Fig. 6. Average degrees of protection provided by sprinkling during 1978 frost.

During the period between 3:30 and 4:00 (Fig. 5), although the sprinkling rate was adequate, the 4 min off time was too long and allowed the blossom to cool more than it could warm during the on period and subsequent freezing period. Therefore, overall cooling occurred. During the period of 4:00 to 4:30 the off time of 1.5 min did provide protection. Thus one can conclude the optimum off time to be between 1.5 and 4.0 min. Eq. 1 predicts a maximum off time of 2.8 min for the existing conditions. Although this particular off time was not observed, it is within the limits determined from the data. Granting the data does not provide decisive evidence for the predicted 2.8 min off time, even at the lower limit of 1.5 min a 60% reduction in application rate from 1.14 to 0.46 cm/hr is obtained.

Another way to view the effect of sprinkling and pulsing is to consider degrees of protection. Degrees of protection are the degrees a representative sprinkled blossom is above a representative unsprinkled blossom (Fig. 6). Between 3:30 and 4:00, no protection was provided, but between 4:00 and 4:30 the blossom was protected. This demonstrates the importance of the appropriate pulsing cycle, even when the application rate is sufficient.

Pulsing provides a method by which the amount of water required for sprinkling for frost protection may be reduced. However, it is essential to not only determine the appropriate amount of water to be applied, but also the appropriate pulsing cycle to make it work successfully.

**Literature Cited**


**Turbulent Heat Fluxes above a Heated Orchard**

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Abstract. Spatial and temporal components of the turbulent heat flux above a heated orchard are discussed. Direct measurements of the temporal component of the turbulent flux at 2 locations are reported. Drag anemometry and fine-wire thermocouples provided measurements of u, v, w, and T at 30 Hz. About 10% of the energy provided by heating escaped the crop zone by the temporal flux. Variation in the flux measured at a given location was caused by changes in wind speed and direction, and heater proximity.

Rising fuel costs and the uncertainty of supply at any price necessitate maximizing the efficiency of orchard heating. The USDA estimates over 6 million barrels of oil are burned annually to protect fruit crops from cold (E. E. Garett, personal communication). Ways of conserving some of this oil should result from study of current orchard heating techniques. Martsolf and Panofsky (3) developed a complete energy budget for a hypothetical box of dimensions dxdydz containing a heated orchard. Transport of energy through the facets of the box was via 3 fluxes: radiation divergence, mean flow, and turbulent mixing. The turbulent heat transport at the top of the box was written (3):

\[ Q = -\rho c_p \int w' T' \, dx \, dy \]  

([Eq. 1])
where

\[ Q = \text{turbulent heat transport}, \]
\[ \rho = \text{the density of air}, \]
\[ c_p = \text{the specific heat of air at constant pressure}, \]
\[ w' = \text{instantaneous departure of the vertical wind from the time mean}, \]
\[ T' = \text{instantaneous departure of temperature from the time mean}. \]

The overbar indicates a temporal average.

Martsolf and Panofsky (3) defined \( w' \) and \( T' \) as departures of instantaneous values \((w \text{ and } T)\) from time means of those values \((\bar{w} \text{ and } \bar{T})\). Integration of \( w'T' \) over the orchard then resulted in \( Q \). However, local values of \( w'T' \) do not yield all of the turbulent heat loss because the flux can vary systematically in space. This can be represented by rewriting Equation 1 as an area average,

\[ Q = -\rho c_p \overline{w'T'} A \]  \hspace{1cm} [Eq. 2]

where the tilde (~) indicates a spatial average and \( A \) is the area over which the integration is carried out. Rewriting Equation 2 in terms of a flux, \( H = \frac{Q}{A} \) yields:

\[ H = -\rho c_p \overline{w'T'} \] \hspace{1cm} [Eq. 3]

Equation 3 may then be transformed by putting

\[ w' = \overline{w'w} \] \hspace{1cm} [Eq. 4]

Two components of \( w' \) are partitioned by expanding Equation 4 to:

\[ w' = (w-w) + (w-w) \] \hspace{1cm} [Eq. 5]

By Equation 5, \( w' \) is sum of 2 values: departures of the instantaneous value of \( w \) from the local time mean \((w-w)\) and departures of the local mean from the time-space mean \((w-w)\). Define \( w'' \) and \( w''' \) as:

\[ w'' = w-w \] \hspace{1cm} [Eq. 6]
\[ w''' = w-w \] \hspace{1cm} [Eq. 7]

Substitution of Equations 6 and 7 into Equation 5 yields:

\[ w' = w'' + w''' \] \hspace{1cm} [Eq. 8]

A similar development with \( T' \) leads to formation of the product of \( w' \) and \( T' \) as follows:

\[ w'T' = w'T'' + w'T''' + w'T'' + w'T''' \] \hspace{1cm} [Eq. 9]

