MASTER

Turbulent Energy Losses During Orchard Heating¹

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The Pennsylvania State University

The Graduate School

Department of Horticulture

Turbulent Energy Losses During
Orchard Heating

A Thesis in

Horticulture

by

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Abstract

Two rapid-response drag anemometers and low time constant thermocouples, all at 4 m above a heated orchard floor, sampled w and T at 30 Hz. The turbulent heat flux calculated revealed not more than 10% of the heat lost from the orchard was via turbulent transport. The observations failed to support previous estimates that at least a third of the energy applied was lost through turbulent transport. Underestimation of heat loss due to mean flow and a newly revealed flux due to spatial variations in the mean flow may explain the unaccounted-for loss.

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Introduction

The energy efficiency of orchard air heating by current methods rarely surpasses 5%¹. A five-fold increase in the cost of fuel used for heating is incentive to search for ways of increasing this efficiency. At least 75% of a heater's energy output is in the form of heated air, the rest is radiant energy (Perry, et al., 1977). The effectiveness of radiant energy in protecting plants from cold has been well documented (Perry, et al., 1977, and Welles, et al., 1978). Welles, et al. (1978) found an increase in over-all heating effectiveness with an increase in the radiant fraction of a heater's output. The majority of the energy released, however, is convective. Understanding the fate of the convective energy output could lead to increases in heating efficiency. This thesis reports measurements of the turbulent heat flux above a heated orchard. Models of the heated orchard (Gerber, 1969, Crawford, 1964, and Martsolf and Panofsky, 1975) and their considerations of fluctuations in the vertical mean flow--the vertical turbulent heat flux--are considered.

¹A temperature increase of 3°C in 1 hour requires 1 Wm^{-3} for an orchard 5 m thick. Convective energy inputs during orchard heating are typically on the order of 40 Wm^{-3} .

Chapter 1

Literature Review

1.1 Introduction

Efforts at writing the energy budget of a heated orchard are contained in three papers: Gerber (1969), Crawford (1964), and Martsolf and Panofsky (1975). The first two of these papers, Crawford (1964), and Gerber (1969), are models. They were written with the intent of providing a simplified description of the physical processes occurring during orchard heating. The simplified energy budgets, or models, then provided estimates of the energy inputs required to provide frost protection. Gerber (1969) and Crawford (1964) provided the heating practitioner with requirement guidelines. Martsolf and Panofsky (1975) attempted to clarify the nature of the energy fluxes that must be evaluated in order to predict orchard temperatures during orchard heating. It is the only approach that explicitly recognizes turbulent transport as a flux to be evaluated. Its intent was to provide a framework on which to organize research efforts.

Welles, et al. (1978) modelled orchard foliage temperatures with an approach distinctly different from the orchard energy budgets. The fate of radiant energy from the heaters was predicted by rigorous radiative transfer and canopy extinction equations. Calculating the radiant energy incident on individual foliage elements permitted the solution of that element's energy budget. The percentage of foliage protected under various meteorological and energy inputs was computed stochastically.

This review focuses on the three energy budgets of the heated

orchard: Crawford (1969), Gerber (1964), and Martsolf and Panofsky (1975). A review of the basic equation stated by Martsolf and Panofsky (1975) is followed by summaries of the two models. Particular attention is given to the terms in all three papers concerned with turbulent heat fluxes in the vertical.

1.2 A basic energy budget

Martsolf and Panofsky (1975) described a fundamental 3-dimensional energy budget based on the conservation of mass and energy in the orchard volume. Turbulent transport terms as well as the more obvious mean flow terms are explicitly described. Their final equation was:

$$\begin{aligned}
& \{1/\Delta t \iiint \bar{\rho} C_p T dx dy dz\}_{t_2} - \{1/\Delta t \iiint \bar{\rho} C_p T dx dy dz\}_{t_1} = \\
& -\bar{\rho} C_p \{ \iiint (\bar{u}_3 \bar{T}_3 - \bar{u}_1 \bar{T}_1) dy dz + \iiint (\bar{v}_4 \bar{T}_4 - \bar{v}_2 \bar{T}_2) dx dz \\
& \quad + \iiint \bar{w}_t \bar{T}_t dx dy \} \\
& -\bar{\rho} C_p \{ \iiint (\bar{u}'_3 \bar{T}'_3 - \bar{u}'_1 \bar{T}'_1) dy dz + \iiint (\bar{v}'_4 \bar{T}'_4 - \bar{v}'_2 \bar{T}'_2) dx dz \\
& \quad + \iiint (\bar{w}'_t \bar{T}'_t) dx dy \} \\
& - \iiint (\bar{F}_3 - \bar{F}_1) dy dz - \iiint (\bar{F}_4 - \bar{F}_2) dx dz - \iiint (\bar{F}_t - \bar{F}_0) dx dy \\
& \quad + \iiint \bar{S} dx dy dz
\end{aligned} \tag{1}$$

where, t =time between t_1 and t_2 ,
 ρ =density of air,
 T =temperature,
 C_p =heat capacity of air,
 u =component of wind in the x-direction,
 v =component of wind in the y-direction,
 w =component of wind in the z-direction,
 F =radiant flux,
 S =sources and sinks within the orchard volume.

Most subscripts refer to the faces of the box. Faces one and three are perpendicular to the y-axis, while faces two and four are perpendicular to the x-axis. Subscripts t and 0 refer to the top and bottom of the box, respectively. The primes indicated local fluctuations about the time mean, and the overbars were averages over the time interval (t_1 - t_2).

Energy gain at the top due to vertical motion was contained in two terms:

$$Q_m = -\rho C_p \iint \bar{w}_t \bar{T}_t dx dy \quad (2)$$

and,

$$Q_f = -\rho C_p \iint (\overline{w'T'})_t dx dy \quad (3)$$

where, Q_m = energy flux due to mean flow,

Q_f = energy flux due to turbulent fluxes,

ρ = density of air,

C_p = heat capacity of air,

w = vertical wind component,

T = temperature, and the subscript t indicates

values at the top of the box.

An implicit component of this flux is revealed by rewriting Equation 2. Using a notation for spatial averaging in place of the area integration and assuming all values are taken at the top of the box, Equation 2 is written:

$$Q_m = -\rho C_p (\widetilde{wT})A \quad (4)$$

then,

$$Q_m / -\rho C_p A = \widetilde{wT} \quad (5)$$

where A = area of the box of dimensions $dx dy$, and the tilde represents a spatial mean.

