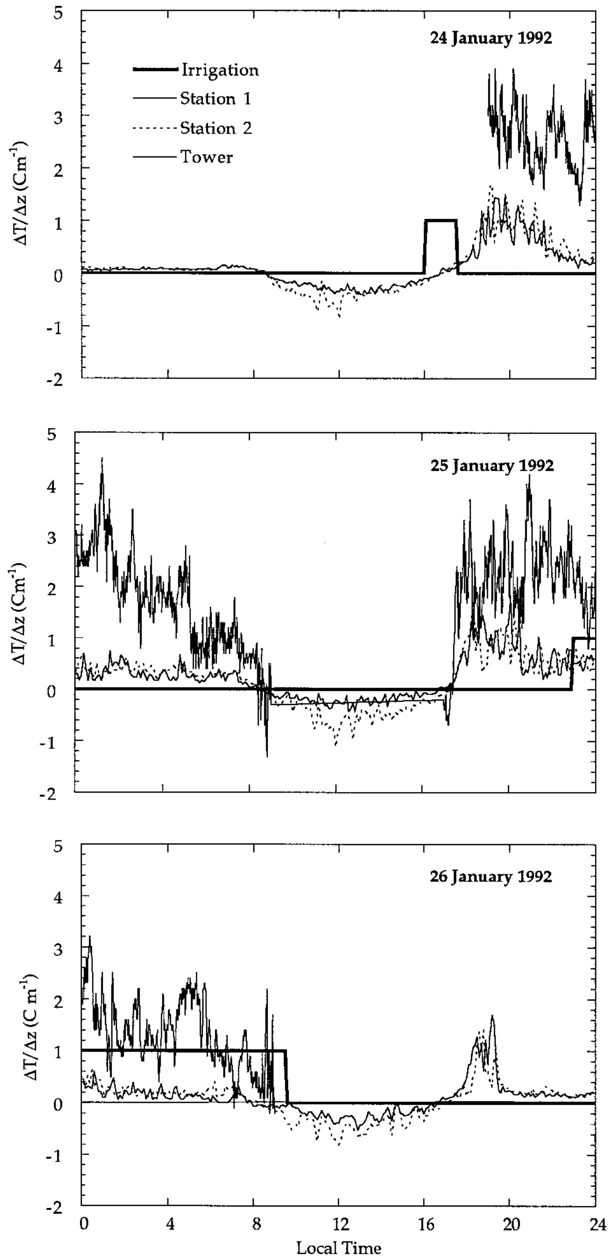

FIG. 5a. Surface-layer lapse rates measured at both SREBS stations and temperature gradients at the inversion tower for the first freeze period of 24–26 January. The SREBS results are given as lapse rates (°C m^{-1}) while the tower data are given as absolute temperature gradients (°C) between the 1.5- and 15-m tower sensor levels. This facilitates the intercomparison between SREBS and tower measurements. Irrigation periods are indicated by a thick black line plotted as a 1°C m^{-1} lapse rate.

where $z_2 = 2.5$ m, $z_1 = 1.5$ m, and $\Delta z = 1.0$ m, and since the time rate of change of temperature is $-\overline{w}\Gamma$, we can evaluate the time derivative of Γ as

$$\frac{d\Gamma}{dt} = -2.1505 \times 10^{-4}\, \Gamma \text{ K m}^{-1} \text{ s}^{-1}. \qquad (17)$$

