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FREEZE CLIMATOLOGY OF MICHIGAN

By

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ABSTRACT

FREEZE CLIMATOLOGY OF MICHIGAN

By

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Knowledge of the freeze climatology of Michigan, 1950 through 1979, was augmented by computing the probabilities of freezes during spring and fall for selected agricultural weather stations in western Michigan, a data network which had not been analyzed prior to this study. The agricultural weather network, which was established in 1962, necessitated the estimation of minimum temperatures from the longer-term climatological network by the statistical technique of linear regression. A computer program provided by the Michigan Department of Agriculture/Michigan Weather Service was used to generate freeze dates, assuming that the freeze dates were normally distributed.

Vertical temperature profiles were monitored in two grape vineyards near Texas Corners, Michigan during the spring months of 1978, 1979 and 1980 by copper-constantan thermocouples attached to an instrumentation tower. Graphs depicting the temperature inversion between 1.0 and 15.2 meters, and between 1.0 and 17.4 meters, are reported.

Larry Jay Levitt

A minimum temperature forecasting scheme developed by the National Weather Service for agricultural weather stations in western Michigan was evaluated. The 4 p.m. temperature, dew point, cloud cover, and anticipated 850 mb temperature trend were used to predict the Grand Rapids minimum temperature. This prediction served as a basis to establish a forecast for 25 agricultural weather stations in western Michigan, provided that an average difference between Grand Rapids and the station in question, for different synoptic conditions, had been determined. The technique was tested for 1977 and 1978, with the results indicating that the method is a useful guide for forecasting nocturnal minimum temperatures in western Michigan.

ACKNOWLEDGMENTS

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I would like to thank Dr. Dale Linvill, former Assistant Professor of Agricultural Engineering, Michigan State University, for initiating this project and coordinating the field research, and to whom I am grateful for introducing me to the discipline of agrometeorology. I would also like to express my appreciation to Dr. Jon Bartholic, assistant director of the Michigan Agricultural Experiment Station, and to Mr. Ceel Van Den Brink, advisory agricultural meteorologist (Agricultural Engineering/Entomology), Michigan State University, for their useful comments. Mr. John Jensensius kindly provided the data from the TDL Agricultural Weather Guidance. I am grateful to Mr. Gary Connors and Mr. Al Shields, Agricultural Engineering, Michigan State University, for their assistance with the vineyard instrumentation. Finally, the owners of the two vineyards in which the research was conducted, Mr. Peter Dragecivich and Mr. Del Kellogg, must be thanked for their endless cooperation.

The source of the data for the agricultural weather stations was the individual records from the Cooperative Weather Observers, which are on file at the Agricultural Weather Office, Room 230, Natural Science Building, Michigan State University. The climatological data are published by the National Climatic Center (NCC) through their series entitled "Michigan Climatological Data" (MCD), and is available at the Agricultural Weather Service Office, Documents Center, Main Library, Michigan State University, and the Michigan Weather Service, Room 240 Nisbet Building, 1407 S. Harrison, East Lansing.

Finally, I would like to thank Dr. Fred Nurnberger, State Climatologist of Michigan (adjunct associate professor of Agricultural Engineering, Michigan State University), for his patience and forbearance while serving as the major professor.

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LIST OF SYMBOLS

a	regression constant in hygrometric formulas
A	area influenced by a wind machine
α	level of significance
b	regression constant in hygrometric formulas
β	coefficient of mass transfer
C	heat capacity per unit horizontal area of a leaf
C_F	thrust coefficient of a wind machine
C_P	power coefficient of a wind machine
C_S	specific heat of the soil
C_V	soil heat capacity per unit volume
C_0	constant in soil temperature profile equation
χ^2	chi-square statistic
d	effective leaf diameter
d_{wm}	diameter of wind machine propeller
D	damping depth
e	vapor pressure
e_a	vapor pressure of the air
e_l	vapor pressure of the leaf
E	net outgoing radiation
ε	emissivity