Obtaining Equation 3 requires averaging of Equation 9 over time and space. Recalling that by Reynold’s postulates (6) products of a fluctuating quantity and a mean quantity are zero, Equation 9 becomes:

\[ \overline{w'T'} = w'T'' + w'T''' \] \hspace{1cm} [Eq. 10]

Substituting Equation 10 into Equation 3 yields:

\[ H = -\rho c_p \overline{(w''T'' + w'''T''')} \] \hspace{1cm} [Eq. 11]

Notice the turbulent flux has two components:

\[ H_t = -\rho c_p \overline{(w''T'')} \] \hspace{1cm} [Eq. 12]
\[ H_s = -\rho c_p \overline{(w'''T'')} \] \hspace{1cm} [Eq. 13]

where

\[ H_t = \text{the flux due to temporal fluctuations in the variables}, \]
\[ H_s = \text{flux due to spatial fluctuations}. \]

By Equation 6, the product \( \overline{w''T''} \) is seen to be due to departures of the instantaneous values from the local time mean of the variables. The quantity \( \overline{w'''T'''} \) results from fluctuations of the local time means about the time-space mean by Equation 7.

Physically, the temporal turbulent heat flux \((H_t)\) is due to mixing between the heated air in the crop zone and cooler air above by vertical motions varying in time. Steady convective eddies created by the buoyant heater plumes yield the spatial turbulent heat flux \((H_s)\). Cool air sinks between the heaters to replace the rising warm air.

The magnitude of \( Q \) in both the horizontal and vertical has been estimated by treating it as a residual (4). It was suggested that up to 60% of the energy supplied by heating might escape by turbulent transport. Observations of the temporal component \((H_t)\) of \( H \) in the vertical at 4 m above the floor of a heated orchard are presented. Influences of wind direction and heater proximity on the flux measured at a given location are discussed.

### Materials and Methods

Wind measurements were made by 2 rapid-response drag anemometers, like the one pictured in Fig. 1. They were developed and built at The Pennsylvania State University (5). A vertically oriented element senses the \( u \) and \( v \), or horizontal, wind components. The vertical wind component, \( w \), is measured by the horizontally displayed element.

Wind speed is measured when moving air strikes the exposed drag element. The force exerted on the drag element by the wind is transmitted through a ceramic rod to a steel cantilever. Distortion of the cantilever results. Sensitive strain gauges affixed to the cantilever convert the distortions to electrical signals. Fluctuating temperature was sensed by 0.025 mm chromel-constantan thermocouple.

Zero drift in the amplification circuitry was compensated by periodic “zeroing” runs. Tubular shrouds (retracted in Fig. 1) were used to shield the drag elements from air movement. Zero values were recorded with the elements covered.

The wind components and temperatures were scanned at 30 Hz. A DEC PDP 11/10 computer controlled the data acquisition. Analog-to-digital conversion was by a modified Burr-Brown SDM 835 A/D converter. Data was written on magnetic tape in the field. This field data tape was read on the PSU IBM Systems 370/168 computer and the voltages were converted to velocities and temperatures. Fluxes were then calculated from these velocities and temperatures.

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 built at the University of Guelph, Guelph, Ontario. Acceptable agreement has also been documented with sonic anemometers at Risø, Røskilde, Denmark (5).

The measurements were made in a 1 ha orchard of Golden Delicious apple trees on MM 104 rootstocks. The trees are planted on a 7.3m by 4.9m rectangle, with the rows oriented N-S. The orchard site is relatively flat and surrounded by mown grass for about 100m on each side. Two pipeline heating systems are permanently installed in the orchard at a density of 87 heater/ha. One system consists of Scheu Auto Clean Stack heaters (Scheu Products Co., Upland, California) and the other is a Scheu Large Cone heater system. The orchard is located at the Rock Springs Agricultural Research Center of The Pennsylvania State University, 15km SW of State College. The experiment was performed on the cold, clear night of December 3, 1977.

Both drag anemometers and thermocouples were mounted on a tower in the center of the N-W quadrant of the orchard. The tower location in relation to adjacent upwind trees and heaters is indicated in Fig. 3, and will be discussed later. One anemometer was on the west side of the tower and the other on the east side.

### Results and Discussion

During portions of the experiment when no heating was conducted the turbulent heat flux measured was negative...
Fig. 1. A drag anemometer and thermocouple used to measure turbulent heat fluxes, viewed from downwind. The 2 cylindrical drag elements mounted on their ceramic stalks are visible in the lower right corner of the figure. Horizontal components of the wind are sensed by the vertical element; the horizontal element senses the vertical wind component. Tubular shrouds and circular end-caps that cover the elements during amplifier zeroing runs are retracted for measurements. The thermocouple is at the end of the horizontal tube below the lower drag element.