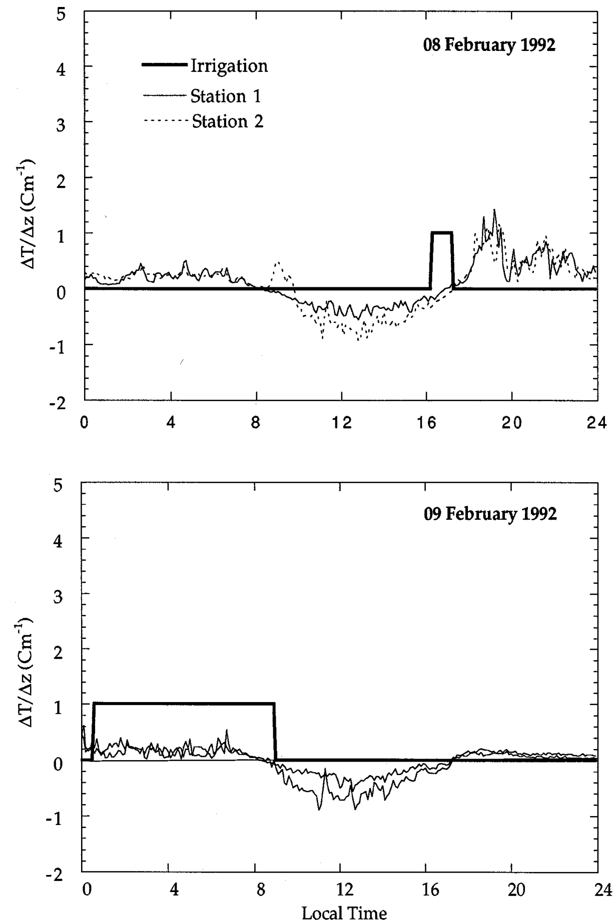

FIG. 5b. Same as Fig. 5b except for the second freeze on 8–9 February (the tower was not operational).

Since the derivative is negative, we have the necessary mechanism to reduce the thermal stability in the surface layer and to buoyantly mix down warm air. For example, allowing this process to take place over a period of 1.29 h would eliminate an initial lapse rate of 1.75 K m^{-1}. The magnitude chosen for the initial lapse rate reflects the largest expected value during an unirrigated period (see Figs. 6a,b). Of course, these lapse rate changes would not be persistent, but even if processes like these operated briefly, they would be sufficient to reduce the lapse rates observed at the SREBS stations.

4. Results of data analysis

At each 6-min period during the six continuous weeks of operation from 18 January to 28 February, the near-surface temperature gradients and lapse rates were calculated at both of the SREBS stations. The two datasets are illustrated by the temperature gradient distributions shown in Figs. 3a,b. Figure 3a shows the distribution for the northern site, while Fig. 3b shows a similar distribution for the southern site. The degree of shading denotes the frequency of occurrence at each location in

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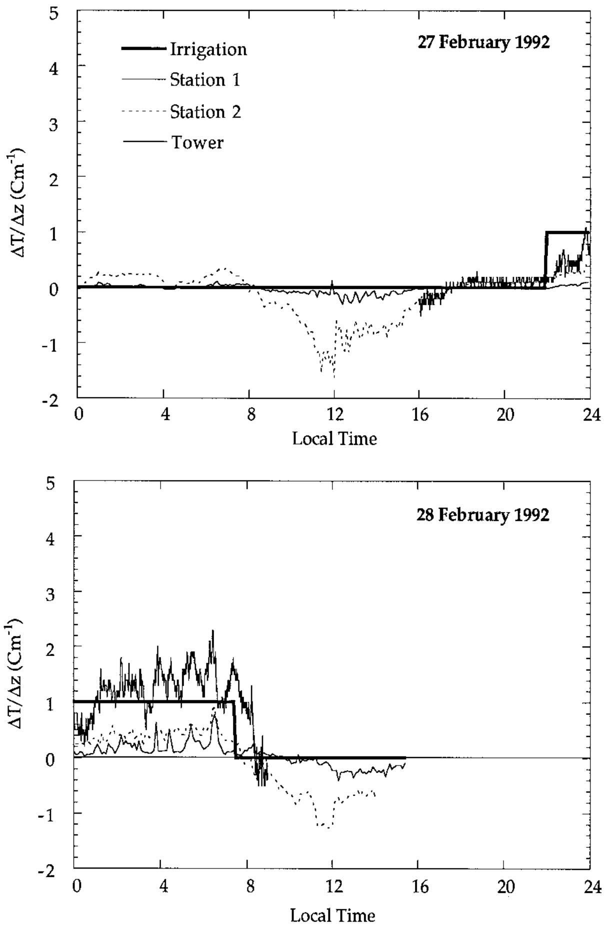