ε_s	emissivity of the surface
f(Y)	density function for a normal random variable Y
F	thrust of the wind machine
F_e	latent heat flux density
F_h	sensible heat flux density
F_H	convective heat flux
F_p	required energy to maintain plant at the minimum tolerable temperature
$(F_n)_{sky}$	net radiation above the leaf
$(F_n)_{surface}$	net radiation above the surface
G	counter radiation from the atmosphere
γ	ratio of longwave sky radiation to black body radiation from surface
Γ	dry-adiabatic lapse rate (temperature)
Γ_s	lapse rate (temperature) at sunset
h	relative humidity
h_r	derivative of Stefan-Boltzmann equation for radiative flux
h_t	coefficient of heat transfer
k	von Karman's constant
K	thermal conductivity
K_H	exchange coefficient
K_n	constant according to cloud type
K_s	thermal diffusivity of the soil
L	latent heat of vaporization
λ	eddy conductivity
λ_{max}	wavelength at which the earth emits maximum black-body radiation

N	revolutions per minute of wind machine propeller
PW	percent water in the soil on a volume basis
r	correlation coefficient
R	total longwave radiation under a couldless sky
R_N	net radiation
$R_{n(o)}$	net radiation from the soil surface
$R_{N(a)}$	radiation balance of the air
R_w	specific gas constant for water vapor
ρ	density of the air
ρ_B	bulk density of the soil
ρ_S	density of the soil (dry bulk density)
S(O)	soil heat flux
$S(O)_n$	flux of terrestrial radiation (n tenths of clouds)
$S(O)_o$	flux of terrestrial radiation (clear skies)
$S(\bar{Y})$	estimated standard deviation
S^2	sample variance of the freeze statistics
σ	Stefan-Boltzmann constant
σ_n	standard deviation of the normal distribution
σ_Y	standard deviation of the minimum temperature at Grand Rapids
σ^2	population variance of the freeze statistics
t	time
T	absolute temperature (^{o}K) of a black body

T_a	air temperature at screen height
T_A	average soil temperature
T_b	radiating temperature of black copper plate facing the ground
T_d	dew point temperature
T_e	effective sky temperature
T_l	leaf temperature
T_{LAKE}	lake temperature
T_m	minimum temperature forecast
T_{mt}	minimum tolerable leaf temperature
T_R	air temperature at 150 cm
T_s	surface temperature
T_t	radiating temperature of black copper plate facing the sky
T_x	maximum air temperature
T_w	wet bulb temperature
T_z	temperature at height z
T_*	Lumley-Panofsky scaling temperature
T_{xi}	maximum soil temperature for the day at i = 0, 5, 10, 20 and 50 cm
T_{ni}	minimum soil temperatures for the day at i = 0, 5, 10, 20 and 50 cm
Θ	potential temperature
Θ_o	potential temperature at a chosen reference level
$\bar{U}$	mean wind speed
U_*	friction velocity
μ	mean frost date

V_d	number depending on d
V_H	variable depending on h
w	$2\pi/P$, where P is the period
X	climatological station
y	minimum temperature
Y	agricultural weather station
Y_{m-d}	difference between the minimum temperature and the evening dew point
$\bar{Y}$	sample mean
Z	height in the atmosphere
dT/dZ	temperature profile gradient
dU/dZ	wind profile gradient

INTRODUCTION

The grape industry of Michigan is an important segment of the state economy. People who rely upon grapes for all or part of their livelihood include over 1000 farm families, 400 to 500 processor and winery employees, and potentially 2000 to 3000 seasonal part-time employees (Michigan Grape Cooperative).

According to the Michigan Agricultural Reporting Service, Michigan grape yields have been highly variable over the past 15 years. Grape production has ranged from 71,500 tons (4.3 tons per acre) in 1965 to 14,500 tons (0.9 tons per acre) in 1976. In the last 10 years, the raw product value of the grape commodities often exceeded 8 million dollars. Appendix A contains data from the Agricultural Reporting Service indicating acreage, yield, uses, and raw product values. Grape production has often been adversely affected by frost and the occurrence of freezes during the spring.

Few published accounts of the cold temperature and freeze hazards to the horticulture industry of Michigan exist. The Michigan Freeze Bulletin (1965) describes the cold hazard to fruits, farm crops, and vegetable production in Michigan. This publication contains tables of the probability of selected temperatures occurring during spring and fall for 85 locations in Michigan. From the probability tables in this work, one may infer the cold hazard to any crop grown provided one is aware of the cold tolerance of the plant or fruit.