By Reynold's convention, the local values $\bar{w}$ and $\bar{T}$ may be described as the sum of a time-space mean component, $\bar{\bar{w}}$ or $\bar{\bar{T}}$, and fluctuations from that mean due to spatial variation, indicated by w'' and T'' , so that;

$$\bar{w} = \bar{\bar{w}} + w'' \quad (6)$$

and,

$$\bar{T} = \bar{\bar{T}} + T'' \quad (7)$$

Reforming the product of w and T yields;

$$\bar{wT} = \bar{\bar{wT}} + \bar{\bar{w}}T'' + \bar{\bar{T}}w'' + \bar{w''T''} \quad (8)$$

By Equation 4 it is necessary to average over space. Since by definition $w''=0$, and $T''=0$, products containing a fluctuating variable and a mean are small and may be neglected. Equation 8 is then:

$$\bar{wT} = \bar{\bar{wT}} + \overline{w''T''} \quad (9)$$

Substituting Equation 9 into Equation 5 yields:

$$Q_m / -\rho C_p A = \bar{\bar{wT}} + \overline{w''T''} \quad (10)$$

Reversing the steps employed to obtain Equations 4 and 5 results in:

$$Q_m = -\rho C_p (\bar{\bar{wT}} + \overline{w''T''}) A \quad (11)$$

and,

$$Q_M = -\rho C_p \iint (\bar{w}\bar{T} + w''T'') dx dy \quad (12)$$

By Equation 12 it is seen the flux Q_M is the flux by the time-space mean, $\bar{w}\bar{T}$, plus a perturbation, $w''T''$. Equation 12 suggests that there is a flux due to spatial variations contained in Equation 2.

Stepp and Martsolf (1973) argued that useful estimates of w could be determined by applying continuity to measurements of the horizontal wind components, u and v , at the sides of the box. Physically, continuity provides an estimate of $\bar{w}$, the time-space mean. By Equation 12 it is seen Q_M is not a function solely of time-space averages alone. There is an additional term $w''T''$, contributing to the flux. A similar argument can be made to apply to the sides of the box, i.e., $u''T''$ and $v''T''$.

The terms w'' and T'' are perturbations in space on the time-space means. A flux due to these fluctuations would arise through covariance of w'' and T'' . Just such a covariance seems reasonable in the heated orchard. Above the heater rows the warm heated air will rise. Between the heater rows it is envisioned cool air might sink to replace the rising air. Thus a flux is present through the box top due to spatial variations.

While the flux due to spatial variations, $w''T''$, is included in Equation 2, it could be viewed as a turbulent flux. Spatially, it is due to fluctuations about the means. But temporally it is a mean flow term. Regardless, it is important to recognize that horizontal divergence can yield only $\bar{w}$. Similarly, any number of thermometers at

the box top yields only $\bar{T}$. From Equation 12 it is seen $\bar{w}$ and $\bar{T}$ does not completely describe the energy loss due to mean flow, Q_m .

Equation 4 suggests Q_m could be estimated by taking a spatial average of $\bar{wT}$ measurements. Taking numerous measurements of $\bar{wT}$ would account for covariance between them. Note the product $\bar{wT}$ must be from simultaneous measurements of both at one location. Wind measurements of the precision necessary to provide useful local values of $\bar{w}$ are difficult to make. It is the small size of the $\bar{w}$ values that led Stepp and Martsolf (1973) to suggest an alternative to direct measurement. Continuity applied to horizontal divergence cannot, however, supply the $\bar{w}$ required by Equation 2.

Estimates of the loss due to mean-flow (horizontal and vertical) range from 10% to 50% of the energy supplied during heating (Martsolf, et al., 1971 and Martsolf and Stepp, 1972). These estimates are probably best viewed as the flux due to the time-space means. In the vertical this is $\bar{wT}$, as in Equation 12.

Martsolf and Stepp (1972) estimated the turbulent flux described by Equation 3. Treating the flux as a residual, they calculated that up to 60% of the energy input could be escaping in this fashion. Perhaps the flux due to spatial variations, $\overline{w'T'}$, comprised part of the same residual.

Radiation divergence terms in the energy budget were studied by Martsolf (1976). A two-fold increase in radiant loss was shown to occur with firing of the heaters. As the article pointed out, care must be taken in integrating measured losses over the orchard, as great spatial variation was noted. Martsolf (1976) stated that loss through the orchard sides becomes significant (more than 5% of the vertical loss)

when an orchard is smaller than 3 ha or when concentrated border heating is practiced. Further insights into the spatial variation of radiant energy in an unheated orchard can be obtained from Fritton, et al. (1976). The orchard heater and its effect on soil heat flow was presented in Fritton and Martsolf (1976).

The energy outputs from the orchard heaters are included in the final term of Equation 1--the source-sink term. Besides heaters, other sources of energy might include the latent heats of evaporation, condensation, sublimation, and fusion. Sink terms of concern in the heated orchard would be the crop plants and the air. The storage of energy by the air is accounted for by the left-hand side of Equation 1, leaving only storage by the trees to constitute a sink.

Perry, et al. (1977) partitioned energy released by the burning heaters into radiation and convection. By careful measurement of the stack temperatures of popular orchard heaters, the radiant energy output was calculated by the Stefan-Boltzmann equation. The effectiveness of a heater's radiant output in protecting foliage was modelled by Welles, et al. (1978). Welles's Orchard Foliage Temperature (OFT) model predicted the foliage heating effect of various configurations of orchard heaters.

1.3 Crawford's model

Crawford (1964) developed a mathematical model that described the effect of orchard heating. Its intent was to model the heated orchard energy budget in order to predict heating requirements. Crawford (1964) partitioned the heat loss into three terms he considered of equal order of magnitude. The budget was given by:

$$H = \text{Loss by (Advection + Induced Flow + Radiation)}$$

(13)

where H = heat added to the orchard. Each term is discussed in detail below.

The radiative term was computed from the Stefan-Boltzmann law. Orchard air temperature was the radiating temperature employed and emissivity was taken equal to one. A constant between 0.7 and 0.8 accounted for incoming sky radiation.

Horizontal advective loss was described by the product of the wind profile in the heated orchard and the horizontal temperature gradient between the heated orchard and the unheated upwind area. The wind profile was approximated by a power law, while the heating effect with height was modelled by part of a cosine curve.