FIG. 5c. Same as 5a except for the third freeze on 27–28 February.

the ΔT time plane. It is clear that gradients go through the expected cycle of instability (negative ΔT's) during the late morning and afternoon, and of stability (positive ΔT's) during nighttime hours. The largest absolute magnitudes occur just after midday and in the early evening. The daytime instabilities tend to be greater at the southern site, while the nighttime gradients exhibit no obvious differences between the two sites. This is also seen in Fig. 4, which shows that while the negative temperature gradients at station 2 are more widely distributed than at station 1, the nighttime distributions of positive temperature gradients are similar at both locations. Thus, while there may be differences in daytime processes due to location, both stations respond to nighttime processes in a similar fashion. Figures 3 and 4 are the results of calculations made from 9004 observations at station 1 and 9595 observations made at station 2.

a. *Vertical temperature gradients during three freeze events*

During certain periods of each of the three freeze events, the irrigation system was turned on, injecting water into the orchard at a nominal rate of 1.682×10^{-5} $m^3\ s^{-1}$ (16 gal h^{-1}) under each of the 459 trees in the planted blocks. The relationships between the temperature gradients measured between 1.5 and 15 m at the inversion tower and the lapse rates at each of the SREBS stations, as well as the irrigation status, are seen in Figs. 5a–c for the three events. The SREBS sites were located in open areas close to the trees and were not directly above or beneath sprinklers. However, the response of the temperature gradients at the SREBS sites and the response of the tower temperature gradients directly above the irrigated trees show temporal consistency with the lapse rate observations taken at the two SREBS sites for all three cases. The measurements made by the three independent data collection systems substantiate the presence of a stable layer at low levels. The implication is that any mixing in the vertical, initiated in the surface layer, should produce warmer temperatures at the surface, even if the length scales of mixing eddies are only on the order of a few meters.

Figure 5a shows the general variability with time of the tower-based temperature gradients and lapse rates at both SREBS stations during the first freeze. The early hours of 24 January indicate low positive lapse rates at both stations, followed by negative lapse rates in the afternoon. By 1800 LT the lapse rates are again positive, while between 1800 and 2000 LT the stable-layer lapse rates increase rapidly, after which they decrease gradually during the remainder of the night. The tower gradient data also show large positive values during the evening and after midnight, decreasing as morning approaches. Similar patterns are observed during the night of 25 January. The early evening and late night of 26 January are different in that the initial burst of strong positive gradients, which begins shortly after 1700 LT, diminishes rapidly until 2000 LT, after which the temperature gradients, while positive, are relatively small.

Lapse rates during the second freeze, on the nights of 8–9 February, exhibit a similar pattern (Fig. 5b). (During this freeze, tower data were not available.) The positive lapse rates during the early hours of 8 February are large, switching to unstable during the day, then positive again during the early evening hours. The larger positive lapse rates then fall off until morning, similar to the first freeze. The evening of 9 February indicates very small positive lapse rates up until midnight.

The third freeze, on 27–28 February, is similar to the first two freezes, except that the early evening increase in positive gradients and lapse rates is suppressed, with station 2 showing greater extremes of instability during the daylight hours on both days (Fig. 5c). It is possible that this freeze was more advective in nature than the two previous freezes, which were largely responding to only radiative cooling processes on the local scale. No complete explanation can be offered for the observed difference other than that it resulted from different levels of exposure within the grove to advective processes. However, it should be noted that there is close temporal