The statistics that are available from the Michigan Freeze Bulletin (1965) show some degree of freeze and cold temperature hazard to all agricultural areas of the state. The critical threshold temperature varies among plant species and is different for parts of the same plant. Gerber and Hashemi (1965) found that the freezing point of citrus leaves also varied with time of season. Hendershott (1962) deduced from observations in a portable freeze chamber that the critical temperature for citrus fruit is near 28^{o}F, citrus leaves near 20-22^{o}F, and small twigs and branches near 20^{o}F. The air temperatures (in shelters at the 5-foot level) that may be endured for 30 minutes or less by deciduous fruits were reported by Young (1940), and are listed in Table 1. He specified three stages of development: buds closed but showing color, full bloom, and small green fruits.

The methods of protecting plants from cold include effective use of natural heat sources. The soil heat flux can be modified by irrigating before the freeze, clean cultivation, and forced harvesting. These passive

TABLE 1

AIR TEMPERATURES (SHELTERED THERMOMETERS) ENDURED FOR 30 MINUTES OR LESS BY DECIDUOUS FRUITS IN SELECTED STAGES OF DEVELOPMENT (YOUNG, 1940)

FRUIT	STAGE OF DEVELOPMENT		
	Buds Closed But Showing Color	Full Bloom	Small Green Fruits
Apples	25°F	28°F	29°F
Peaches	25	27	30
Cherries	28	28	30
Pears	25	28	30
Plums	25	28	30
Apricots	25	28	31
Prunes, Italian	23	27	30
Almonds	24	26	30
Grapes	30	31	31
Walnuts, English	30	30	30

SOURCE: Brooks, Physical Microclimatology (1960)

practices increase the soil thermal conductivity and heat storage capacity, which increases the heat flux at night and thereby minimizes the rate of cooling. In contrast, active methods modify the nocturnal microclimate by the use of heat, freezing water, man-made fog, foam, or by employing wind machines to increase the turbulence and enhance the heat flux to the surface.

Successful applications of man-made fog for freeze protection is a current development, having only been reported during the last 10 years (approximately). In particular, an atomization method has been found that efficiently produces droplets of 10 to 20 μm diameter, and at a high enough rate to saturate the atmosphere and produce a stable fog in the lower 10 m of the atmosphere (Mee and Bartholic, 1979). The energy requirement for the atomization method is quite noteworthy, in that 100 times less energy is required than if heaters were used to obtain comparable results.

Bartholic and Brand (1979) have demonstrated that foam insulation for freeze protection may increase low-growing crop temperatures by 10°C. Difficulties in applying foam over a large area in a short time span, as well as the cost of the foam agents, have limited its use.

Regardless of whether an active or passive cold protection method is chosen, an accurate prediction of minimum air temperature coupled with quantitative knowledge of the nocturnal temperature inversion will aid the grower in deciding whether or not to employ protective practices.

The purpose of this work is to establish the freeze climatology for various agricultural weather stations, report the results of microclimate monitoring in two grape vineyards, and evaluate an empirical minimum temperature forecasting scheme for agricultural weather stations in western Michigan.

LITERATURE REVIEW

1. Freeze Climatology

The purpose of this section is to discuss probabilities of occurrence of minimum temperatures computed at selected agricultural weather stations in western Michigan. The probable dates of the last occurrence in the spring and the first occurrence in the fall for the five temperature thresholds of 20, 24, 28, 32, and 36°F are shown in Tables C1-C17 (Appendix C). This allows for computation of the growing season, which is important when determining the adaptability of various cultivars to different climates. Knowledge of the probability of freezes enables the fruit farmer to make management decisions concerning frequency of spring freezes and the effect of delaying harvest in the fall. Many other agricultural experiment stations have published research of this nature, e. g. Nevada (Sakamoto and Gifford, 1960), Indiana (Schaal et al., 1961), and Iowa (Shaw et al., 1954).

Thom and Shaw (1958) discussed at some length their rationale for assuming that the freeze series was random in contrast to a linear trend, and normally distributed. A freeze series consists of the sequence of dates of annual occurrence of last spring or first fall freeze dates, with the sensor exposed roughly five feet above the ground. They applied the auto correlation test, and formulated an acceptance region surrounding zero based upon the number of observations in their series. As these coefficients were very small, they assumed that their freeze dates were random when evaluating its frequency distribution. Calculating kurtosis and skewness statistics and hypothesizing the existence of an acceptance region (Geary-Pearson test), they concluded that the freeze data may be represented by a normal distribution.