Crawford's (1964) induced flow loss accounted for some of the energy lost due to buoyancy of the heated orchard air. The mean flow vertical loss in the energy budget by Martsolf and Panofsky (1975) can be viewed as essentially the same process. Equation 14 is the induced flow (IF) in Crawford's (1964) model.

$$IF = \frac{4\rho C k(\Delta T)^{0.5}}{x} \int_0^{0.33z_h} \sin\left[\frac{3\pi z}{z_h}\right] \cos\left[\frac{(z-10)}{(z_h-10)}\right] dz \quad (14)$$

where, ρ = density of air,

k = a proportionality constant,

ΔT = temperature difference between

heated and unheated areas at 3 m,

x = length of a side of the square orchard,

z_h = depth of the heated layer, and

z = height above ground.

The above equation as it appeared in the original article had (T) raised to the 1.5 power. In the text of Crawford's (1964) article the wind speed of the air drawn into each side of the box was described as a function of the square root of (ΔT) , based on fluid dynamics principles. It seems reasonable to assume the relation should be the same in the complete equation reproduced here as Equation 14. A lessening of the heating effect on the downwind side of a heated orchard, varying with height, noted by Kepner (1951), led Crawford (1964) to conclude that the top of the induced flow was about $0.33z_h$, where z_h is the height to which the effect of heating extends. Additionally, the flow would have to be zero at $z=0$, so $0.167z_h$ might well be the height of maximum inflow. Thus a simple sine function described the variation of the air inflow with height.

The cosine term in Equation 14 described the variation of the heating effect with height as in the advection term.

An important part of Crawford's (1964) model was the calculation, through basic plume rise equations, of the height to which the heating

effect extends, z_h . Nomographs yielding z_h as a function of fire size and wind speed were provided. Crawford visualized a box with its upper surface allowed to float. The height at which the heaters no longer have any effect on temperature, z_h , serves as the box top. Another model by Gerber (1969), to be discussed in the next section, employed a similar depth of heating in its advection term in the same way as Crawford. There is no loss through the top of a box defined by z_h . Martsolf and Panofsky (1975) specified a box of fixed height, dz . This height remained the same, regardless of meteorological or energy input variables. A meter or two above the crop top was a typical dz .

Crawford (1964) and Gerber (1969) let the heated air rise to z_h and be advected away. Martsolf and Panofsky (1975) debited the budget as the energy escaped through the box top. This is a fundamental difference between the two models and the complete energy budget. Differences such as this make it impossible to state term-by-term equivalencies between the three publications.

Both Crawford's (1964) and Gerber's (1969) z_h was the theoretical maximum height a heater plume reaches. As Crawford pointed out, the temperature difference of the heated air and the environment disappears at $0.71z_h$, but momentum carries the warm parcel to z_h . Since this overshooting the temperature equilibrium and falling back would keep the air between z_h and $0.71z_h$ well mixed, z_h was chosen as the depth of the heated layer. Therefore, Crawford (1964) implicitly included turbulent mixing in calculating the heat necessary for protection by its presence in the determination of z_h .

1.4 Gerber's model

The model by Gerber (1969) was formulated with the intent of permitting anyone with some experience to make heating requirement estimates. Computation was meant to be easier and the equations more flexible than those of Crawford (1964). An earlier version of the model was published in 1964 (Gerber, 1964). The later version (Gerber, 1969) included an advection term and a discussion of Crawford's model (1964). Energy requirements for frost protection calculated by Gerber (1969) were based on the heat balance of an individual leaf, and the advective loss from the grove. The energy necessary to maintain a leaf at a given temperature was calculated as a function of radiative and convective terms. This budget was then extrapolated to orchard dimensions. Thus, an engineering approach was taken to foliage temperatures.

Energy lost by advection was computed separately and added to the foliage needs. A logarithmic wind profile multiplied by the horizontal temperature gradient between heated and unheated areas provided the advection estimate. Roughness length and displacement height were necessary inputs. The advective loss was summed to the height to which heating extends. Gerber (1969) appealed to either Crawford's (1964) nomographs or direct measurement in determining this height.

A number of typesetting errors, inadequate table labeling, and unit conversion mistakes mar Gerber's paper (1969). A thorough diagnosis and treatment of these problems was provided by Martsolf (1978). Gerber's model did not include a term resembling Crawford's (1964) induced flow term.

Chapter 2

Measurements of the Turbulent Flux

2.1 Introduction

The methodology and results of measurements of the vertical turbulent heat flux due to temporal variation in the local time-space mean in the heated orchard energy budget as described by Martsolf and Panofsky (1975) are reported. Measurements of the heat flux during orchard heating will be presented separately from measurements made when the orchard was unheated.

2.2 Facilities and equipment2.2.1 The orchard and heating systems

Measurements of components of the turbulent heat flux at 4 m were made in a 1 ha orchard of Golden Delicious apple trees (Malus domestica) on MM 104 rootstocks. The orchard is located at the Rock Springs Agricultural Research Center of The Pennsylvania State University, near Pine Grove Mills, Pennsylvania. Figure 7, presented later in this chapter, is a map of the orchard, with the heaters that were burned indicated. The trees, planted on a 4.9 m by 7.3 m grid, were about 3 m tall at the time of the experiment. The measurements were made on December 4, 1977, when the trees were barren of fruit or leaves. The orchard site is fairly flat. It is surrounded by mown grass for at least one orchard width on all sides.

Two pipeline heating systems are permanently installed in the orchard, both supplied by the same central pump and oil storage tank. One set of heaters are Scheu¹ Auto Clean Stack heaters equipped with 0.9 nozzles. At a pressure of 551 kPa--that used in the experiment--each heater releases 33.06 kW of energy. The other system in the orchard consists of Scheu Large Cone heaters with 0.6 nozzles. At 551 kPa each liberates 22.04 kW. During the course of the measurements, portions of both systems were burned.

2.2.2 Mean flow anemometry

Sensitive cup anemometers² provided wind speeds at 2, 4, and 6 m above the ground on the west face of the orchard. The Appendix contains the 6 m wind speeds as a function of time. These anemometers are light chopping, interrupting a beam of light with every rotation. The light beam strikes a photocell, and every time it is interrupted, an electrical pulse is created. A digital counter accumulated the pulses over three minutes, at which time the number of pulses was dumped onto punched paper tape by a Honeywell data acquisition system. The Honeywell system consists of a Model 707 Crossbar scanner, Model 623 Pre-amplifier, and a Model 620 Digital voltmeter.