Fig. 2. Turbulent heat flux (H) as a function of wind speed (U) in a temperature inversion at 4m above the floor of an unheated orchard.

Fig. 3. Map of the experimental orchard immediately upwind of the instrument site. The instrument tower is the triangle between the northern most trees on the figure. AC and LC refer to Auto Clean Stack and Large Cone heaters respectively. The thermocouple/anemometer sets are indicated by small lines and circles to the west and east of the tower. Mean wind directions during the 4-min period ending 0305 measured by each anemometer are represented by the lines ending at the anemometers and labelled 0305.
To test this estimate of plume growth a basic plume growth equation can be applied. In the earliest stages of plume rise the effect of the discs on plumes are bent under the discs to a large extent. As a result, efficient heating should result. Under windy conditions, the plume edge could have struck the west anemometer and thermocouple. The east anemometer and thermocouple were too far from the plume centerline to be in the plume.

Wind direction during both 4-minute periods was nearly equal. During the period ending 0305 an exceptionally large flux (downward). Turbulence at night, in the absence of surface heat sources, is mechanically driven. Mechanical mixing in an inversion (the temperature structure normally present during a radiation frost) should cause a negative heat flux. The magnitude of a heat flux due to mechanical mixing can be related to the local temperature structure through the eddy transfer coefficient for heat, which is known to be positively correlated with wind speed. Four minute averages of the turbulent heat flux and wind speed, plotted in Fig. 2, support the relationship of the turbulent heat flux and wind speed. Downward mixing by mechanical turbulence often provides enough energy in an orchard to prevent a frost which might have occurred without wind.

The Auto Clean Stack heating system was lit about 0300. Data collected during the period of heating is presented in Table 1. The data are 4-minute averages of the turbulent heat flux (H), wind speed (U), and wind direction (θ) ending at the time indicated. Wind direction values are in degrees from due South, with negative values indicating wind from the west of south. Discussion of specific periods follows.

Fig. 3 is a map of the portion of the orchard upwind of the instrument tower. The instrument tower is the triangle, and the anemometers are represented by the small dots to the east and west of the tower. Heaters are indicated by the large dots labelled AC for an Auto Clean Stack heater, and LC for a Large Cone heater. The wind direction for the period ending 0305 as sensed by both anemometers is indicated by the lines labelled 0305 that extended from each anemometer.

Wind speed during the period ending 0305 was limited by the nearest burning upwind heater (labelled AC in Fig. 3). The plume centreline would most likely have followed the mean wind direction. When the plume passed the instruments it had grown sufficiently to include the west anemometer and thermocouple. The instruments on the east side of the tower measured a much smaller flux, indicating the plume had not grown sufficiently to pass directly over them.

To test this estimate of plume growth a basic plume growth equation can be applied. In the earliest stages of plume rise the radius of the plume, r, can be considered proportional to the time indicated. Ht was calculated from measurements of w'T"; θ is in degrees from due South, with negative values indicating a westerly component; and U is in ms−1. One anemometer/thermocouple set was mounted on the west side of the instrument tower, the other set was to the east.

<table>
<thead>
<tr>
<th>Time</th>
<th>West</th>
<th>East</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H(Wm⁻²)</td>
<td>U(ms⁻¹)</td>
</tr>
<tr>
<td>0301</td>
<td>56.7 -10.8</td>
<td>1.2</td>
</tr>
<tr>
<td>0305</td>
<td>401.5 -19.8</td>
<td>1.4</td>
</tr>
<tr>
<td>0309</td>
<td>-2.6 -35.6</td>
<td>1.2</td>
</tr>
<tr>
<td>0313</td>
<td>18.1 -25.8</td>
<td>1.5</td>
</tr>
<tr>
<td>0317</td>
<td>35.9 -28.8</td>
<td>1.4</td>
</tr>
<tr>
<td>0321</td>
<td>28.6 -25.6</td>
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</tr>
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<td>0325</td>
<td>5.4 -12.7</td>
<td>2.2</td>
</tr>
<tr>
<td>0329</td>
<td>0.3 -4.7</td>
<td>2.4</td>
</tr>
<tr>
<td>0333</td>
<td>-26.0 -0.9</td>
<td>2.6</td>
</tr>
<tr>
<td>0353</td>
<td>58.4 -12.2</td>
<td>2.9</td>
</tr>
<tr>
<td>0357</td>
<td>43.5 -13.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>

The minor axis is the plume radius, r. The major axis is a function of wind speed. As wind speed increases, the plume travels further downwind before rising to a given height, resulting in a larger major axis.

The plume dispersed closer to the ground and, therefore, more spatial variation in w and T exists across the orchard. As a plume is bent by the wind, its cross-sectional area as it passes through a horizontal plane above the orchard is an ellipse.