The interpretation of a freeze in meteorology considers that an effect produced by a critical value is also produced by any temperature lower than that value. Thus, a t-degree freeze is the occurrence of a minimum temperature of t degrees or lower.

The range of critical temperatures that will cause freezing damage to plants will depend upon the crop and its stage of development. It has been speculated that the young shoots and flower clusters of grapes are more sensitive to freeze than any other commercially grown fruit in Michigan (Michigan Freeze Bulletin, 1965). This is because temperatures of 30^{o}F or lower may cause considerable damage if growth has begun. All growing shoots may be killed at temperatures of 26^{o}F. Nevertheless, the extent of damage to the plant depends upon the duration of exposure to the critical temperature. A grape bud exhibits apical dominance; that is, a secondary shoot may emerge from the same stem, resulting in a partial crop if the primary bud is killed.

Terminology often encountered in freeze studies includes hoar-frost, white frost, and black frost. Hoar-frost is synonymous with frost, referring to the interlocking matrix of ice crystals that form on exposed objects. A white frost is a particularly heavy coating of hoarfrost that is deposited by sublimation. This is to be distinguished from black frost, in which no ice crystals may be seen, but plant tissues are injured.

A white frost, by insulating the plant from further cold and by releasing the latent heat of fusion, may only result in modest damage to the plant. The internal freezing of vegetation that is associated with a black frost is indicative of the dew point being lower than ambient temperature. There is no latent heat of fusion released to offset the drop in temperature and, therefore, this is the most damaging type of frost.

Meteorologists define two distinct types of freezes based upon the physical process involved, the radiation freeze and the advection freeze. The radiation freeze is most often encountered in Michigan, as typified by high pressure systems moving in from the northwest. The clear, dry, and low wind speed conditions are conducive to the formation of temperature inversions near the ground. The advection freeze that occasionally occurs is associated with cold fronts; it is this type of freeze, with the accompanying winds and cloud cover against which a wind machine is useless. If the cold front passes during the day and the skies clear later that evening without the winds subsiding, a "radiation-advection" freeze is said to occur.

2. Freeze Protection with Wind Machines

A. Long Wavelength Radiation at Night. Solar radiation will be reflected and scattered by the atmosphere and absorbed by the earth's surface, which becomes a source of longwave radiation. The total energy radiated by any object above a temperature of absolute zero will be proportional to the fourth power of the temperature of the radiating surface, as stated in the Stefan-Boltzmann law:

$$R = \varepsilon\sigma T^4 \qquad (2.1)$$

where T is the abolute temperature in $^{\circ}K$, σ is the Stefan-Boltzmann constant (7.92×10^{-11} cal cm^{-2} ($^{\circ}$K)$^{-4}$ min^{-1}), and ε is the emissivity. Assuming that the average temperature of the earth's surface is 287°K, the Wien displacement law indicates that most of the radiation is emitted in the infrared spectral region with a peak at 10 μm:

$$\lambda_{max} = 2897/T \qquad (2.2)$$

Almost all of the sun's radiation is encompassed by short wavelengths from 0.15 μm to 4.0 μm, with maximum emission at 0.5 μm. Most of the radiation emitted by the earth's surface is in the infrared region from 4 μm to 50 μm. Infrared radiation is emitted during the day as well as the night.

During the night, without contributions from the direct solar beam, its diffuse components, or short wave reflected radiation, the long wavelength balance is

$$-R_N = \sigma T^4 - G \qquad (2.3)$$

where R_N is the net radiation, and G is the counter radiation from the atmosphere.

Except for thin cirrus, clouds will radiate in the manner of black bodies according to the temperature of their base or top. For example, clouds at $0^{o}C$ will be a source of 0.44 cal cm^{-2} min^{-1} that is radiated downward towards the earth (Gates, 1965).