Component anemometers³ with Gill⁴ helical propellers were displayed in a horizontal plane at 2 m on the primary instrument tower. This

¹ Scheu Products, Upland, Calif.

² C.W. Thornthwaite Assoc., Centerton, New Jersey.

³ Model WC-10, Climatronics Corp., Hauppauge, N.Y.

⁴ Gill helical 4 blade, 23 cm diameter propeller, R.M. Young Co., Traverse, Mi.

tower was located 4 tree rows (25.5 m) from the west face of the orchard and 5 rows (22.0 m) from the north face. One anemometer was pointed due north, the other to the west. These anemometers work on the same light-chopping principle as the cup anemometers described previously. Their outputs were recorded by the same Honeywell data acquisition system described above.

2.2.3 Mean temperature sensors

Mean temperatures at 1 m and 15 m were recorded. These data are presented in the Appendix. Copper-constantan thermocouples in Young¹ radiation shields were placed on the primary instrument tower at 1 m and 15 m. A Kaye² 100 junction reference oven interfaced the thermocouples and the Honeywell data acquisition system.

2.2.4 Drag anemometers

Turbulence measurements were made by 2 fast-response drag anemometers, like the one pictured in Figure 1, developed and built at The Pennsylvania State University (Perry, et al., 1978). As the air moves past the 1.5 cm x 4.5 cm cylindrical drag elements, the drag on the elements is transmitted by a ceramic rod to steel cantilevers. Sensitive strain gauges affixed to the cantilevers convert the stresses caused by the wind to electrical signals via a Wheatstone Bridge

¹Aspirated temperature-radiation shield, Model 43404, R.M. Young Co., Traverse City, Mi.

²Model K 280-36 Thermocouple reference system, Kaye Instruments, Cambridge, Mass.

Figure 1. A drag anemometer with drag element exposed.

circuit. The u and v components of the wind are measured by one vertical drag element attached to two orthogonal cantilevers. A horizontal element and strain gauge measures the w component. Fluctuating temperature is sensed by a 0.025 mm chromel-constantan thermocouple. This thermocouple is soldered to copper leads and these junctions potted in epoxy and shielded, so they vary only slowly and together.

Possible zero drift in the amplification circuitry is partially compensated for by occasional zeroing runs. Tubular shrouds are used to cover the drag elements. Readings are taken for about 5 minutes with the drag elements covered. The zero values before and after each run are interpolated to yield offsets that are removed during data reduction.

The four components of each anemometer (u, v, w, T) were scanned at 30 Hz. A Digital Equipment Corporation PDP 11/10 computer with 16k bytes of memory and an RK05 moving head disc controlled the data acquisition from the drag anemometers. A/D conversion was by a Burr-Brown SDM 835 A/D converter. The converter output was written on magnetic tape by a Digit-Data 1600 bpi, 45 ips tape drive and controller. The field data tape was read on the PSU IBM 370/168 system, the voltages converted to velocities, and a new tape written. Another program took the velocities, made cosine and temperature corrections, and calculated the fluxes.

Comparisons with established types of anemometry have demonstrated the accuracy of the drag anemometers. Spectra produced by the anemometers were nearly identical to those produced by pressure-sphere anemometers at the University of Guelph, Guelph, Ontario. Good agreement

has also been documented with sonic anemometry at Riso, Roskilde, Denmark (Perry, et al., 1978).

2.3 Drag anemometer measurements

Tables 1 and 3 are summaries of 4-minute averages of wind direction (θ), wind speed (U), and the turbulent heat flux due to temporal variations in the variables (H), by the two anemometers. Table 1 contains data recorded during non-heated periods. Measurements during heating are in Table 3. Discontinuities following 0223 and 0333 are periods during which the anemometer drag elements were shrouded and the strain gauge circuitry zeroed. Negative θ was chosen to be west of south. Measurements through the period ending 0257 are before the heaters were lit. Firing of the heaters began during the period ending 0301, and by 0309 all heaters indicated in Figure 7 (discussed later) were burning steadily. The heating system was shut off during the period ending 0401. About 37 minutes of measurements were made following heater shut-off.

2.3.1 Periods without heating

During the non-heated periods, Table 1, the turbulent heat flux H , was negative.

The turbulent heat flux is given by:

$$H = -\rho C_p K_h d\theta/dz \quad (15)$$

C_p = heat capacity of air,

ρ = density of air,

K_h = eddy transfer coefficient for heat, and

$d\theta/dz$ = potential temperature gradient.

From Appendix A, it is noted $d\theta/dz$ was positive throughout the experiment. In other words, there was a temperature inversion between 1m and 15m, creating atmospheric stability. A negative heat flux is then predicted by Equation 15.

Since the atmosphere was stable and the heaters were not burning, the turbulent heat flux had to be due to mechanical mixing. At night, only mechanical turbulence is expected unless there is a heat source close to the ground.

The magnitude of the heat flux due to mechanical turbulence is related to the wind speed through the eddy transfer coefficient for heat, K_h . Geiger (1965) states that during clear nights, and so presumably stable conditions, K_h will increase rapidly with increasing wind speed.

K_h , the eddy transfer coefficient for heat is thought to be nearly

Table 1. Turbulent heat flux (H), wind direction (θ), and wind speed (U), averaged over 4 minutes, without heating.

Time	-----Anem. 1-----			-----Anem. 2-----		
	$H(\text{Wm}^{-2})$	$\theta(\text{deg})$	$U(\text{ms}^{-1})$	$H(\text{Wm}^{-2})$	$\theta(\text{deg})$	$U(\text{ms}^{-1})$
0203	-5.8	-11.6	1.9	-4.9	-17.1	1.9
0207	-1.2	-4.7	1.8	-6.7	-9.9	1.8
0211	-5.9	12.0	1.4	-6.8	8.9	1.4
0215	-2.9	9.7	1.2	-1.8	8.4	1.2
0219	-2.3	-5.2	0.9	-4.8	-3.5	0.8
0223	-0.7	19.4	0.6	-2.2	26.0	0.6
0245	3.6	32.5	1.0	0.8	36.5	1.0
0249	-1.7	32.5	1.2	-1.4	35.8	1.2
0253	-1.4	21.0	1.3	-1.3	20.3	1.2
0257	-0.8	9.5	1.1	-0.7	4.8	1.1
0401	-11.1	-5.3	3.2	-19.7	-13.1	3.5
0405	-25.8	-2.6	3.1	-30.5	-13.8	3.5
0409	-14.4	-12.6	3.0	-20.8	-11.1	3.4
0413	-36.4	-13.6	2.3	-29.3	-17.0	2.9
0417	-28.5	-11.8	2.0	-20.1	-14.7	2.3
0421	-12.6	-15.1	1.6	-4.4	-15.2	1.7
0425	-7.8	-12.2	1.9	-18.6	-16.9	2.2
0429	-27.2	-1.0	2.8	-23.4	-12.3	3.3
0433	-42.6	1.6	2.9	-42.8	-18.1	3.4
0437	-35.3	-0.8	3.3	-31.3	-8.2	3.7