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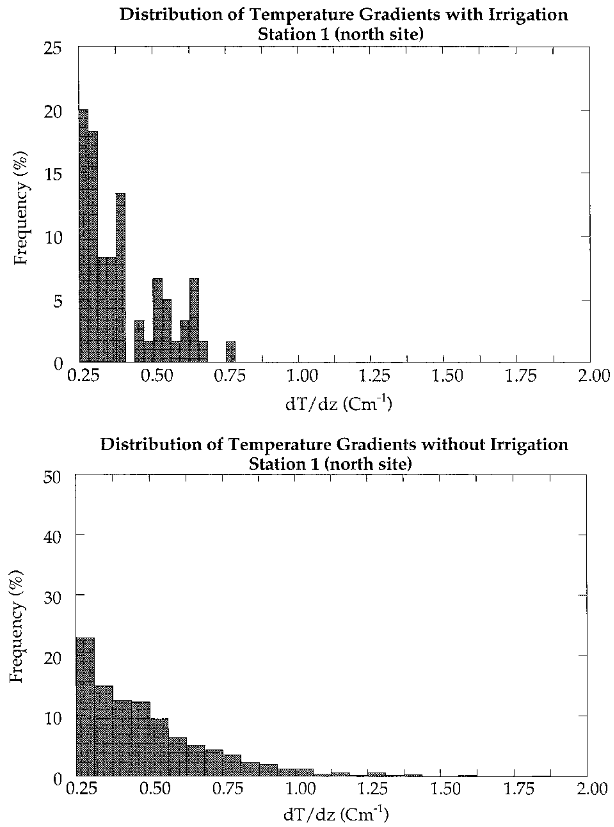

FIG. 6. (a) A comparison of the distribution of lapse rates at station 1 under similar conditions when irrigation was taking place (top panel) versus when irrigation was not taking place (bottom panel). (b) Same as (a) except for station 2.

coherence between the nighttime tower data and the observations at the two SREBS stations, thus upholding the advection argument as a final explanation.

In all three of these figures, the periods of irrigation are noted by a thick black line plotted as a 1°C m^{-1} lapse rate when irrigation is on and zero when it is off. The rate of irrigation is constant.

b. Effects of irrigation on nighttime vertical temperature gradients

In order to isolate the effects of irrigation, the temperature gradients during irrigated and nonirrigated periods are compared under similar conditions of stability, as represented by the temperature gradients measured at the two SREBS stations. Referring to Figs. 3a,b, gradients greater than +0.25°C m^{-1} were extracted from the entire dataset at each station. This limits the analysis to cases in which the gradients are relatively large and positive, a condition expected during freeze events. From Figs. 3a,b it can be seen that the positive gradients occurred almost exclusively at night. Using this selection procedure, a total of 1181 samples were taken from the station 1 dataset and 1461 cases from the station 2 dataset. These two sets of observations represent the upper 15.2th percentile of all observations at station 1 and the upper 13.1th percentile of all observations at station 2 (see Fig. 4). Since Figs. 5a–c show that the rapid increase in positive gradients and lapse rates between 1700 and 2000 LT may be independent of irrigation, both sets of extracted observations were further limited to those that occurred during the time period between 2000 and 0800 LT the following morning. This constraint eliminates most of the large positive gradients that occurred during the freeze events in the early evening. At station 1, this final category consisted of 895 measurements, or 75.8% of all of the extracted data, and at station 2, 1080 measurements, or 73.9% of the extracted data. The resulting subsets of data are thus equally balanced between the two stations.

These two datasets were then separated into cases in which the irrigation system was turned on and when it was off. The results are shown in Figs. 6a,b plotted as frequency distributions in terms of lapse rate. The larger positive lapse rates, which occur naturally when the irrigation system is not operating, do not occur when the irrigation system is turned on. This is the case at both stations, suggesting the possibility that the mixing effect of buoyant plumes introduced into the orchard either by the release of latent heat of fusion or condensation of water vapor released at the sprayer heads or by elevated mixing ratios and hence elevated virtual

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temperatures of parcels within the canopy (which would increase relative buoyancy) may be causing local overturning of previously stable air. This would lead to the observed decreases in the magnitudes of positive lapse rates to a greater extent than seen in the nonirrigated cases.