The clear night sky possesses semi-transparency to longwave infrared radiation, in which the minor atmospheric constituents, water vapor, carbon dioxide, and ozone, selectively absorb and emit energy. Absorption spectra for these gases as a function of wavelength also indicate the range in which they will radiate. Water vapor displays a sharp absorption band at 2.7 μm, and broad absorption bands at 6.3 μm, and also beyond 22 μm. Carbon dioxide has its only significant absorption bands at 2.8 μm, 4.3 μm, and 14.9 μm, contributing about 1/6 of the counter radiation (Geiger, 1965). This gas is uniformly mixed throughout the atmosphere; its flux of radiation would be a nearly constant contribution. Water vapor and carbon dioxide reradiate their captured energy to space and back to earth at a lower temperature than the ground. Beyond about 14 μm, the atmosphere gradually takes on opaque characteristics, tending towards a condition where all radiation is absorbed.

The spectral range of 8 to 14 μm is often referred to as a "window" in which absorption is approximately 10%, and is of major importance in considering the nocturnal radiation balance. The atmosphere radiates less energy downwards as a result of this phenomenon, accounting for the surface cooling at night as net radiation is negative.

Emissivity is the fraction of the total black body radiation intensity emitted or absorbed by a layer or column, and varies according to the specified amount of gas. It usually increases as one descends in the atmosphere, as a corollary to the rise in the gas concentration. The widths of the absorption bands for water vapor, ozone, and carbon dioxide are directly related to the number of collisions that the gas molecules undergo per unit of time, and will, therefore, be proportional to the total air pressure.

To properly synthesize this knowledge with respect to infrared radiation, the "true depth" of a given gas must be substituted for its counterpart, "corrected optical depth." The true depth is the length of a column of pure gas at standard temperature ($288^{o}K$) and pressure. If this value is multiplied by the ratio of the mean pressure of the layer to standard sea level pressure (1013.25 mb), the corrected optical depth for water vapor is obtained. Emissivities as a function of path length and temperature are reported by Sellers (1965).

Conceptually, every layer of the atmosphere plays a role in the counter radiation of energy to the earth's surface, which exceeds that to space (except near the poles). A good deal of this counter radiation will originate in the lowest 100 meters of the atmosphere, which is warmer than the upper layers, which serves as the source of the upward flux. A rather unique set of observations as deduced from an early-morning sounding conducted during the 1953 O'Neill, Nebraska micrometeorology experiments is reported in Table 2. Approximately 90% of the counter radiation emanates from the lowest 800 to 1600 meters of the atmosphere (Sellers, 1965).

B. Energy Budgets of Leaf and Fruit.

1. Radiation and the notion of effective sky temperature. The purpose of this sub-section is to acquire an understanding of the interrelationships between physical processes at the earth-air interface (i. e., radiation, convection, and evaporation) and the plant. Factors that determine leaf temperature are summarized at the end in an equation that expresses its energy budget. The leaf temperature may fall below air temperature, and it is imperative to consider this in regard to freeze protection. Characterizing the magnitude of this difference

TABLE 2

TOTAL COUNTER RADIATION AT 0635 CST 8/31/53
O'NEILL, NEBRASKA

Percent	Originating Below
9.3	0.1 m
15.9	0.4
20.3	0.8
25.8	2.0
35.0	6.0
44.6	20.0
58.9	100.0
74.6	400.0
84.8	1000.0
98.5	4000.0

SOURCE: Physical Climatology, by Sellers (1965)

may serve as criteria in determining the amount of energy needed for freeze protection and the suitability of various types of freeze-protection equipment.

A model leaf and a sphere to represent its young fruit are shown in Figure 1, with the longwave radiative flux density that it receives from the sky being σT_e^4, where T_e is the "effective sky temperature," and from the earth's surface $\varepsilon_s \sigma T_s^4$, where T_s is the surface temperature and ε_s is the emissivity of the surface. The emissivity of water, soil, and natural surfaces varies between .71 and .96 (Brooks, 1959); infrared spectrometer determinations of