equal to K_m , the eddy transfer coefficient for momentum, under stable conditions. K_m can be calculated by the relation:

$$K_m = \frac{ku_*z}{1+5z/L} \quad (16)$$

where, k =von Karman's constant,
 u_* =friction velocity,
 z =height, and
 L =Monin-Obukov scaling length.

An increase in wind speed will increase u_* , as u_* can be estimated from:

$$u_* = \frac{ku}{\ln z/z_0 - 5z/L} \quad (17)$$

where z_0 =roughness length, and u =wind speed.

From Equations 16 and 17 it is seen the eddy transfer coefficient, K_m , is a function of the friction velocity, u_* , which is in turn a function of the wind speed. Additionally, the Monin-Obukov scaling length, L , is defined with a u_*^3 in the numerator. K_h is seen to be a function of the fourth power of u_* in very stable air. The dependence of K_h on wind speed is apparent. Measurements in Table 1 also demonstrate a larger heat flux with greater wind speeds. Figure 2 is a

Figure 2. Turbulent heat flux (H) as a function of wind speed (U) in a stable atmosphere during non-heated periods, at 4 m above the orchard floor.

plot of H as a function of the wind speed, U , for the periods in Table 1 after 0417. Data collected before the heating period were not used since a change in the temperature structure of the atmosphere can be noted in the Appendix. Periods between heater shut-off and 0417 were not included in order to minimize any effect the previous periods of heating might have. A rapid increase in H is noted with increasing wind speed.

To obtain the best estimate of the turbulent heat flux it is desirable to average over a length of time between 20 minutes and an hour. Some significant high-pass filtering could occur when the data are broken down into segments as short as 4 minutes. By averaging over only 4 minutes, fluctuations of periods longer than 8 minutes are largely removed, and so do not contribute to the flux. Table 2 contains averages over the longest periods possible before and after heating.

Table 2. Turbulent heat fluxes, averaged over the entire data set, without heating.

	$H(Wm^{-2})$	
	Anem. 1	Anem. 2
Before heating		
(0159-0257)	-1.9	-3.0
After heating		
(0358-0437)	-24.2	-24.1

2.3.2 Periods with heating

Table 3 contains data collected during heating. Firing of the Auto

tower to the west was lit about 0300. Due to complications with another experiment, the row immediately to the west of the instrument tower was shutoff about 0305. The Large Cone heaters in the row were then fired. This explains the exceptional heat flux seen from anemometer 1 for the period ending 0305 and the negative fluxes measured by both instruments during the period following. Examination of this large flux is provided in the discussion referring to Figure 5.

With the period ending 0313, heaters so indicated in Figures 3 and 4 were burning steadily. All were shut-off at 0359, with the exception of the Auto Clean Stack heater in the row immediately to the west of the tower, which was shutoff at 0350. Figures 3 and 4 contain data from anemometers 1 and 2, respectively, for the periods during which the heaters were burning. Each line represents θ for the period indicated, but the lengths of the lines are not indicative of flux magnitude.

Between the periods ending 0313 and 0325, the H values range from 5.4 Wm^{-2} to 51.1 Wm^{-2} . These positive heat fluxes are due to the burning heaters. Now, however, the heat fluxes are convectively driven rather than mechanical, which was the case before and after heating.

Local temperature maxima in the heated orchard might cause some of the variation in H noted in Table 3. Vertical temperature profiles during heating are not well documented. A situation analogous to a city at night is anticipated. The surface heat source, e.g., a city or heaters, creates an unstable lapse rate to some height. Above this height the temperature gradually returns to the profile that would occur if no heat source were present. Where a heat flux measurement is made relative to a temperature maximum in the vertical would influence the measurement. A flux measurement above a temperature maximum would be

Table 3. Turbulent heat flux (H), wind direction (θ), and wind speed (U), averaged over 4 minutes, with heating.

Time	-----Anem. 1-----			-----Anem. 2-----		
	H(Wm^{-2})	θ (deg)	U(ms^{-1})	H(Wm^{-2})	θ (deg)	U(ms^{-1})
0301	56.7	-10.8	1.2	3.0	-12.9	1.2
0305	401.5	-19.8	1.4	55.4	-19.1	1.5
0309	-2.6	-35.6	1.2	-1.6	-35.2	1.3
0313	18.1	-25.8	1.5	29.7	-26.9	1.5
0317	35.9	-28.8	1.4	29.2	-27.7	1.5
0321	28.6	-25.6	1.6	51.1	-24.8	1.7
0325	5.4	-12.7	2.2	33.2	-12.6	2.5
0329	0.3	-4.7	2.4	-7.8	-14.2	3.0
0333	-26.0	-0.9	2.6	-13.1	-15.5	3.2
0353	58.4	-12.2	2.9	7.8	-14.9	3.2
0357	43.5	-13.7	2.8	20.8	-19.8	3.3

measurement. A flux measurement above a temperature maximum would be positive (upward). Below the maximum, the flux would be negative (downward). In both cases, energy is being mixed down a temperature gradient, away from the local maximum. Vertical displacements of the temperature maximum would occur during heating.

For a given situation, it is anticipated the height of the temperature maximum would vary with the output of the surface energy source. Greater energy supplied from below creates a thicker unstable layer, increasing the height of the temperature maximum. In the case of orchard heating, the energy available to create the unstable layer is

Figure 3. Four-minute averages of wind direction for the periods ending 0313 to 0357 as measured by drag anemometer 1, 4 m above the orchard floor. AC and LC indicate Scheu Auto Clean Stack and Large Cone heaters, respectively, burned during the periods indicated in the figure.