Turbulent heat fluxes (Ht) recorded during the period ending 0309 are negative because the Auto Clean Stack heaters in the row immediately west of the instrument tower had to be extinguished after 0305. Complications with another experiment necessitated burning the Large Cone heaters in that row after 0305. The heater labelled LC in Fig. 3 was the nearest burning heater upwind of the instrument tower for the remainder of the experiment.

Wind speed appears to influence the value of Ht measured at a given point. Data collected by the west anemometer during the period ending 0325 and 0353 demonstrate a possible effect. Wind direction during both 4-minute periods was nearly equal. During the period ending 0325, Ht = 5.4 Wm⁻² and U = 2.2 ms⁻¹. When, during the period ending 0353, U increased to 2.9 ms⁻¹, Ht = 58.4 Wm⁻². Perhaps the higher wind speed bent a heater plume such that its hotter center was passing closer to the west anemometer. A larger Ht would result.

Table 1. Temporal turbulent heat flux (Ht), wind direction (θ), and wind speed (U) 4m above the floor of a heated orchard. All values are 4-minute averages, ending at the time indicated. Ht was calculated from measurements of w'T"; θ is in degrees from due South, with negative values indicating a westerly component; and U is in ms⁻¹. One anemometer/thermocouple set was mounted on the west side of the instrument tower, the other set was to the east.
Negative $H_t$ values during heating are noted between 0326 and 0353. This is surprising considering the heaters released an average of 260 Wm$^{-2}$ at the orchard floor. The wind speed at the west anemometer during the period ending 0333 (2.6 ms$^{-1}$) corresponds to a heat flux of about $-23$ Wm$^{-2}$ from Fig. 2. Recall Fig. 2 consists of data collected during periods when no heating was conducted. During the period ending 0333, $H_t = -26$ Wm$^{-2}$. It is seen no effect of the heating operation is apparent during this period.

During these periods of small and negative heat fluxes, small $\theta$ values were recorded. When $\theta = 0$ the wind is from directly between the heater and tree rows. The wind never passes over a burning heater before striking the anemometer and thermocouple. A model of the radiant energy output of the heaters (7) suggests that while the trees and adjacent soil are heated, little warming of inter-row spaces occurs. Thus air traveling between the rows is not warmed by either a heater plume or warm soil and plant parts. If air from between the heater and tree rows is being measured, little effect of heating should be noted. The heat flux measured at a given point is highly dependent on the immediate past history of the air being sensed.

Averages of $H_t$ while the heaters were burning were obtained over the interval 0310 to 0357. Data before 0310 were not used since various different heater configurations were burning. Averaging over the entire period of heating is necessary because some significant high-pass filtering could occur with 4-minute averages. At the west anemometer an average temporal turbulent heat flux of 22.8 Wm$^{-2}$ was recorded. The east anemometer and thermocouple measured a flux of 18.9 Wm$^{-2}$. The difference between the 2 instruments may reflect the slightly upwind location of anemometer 1.

Averaging $H_t$ between the instruments yields a flux of 20.8 Wm$^{-2}$. About 260 Wm$^{-2}$ were released at the orchard floor by the heaters, so less than 10% of the energy input escaped by the temporal turbulent heat flux.

The necessity of adequate spatial samples has been discussed. Admittedly, 2 anemometers and thermocouples may not be sufficient. It is suggested, though, that the variety of wind speeds and directions which occurred during the experiment greatly improved the spatial sample.

The direct measurement of $H_t$ presented here indicates that it is a relatively small term in the heated orchard energy budget, i.e., on the order of 10% of total heat supplied. Derivation of the turbulent flux due to spatial variations ($H_t$) clarifies the turbulent heat flux terms in the budget proposed by Martsolf and Panofsky (3). Balancing this budget requires evaluation of $H_t$ and the energy loss due to mean flow.

### Literature Cited


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### Response of Turfgrass Cultivars to Ozone, Sulfur Dioxide, Nitrogen Dioxide, or their Mixture

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**Abstract.** Eighteen cultivars representing 6 species (*Poa pratensis*, *Agrostis tenuis*, *Agrostis palustris*, *Festuca rubra*, perennial ryegrass, Lolium perenne) were exposed to ozone, sulfur dioxide, and nitrogen dioxide alone or in combination. The combined exposure caused more leaf injury and greater reduction in the leaf area production by most cultivars compared with plants exposed to single gases. Exposure to single pollutants could provide inaccurate estimates of turfgrass cultivar sensitivity outdoors where several pollutants may occur simultaneously.

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Ozone, sulfur dioxide, and nitrogen dioxide are the most pervasive air pollutants affecting vegetation in North America (7). These 3 air pollutants seldom exist alone; the natural air environment contains a complex mixture of these and other gases. Turfgrasses occupy large land areas in the vicinity of urban and industrial development and their sensitivity to...