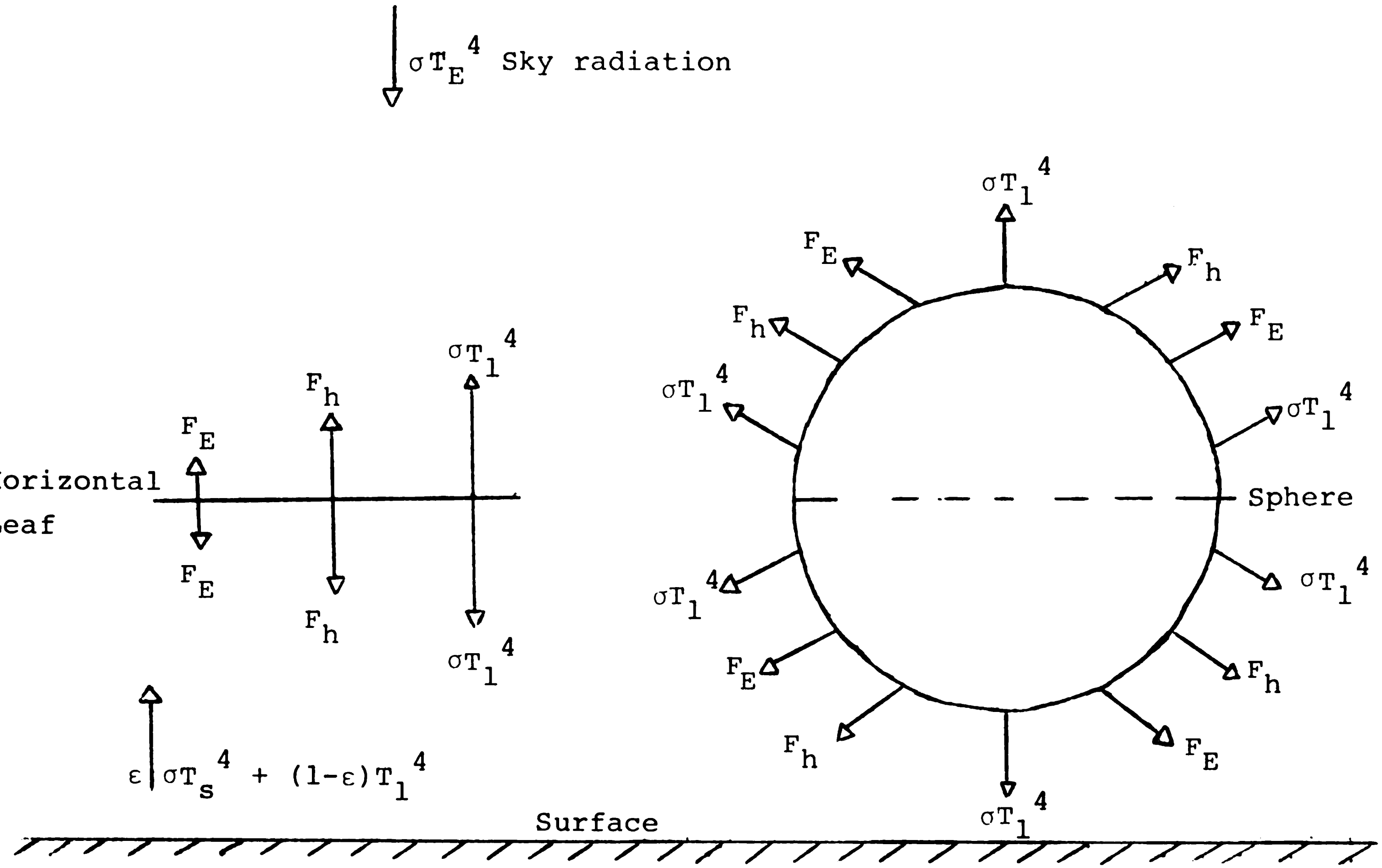


Figure 1. Schematic presentation of the energy flux densities emitted and received by a horizontal leaf and by a sphere. (Source: Businger, 1965)

a leaf's emissivity in the 10 μm region was .97 (Gates and Trantaporn, 1952). However, assuming that the leaf exhibits its black-body behavior for longwave radiation and maintains a uniform temperature, it will emit a radiative flux density of σT_l^4 in either direction, T_l being leaf temperature. Simplifying by setting the emissivity of the surface equal to one, the net radiation F_n above the leaf is:

$$(F_n)_{sky} = \sigma(T_l^4 - T_e^4) \quad (2.4)$$

and

$$(F_n)_{surface} = \sigma(T_s^4 - T_l^4) \quad (2.5)$$

Businger (1965) aptly describes the effective sky temperature (T_e) as the critical variable in the energy budget of the leaf or fruit. This parameter has been correlated with air temperature and/or relative humidity (Brunt, 1939; Goss and Brooks, 1956; Swinbank, 1963). The parameter may be mathematically defined by:

$$T_e^4 = \gamma T_a^4 \quad (2.6)$$

where T_a is the air temperature at screen height, and γ is a dimensionless coefficient of the ratio of longwave sky radiation to black-body radiation from the surface. It is occasionally referred to in the literature as "effective emissivity."