Figure 4. Four-minute averages of wind direction for the periods ending 0313 to 0357 as measured by anemometer 2, at 4 m above the orchard floor. Se Figure 3 for details.

increase due to heating. Kepner (1951) noted variation in the heating effect across a heated orchard. Figure 5, redrawn from Kepner (1951), depicts this situation. As a result of this horizontal heating effect variation, the height of the temperature maximum varies across the orchard. The point is temperature gradients in the heated orchard are complex. As the wind or changes in energy input alter the height of the temperature maximum, or the location of the instrument site is changed, the turbulent flux measurement could be altered.

Superimposed on these temperature gradients are the heater plumes. Certainly the proximity of a hot heater plume to the drag anemometers influences the value of H measured. Because of the influence a plume has on the measurement it is useful to predict plume sizes. From an estimate of plume radius, the area of the plume passing through a plane at 4 m can be calculated.

In the earliest stages of plume rise, the radius of the plume, r , can be considered proportional to the height above the stack to which it has risen, z (Briggs, 1969). For a vertical plume--as would be the case with an orchard heater plume under calm conditions--the constant of proportionality is α . Bent-over plumes, which occur in the orchard when there is a breeze, have an entrainment constant β . It is generally agreed that β is much larger than α (Briggs, 1969). Both types of heaters used in this study have 40 cm diameter discs held approximately 60 cm above the stack opening. Increasing wind speed would decrease the effect of these discs as the plume is bent under them to a large extent. Under calm conditions, though, the discs are expected to increase the value of α .

The radius, r , of a plume early in its development is thus given by

Figure 5. Variation in horizontal heating effect at 1.5 m above the orchard floor, during heating. Redrawn from Kepner (1951).

The radius, r , of a plume early in its development is thus given by Briggs (1969):

$$r = \beta z \quad (18)$$

Bringfelt (1969) found $\beta = 0.52$ for neutral conditions and $\beta = 0.45$ under stable conditions. The β values were the result of observations of small industrial sources, so they seem appropriate to the problem of orchard heaters.

Given the heater stack height as 1 m (Scheu Auto Clean stack), the vertical distance to the drag anemometers is 3 m. By Equation 18, with $\beta = 0.45$, it is seen that the plume radius, r , at three meters above the stack opening is 1.35 m, perpendicular to the plume centerline. As the plume is bent by the wind, its area as it passes through the horizontal plane becomes an ellipse. The semi-minor axis is r . The semi-major axis increases as the angle at which the plume centerline meets the 4 m plane decreases. In the case of the flux measurements of the heater very close to the anemometer (to be discussed in conjunction with Figure 6), the distance from the top of the stack was 4.5 m. For example, if the anemometer was on the plume centerline the semi-major axis would equal 2.88 m, making the horizontal area about 12.2 m^2 . The extreme case of a plume that has traveled 20 m results in an ellipse of 38.17 m^2 at 4 m.

The average heater density in the experimental orchard is 87 heaters per ha. It can be shown each heater is responsible for about 115 m^2 . The plume area at 4 m varies between 12.20 m^2 and 38.17 m^2 , or from 11% to 33% of the area assigned each heater. The heterogeneity of

the heat flux at 4 m is obvious. If the convective output of the heaters burned in the experiment is all lost through the plume, the total flux at 4 m in the plume would be between 2260 Wm^{-2} and 720 Wm^{-2} . The remainder of the 115 m^2 for which the heater is responsible might then have a very small or even negative heat flux. It is anticipated that the mean flow is responsible for many times more of the flux than is turbulent transport.

Under calm conditions, the entrainment constant α , is smaller than the β used here. As a result the plume will constitute a smaller portion of the area above each heater. The problem of heterogeneity is increased.

Figure 6 contains data that appear to reflect a measurement of H directly in a plume, the period ending 0305. Again, $\theta=0$ is south, and the lengths of the lines do not reflect H values. Assuming the plume centerline followed the mean wind, anemometer 1 was 1.6 m away from the plume centerline. The plume area at 4m calculated previously is an ellipse 1.25m by 1.87m, so while anemometer 1 may have been in the plume, anemometer 2, at 2.9m away from the centerline, was not. The total flux density calculated in this plume was 2260 Wm^{-2} , so an off-center measurement of the turbulent component at 401.4 Wm^{-2} might be reasonable. Anemometer 2 was probably reporting other heaters as well. The agreement of the two instruments on θ is very good for this period.

The effects of a temperature maximum in the vertical and plumes on measurements of H provide insight into variations in H measured during heating. Influences of wind speed and direction can be noted in the data in Table 3 by study of a number of the 4-minute periods. Comparison of the fluxes during the periods ending 0325 and 0353 as

Figure 6. Mean wind direction during the period ending 0305 as measured by both anemometers. Anemometer 1 is to the west of the instrument tower ($\triangleleft$) and anemometer 2 is to the east, both at 4 m above the orchard floor. See Figure 3 for details.

AC

LC

0305

0305

Z

measured by anemometer 1 demonstrate the effect of wind speed. Figure 3 indicates the wind transversed the same heaters during both periods. With $U=2.2 \text{ ms}^{-1}$, H was 5.4 Wm^{-2} during the period ending 0325. When, during the period ending 0353, U increased to 2.9 ms^{-1} , H increased to 58.4 Wm^{-2} . Perhaps the higher wind speed bent the plume in such a way that a portion of the plume closer to the centerline, and therefore hotter, was passing the instrument.

From Table 3 and Figures 3 and 4, negative H value is associated with a period during which the wind was coming up between the tree rows (ending 0333). There were 15 rows of heated trees to the south of the instruments, so it is doubtful this is a border effect. Welles, et al. (1978) demonstrated that a 4% savings in energy could accrue from reflecting the energy lost to the soil heat flux for 1m around each heater. Beyond 1 m the flux is too small to be worth reflecting. From Figures 3, 4, and 6 it is seen the heaters are about 5m apart between the rows. This leaves a band of orchard floor approximately 3m wide that is not significantly heated. Additionally, warming of tree and foliage elements to a temperature above the air was predicted by Welles, et al. (1978). The trees and the ground adjacent each heater is then warmer than the middle of the rows. A cold corridor exists between the heater rows.

The wind speed during the interval 0329-0333 was 2.6 ms^{-1} at anemometer 1, and the observed heat flux was -26 Wm^{-2} . From Figure 2, the wind speed corresponds to an H value of about -23 Wm^{-2} . It appears that little effect of the heaters was being noted by anemometer 1. Anemometer 2 during the same period and both of the instruments during the previous period measured non-zero θ values. The H values were

predictably less negative as energy was carried over by the wind. Values of H may be dependent on θ .