5. Conclusions

Observations taken during the winter of 1992 at the University of Florida's IFAS experimental citrus orchard indicate that temperature gradients measured at two surface locations in the grove and by sensors at 1.5 and 15 m on an inversion tower are consistent with one another. The positive nocturnal temperature gradients during freezes were greatest during the evening and immediately after midnight, and then eroded during the night, becoming negative during the daytime period. Previous reports concerning the effectiveness of irrigation during freezes suggest that it is greater than modeling studies indicate, possibly because such models only account for the release of latent heat of fusion as the source of heat and protection from frost. The theoretical explanation and the results of the data analysis suggest that other internal heating mechanisms may operate during irrigation. A comparison of the temperature lapse rates under similar conditions at the two stations in the orchard reveals that the large positive lapse rates observed by both stations when no irrigation is taking place are significantly reduced during irrigation periods, indicating the possibility of increased latent heating and vertical mixing when water vapor evaporates from the nozzles of the sprinklers, condenses, and creates buoyant plumes within the tree canopy. Such mechanisms would add to the effectiveness of undertree sprinklers as protection against crop damage during mild winter freezes.

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REFERENCES

Barfield, B. J., K. B. Perry, J. D. Martsolf, and C. T. Morrow, 1990: Modifying the aerial environment. *Management of Farm Irrigation Systems, ASAE Monogr.,* No. 22, Amer. Soc. Agric. Eng., 825–869.

Batchelor, G. K., 1970: *An Introduction to Fluid Dynamics.* Cambridge University Press, 615 pp.

Businger, J. A., 1965: Frost protection with irrigation. *Agricultural Meteorology, Meteor. Monogr.,* No. 28, Amer. Meteor. Soc., 74–80.

Chen, E., L. H. Allen Jr., J. F. Bartholic, and J. F. Gerber, 1983: Comparison of winter-nocturnal geostationary satellite infrared-surface temperature with shelter-height temperature in Florida. *Remote Sens. Environ.,* **13,** 313–327.

Gerber, J. F., and D. S. Harrison, 1964: Sprinkler irrigation for cold protection of citrus. *Trans. ASAE,* **7,** 464–467.

Gilabert, M. A., D. Segarra, and J. Meliá, 1994: Simulation of citrus orchard reflectance by means of a geometrical canopy model. *Int. J. Remote Sens.,* **15,** 2559–2582.

Kalma, J. D., and M. Fuchs, 1975: Citrus orchards. *Case Studies,* Vol. 2, J. L. Monteith, Ed., *Vegetation and the Atmosphere,* Academic Press, 309–328.

——, G. P. Laughlin, J. M. Caprio, and P. J. C. Hamer, 1992: *The Bioclimatology of Frost.* Springer-Verlag, 144 pp.

Ludlam, F. H., 1980: *Clouds and Storms.* The Pennsylvania State University Press, 405 pp.

Martsolf, J. D., 1990: Cold protection strategies. *Proc. Fl. State. Hortic. Soc.,* **103,** 72–78.

——, 1992a: Energy requirements for frost protection of horticultural crops. *Energy in Farm Production,* R. C. Fluck, Ed., Elsevier, 219–239.

——, 1992b: Cold protection mechanisms. *Proc. Fl. State. Hortic. Soc.,* **105,** 91–94.

——, 1993: Evaporation and wind: Friend or foe in cold protection. *Proc. Fl. State. Hortic. Soc.,* **106,** 65–70.

Oswalt, T. W., and L. R. Parsons, 1981: Observations on micro sprinkler use for cold protection during the 1981 freeze. *Proc. Fl. State. Hortic. Soc.,* **94,** 52–54.

Perry, K. B., J. D. Martsolf, and C. T. Morrow, 1980: Conserving water in sprinkling for frost protection by intermittent application. *J. Amer. Soc. Hortic. Sci.,* **105,** 657–660.

Smith, E. A., W. L. Crosson, and B. D. Tanner, 1992: Estimation of surface heat and moisture fluxes over a prairie grassland. Part I: In situ measurements incorporating a cooled mirror dew point hygrometer. *J. Geophys. Res.,* **97,** 18 583–18 598.

Sutherland, R. A., H. E. Hannah, A. F. Cook, and J. D. Martsolf, 1981: Remote sensing of thermal radiation from an aircraft: An analysis and evaluation of crop freeze methods. *J. Appl. Meteor.,* **20,** 813–820.

Wallis, R., 1963: Effectiveness of freeze protection during the freeze of December, 1962. *Citrus Ind.,* **44,** 21–22.

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