Averages of the turbulent heat flux while the heaters were burning were also obtained over the duration of the burn period. As mentioned previously, some significant high-pass filtering could occur with 4 minute averages. At anemometer 1 the heat flux was $+22.8 \text{ Wm}^{-2}$ during the period of heating, while at anemometer 2 the flux was $+18.9 \text{ Wm}^{-2}$. The difference in the values may reflect the slightly upwind location of anemometer 1. These averages do not include data presented in connection with Figure 6.

With the heater configuration depicted in Figure 7, the average convective output of the heaters was 240 Wm^{-2} . Averaging the turbulent fluxes measured by the two anemometers yields a flux of 22.2 Wm^{-2} --approximately 10% of the energy input. This is considerably less than the 60% residual once ascribed to it (Martsolf and Stepp, 1972). It is likely, though, that Martsolf and Stepp drew their conclusions based on data gathered under more normal frost conditions. Wind speeds during the course of the turbulence measurements reported here were greater than usual for a radiative frost.

The residual they estimated contained both the spatial and temporal turbulent fluxes discussed in Chapter 1. Data presented here reflects only the flux due to temporal variations in the variables. The flux due to spatial variations may explain the rest of the residual. Additionally, as Martsolf and Stepp (1972) pointed out, the accumulated error on the other terms is high. Much of the difference between the residual estimate and the measurement might be due to errors in measuring the other terms.

Figure 7. Map of the experimental orchard, indicating the heaters burned during the experiment. Shaded area is the range of θ values measured.

- = BURNING HEATER
- △ = INSTRUMENT TOWER
- ⊗ = TREE

In assessing the validity of the estimate of H presented here a number of factors must be considered. The most basic question is whether the turbulent fluxes were measured at enough locations that an adequate spatial sample was obtained. Since both anemometers were located between heater rows, this requirement was probably not satisfied. Further measurements employing a larger number of drag anemometers, providing a better spatial sample, would add confidence to the estimate of the flux due to temporal variations, $\overline{w_t' T_t'}$. Arranged to measure a cross section of a cold corridor and an adjacent heater row, five drag anemometers appears the minimum.

Wind speed and direction are other important factors influencing the H value presented here. The effect of wind speed on plume growth has been discussed. It is suggested that the turbulent heat flux values presented in this thesis be viewed as applicable to windy conditions. A radiative frost of horticultural importance in the Northeast is unlikely to occur with wind speeds greater than those measured during the experiment presented here. Measurements over a range of meteorological conditions are necessary to meet the need for adequate temporal means.

In the discussion of heterogeneity earlier in this section, rising plumes were shown to constitute between 6% and 31% of the area of a plane 4 m. above the orchard. A measurement directly in a plume, discussed previously, yields unexpectedly high flux values. With the presence or absence of a plume affecting flux measurements so drastically, wind direction will strongly influence the measurements. It was seen from Figures 3 and 4 and Table 3 that four-minute averages yielded negative fluxes when the wind was coming from between the heater rows. Data collected on a night during which this was the predominant

wind direction might well show a negative flux for the entire burn period. Estimation of the effect of the distribution of wind directions during the measurements presented here is in order. Figure 7 shows the location of all heaters burning in the experiment and the range of values of both instruments combined. If a very small or even negative flux could be expected whenever the wind travels a route free of heaters for a considerable distance, e.g., anemometer 1, periods ending 0329 and 0333), a subjective evaluation of a measurement might be made. There are many other combinations of instrument sites and heater-free paths in the orchard than the one seen in this experiment. On the other hand, if the anemometers were in the heater row, fewer heater-free paths would exist. Very subjectively, the value of H presented here appears the result of a fairly representative sample of wind directions in relation to heater distribution.

Chapter 3

Conclusions

3.1 Balancing the energy budget of a heated orchard

A basic form of the energy budget of a heated orchard suggested by the box model (Martsolf and Panofsky, 1975) partitions the budget as:

$$Q=R+A+H \quad (19)$$

where, Q =energy required for protection, taken equal to 1, R =radiation divergence, A =mean flow loss, and H =temporal turbulent heat flux.

References in the literature to these terms follow:

Martsolf and Stepp (1973): $R=.2$ to $.4$

$A=.2$ to $.6$

$H=\text{up to } .6$

Martsolf, et al. (1971): $A=.1$ to $.3$

Martsolf (1976): $R=.2$ to $.3$

Martsolf and Bartholic (1976): $A=.15$ to $.3$

Estimates of A , H , and R are presumed to include both the horizontal and vertical. The measured value of H presented here, however, is only an estimate of the vertical component. Martsolf (1976) argues the

horizontal component of R is not significant (less than 5% of the vertical) when the orchard is greater than about 3 ha in area. The same argument is taken to apply to H. Sinks, such as the orchard air and the trees, are assumed to be responsible for not more than 0.05 of Q.

Now that an independent estimate of H is available the partitioning in Equation 19 may be improved to:

$$Q=0.3+0.3+0.1+U \quad (20)$$

It is seen that U, the unexplained heat loss, is 0.3Q, i.e., 30% of the heat loss is unexplained.

There appears little reason to doubt the estimate of R provided by Martsolf (1976). The values of A and H are less convincing. Problems associated with measuring the flux due to temporal variations were mentioned in Section 2.3. The existence of a flux due to spatial variations, $\overline{w'T'}$, in the mean flow was discussed in Section 1.2. Measurement of these spatial variations would be very difficult. Differences in wind speed from location to location are small. Thorough documentation of temperature gradients in the orchard appears the best approach to estimating the loss due to spatial variation.

Measurements of the time-space mean flow portion of A appears prone to numerous problems as well. The box model rests on the requirement that continuity be maintained in a small heated orchard. Temperature and velocity measurements at the sides of the box may be unrepresentative of the total heating effect because of the situation depicted in Figure 5. The heated block boundaries were seen to be cooler than the center of the block. An underestimation of mean flow loss

might result. A less error-prone method of estimating horizontal mean flow loss might be by measuring the value of $(\bar{u} dT/dx + \bar{v} dT/dy)$. Current anemometry and more extensive thermometry could provide these data. The magnitude of the loss due to time-space mean flow has implications in determining the effectiveness of windbreaks for frost protection. Frost protection problems associated with higher density plantings are also closely related to mean flow loss.

The flux due to spatial variations in the mean flow, $\overline{w'T'}$ in the vertical, may account for some of the unexplained loss. Estimates of the variation in temperature throughout the heated orchard provide some insight into the size of this flux. Measurements of the vertical wind component of this flux, w , would be difficult. Small differences in wind speed must be documented.

3.2 Summary and suggestions for further work

1. Turbulent transport terms were included in the three energy budgets of the heated orchard. Crawford's (1964) and Gerber's (1969) models recognized turbulent mixing in determining the top of the heated layer. The box model approach (Martsolf and Panofsky, 1975) had terms describing turbulent fluxes across the box faces. Only in the box model approach, however, is direct measurement of turbulent transport suggested.

2. The turbulent heat fluxes described by Martsolf and Panofsky (1975) require adequate temporal and spatial sampling when measured. For the flux due to temporal variations, a minimum of five drag

anemometers appears necessary. This would provide samples through a cold corridor and an adjacent heater row.

3. Mechanical mixing by wind shear in a stable atmosphere was measured by drag anemometry. The anticipated positive correlation between downward heat flux and wind speed was noted.

4. A measurement of the turbulent heat flux due to temporal variations $\overline{w'T'}$, at 4 m above the floor of a heated orchard revealed 10% of the convective energy input escaped by this means. These measurements were made under relatively windy conditions. Energy loss due to turbulent mixing may vary in proportion to total heat loss as a function of wind speed. A better temporal sample of H is necessary, specifically under conditions of lower wind speeds. Temperature gradients and heater plumes cause variability in the heat flux measured at a given point.

5. Study of the actions and influences of individual heater plumes is necessary. The effects of atmospheric stability and wind speed on heater plume growth and dispersion is an attractive approach. An understanding of the individual plume and plume merging could be extrapolated to the entire heating system.

6. Evidence of a cold corridor between the heater rows in the orchard was observed. Measurements of the temporal turbulent heat flux made in such a corridor when the wind was coming directly down the corridor showed little evidence of the burning heaters.

7. A turbulent heat flux due to spatial variations was revealed. This flux is envisioned as rising warm air above the heater rows and cool sinking air between the rows. Perturbations on the mean vertical flow caused by the heater rows may be a neglected loss term in the energy budget. Admittedly, measurement of this flux would be difficult. Knowledge of the temperature structure of the orchard during heating will help document how much variation may exist.

8. An attempt at balancing the energy budget of the heated orchard could not account for about one-third of the energy input. Suggestions for further measurements of the mean flow loss and the temporal turbulent heat flux, $\overline{w'T'}$, were made. Further measurements of these two fluxes and an estimate of the flux due to spatial variations, $\widetilde{w'T'}$, may permit balancing of the budget.

Literature Cited

- Briggs, G. A. 1969. Plume Rise. USAEC Critical Review Series, TID-25075, Clearinghouse for Scientific and Technical Information.
- Bringfelt, B. 1969. A study of buoyant chimney plumes in neutral and stable atmospheres. *Atmos. Environ.*, 3:609-623.
- Crawford, T. V. 1964. Computing the heating requirements for frost protection. *J. Appl. Meteorol.* 3:750-760.
- Fritton, D. D., and Martsof, J. D. 1976. Effect of an orchard heater on soil heat flow. (abstr.) 1976 Annual Meeting of Amer. Soc. Agron., Houston, Tex. 18 Nov.-3 Dec., 1976.
- Fritton, D.D., Martsof, J.D., and Busscher, W. J., 1976. Spatial distribution of soil heat flux under a sour cherry tree. *Soil Sci. Soc. Am. J.* 40(5):644-647.
- Geiger, R. 1965. The Climate Near the Ground. Harvard University Press, Cambridge.
- Gerber, J. F. 1969. Methods of determining nocturnal heat requirements of citrus orchards. In: Chapman, H. D. (Ed). *Proc. First Internl. Citrus Sym.* 2:545-550.
- Gerber, J. F. 1964. The use of heating devices for cold protection. *Proc. Fla. State Hort. Soc.* 77:93-100.
- Kepner, R. A. 1951. Effectiveness of Orchard Heaters. *Calif. Agr. Expt. Sta. Bul.* 723.
- Martsof, J. D. 1978. Heating for frost protection. In: Barfield, B. J., and Gerber, J. F. (eds.) *Modification of the aerial environment of plants*. Amer. Soc. Agr. Engr. Monograph (In press).
- Martsof, J. D. 1976. Observed radiant loss from a heated orchard under frost conditions. *J. Amer. Soc. Hort. Sci.* 101(5):614-617.
- Martsof, J. D., and Bartholic, J. F. 1976. Mean advective loss from a heated orchard. Report submitted to the Annual Meeting of the Technical Committee of NE-48, Univ. of Wisconsin, Madison, Oct. 25-27, 1976.
- Martsof, J. D., and Panofsky, H. A. 1975. A box model approach to frost protection research. *HortScience* 10(2):108-111.
- Martsof, J.D., and Stepp, R. 1972. Partitioning the 3-dimensional energy budget of a small heated orchard (abstr.) *HortScience*, 5(4):305.

- Martsolf, J. D., Gerber, J. F., and Panofsky, H. A. 1971. Heat transfer through the boundaries of a small heated orchard. (abstr.) Bull. Am. Meteorol. Soc., 52(4):310.
- Perry, K. B., Martsolf, J. D., and Norman, J. M. 1977. Radiant output from orchard heaters. J. Amer. Soc. Hort. Sci. 102(2):101-105.
- Perry, S. G., Norman, J. M., Panofsky, H. A., and Martsolf, J. D. 1978. Horizontal coherence decay near large scale mesoscale variations in topography. Journ. Atmos. Sci. 35(10):1885-1889.
- Stepp, R. D., and Martsolf, J. D. 1973. An error analysis of the measurement of horizontal divergence in the wind field of a small, heated orchard. Agric. Meteorol., 12:249-257.
- Welles, J. M., Norman, J. M., and Martsolf, J. D. 1978. An orchard foliage temperature model. J. Amer. Soc. Hort. Sci. (In press).

Appendix

Mean wind speeds and temperatures,
December 4, 1977

Figure 8. Mean wind speed as a function of time 6 m above the orchard floor, on west face of experimental orchard, December 4, 1977.

Figure 9. Aspirated mean air temperatures at primary instrument tower, December 4, 1977. Upper line is 15 m above the orchard floor, lower line is 1 m above the orchard floor.