The downward longwave radiation has been estimated in the past by the construction of Elasser radiation charts for cloudless nights (Brooks, 1952). Researchers who have taken an in-depth look at longwave radiation from clear skies cite two reasons for not using the charts for agricultural purposes. They claim that detailed information of both the distribution of water vapor and temperature in the atmosphere is necessary, which cannot be approximated with sufficient accuracy from distant radiosonde observations (Gates, 1965; Goss and Brooks, 1956; Swinbank, 1963).

Consequently, many people have endeavored to express the intensity of longwave radiation received at the ground from a clear atmosphere. This was originally postulated as an exponential expression by Angstrom, but Brunt's expression was simpler and gained wide acclaim (Brunt, 1939):

$$R/\sigma T^4 = a + b\sqrt{e} \tag{2.7}$$

where R is the total longwave downcoming atmospheric radiation under a cloudless sky, T^4 is the outgoing black body radiation, and e is the mean monthly local vapor pressure in millibars.

Some reported values of constants in Brunt's nocturnal radiation equation for clear skies appear in Table 3. Many of the correlation coefficients are high, but there is a wide range in the values of a and b. This may be attributed to difficulties with instruments, variations of observational techniques, and the manner of specifying the vapor pressure. The Brunt formulation was later modified by assuming a fixed relationship between vertical optical depth of water vapor, and incorporating

TABLE 3

SOME REPORTED VALUES OF CONSTANTS IN
BRUNT'S NOCTURNAL RADIATION EQUATION FOR CLEAR SKIES

Researcher	Location			Correlation Coefficient	Range of e (mb)
Dines	England	0.52	0.065	0.97	7-14
Asklof	Sweden	0.43	0.082	0.83	2-4
Angstrom	Algeria	0.48	0.058	0.73	5-15
Boutaric	France	0.60	0.042	-	3-11
Ramanathan and Desai	India	0.47	0.061	0.92	8-18
Brunt	England	0.55	0.056	0.95	7-14
Anderson	Oklahoma	0.68	0.036	0.92	3-30
Angstrom	California	0.50	0.032	0.30	-
Eckel	Austria	0.47	0.063	0.89	-
Goss and Brooks	California	0.66	0.039	0.89	4-22

SOURCE: Goss and Brooks, 1956)

the pressure dependency of the absorption coefficients of water vapor and observed vapor pressure.

Further investigation by Swinbank (1963) revealed that R can be predicted "to a high degree of accuracy" from the low level air temperature alone. He examined the correlation between R and black-body radiation at the corresponding screen temperature T_a. Analyzing two different sets of observations over a range of temperatures and humidities, a correlation of 0.99 was found.

The correlation between R and σT_a^4 was also 0.99, and the regression equation he obtained was:

$$R = -17.09 + 1.195\ T_a^4 \qquad (2.8)$$

where R is in milliwatts cm^{-2} and T_a is in ^oK.

An alternative formulation which fits the observations with equivalent accuracy, and is better founded physically, is:

$$R = 5.31 \times 10^{-14}\ T_a^6 \qquad (2.9)$$

Either expression will provide an estimate of R in terms of T_a with an error of less than 0.5 mw cm^{-2}.

The emission of longwave radiation by the atmosphere is influenced by the 6.3 μm water vapor absorption bands. The total area under the black body distribution curve varies as the fourth power of the temperature; however, monochromatic emission varies with a higher power of the temperature for wavelengths shorter than the modal (peak), and with a lower power for wavelengths longer than the modal. The 6.3 μm water vapor absorption band is on the short wavelength side of the 300^oK black body spectral distribution, whose modal emission is at 10 μm. The strong temperature influence of this band shows that the dependence of the total emission of radiation by the atmosphere upon the sixth power of the temperature is reasonable from a physical standpoint.

In conclusion, the excellent correlation showing the dependence of R on T may be explained by the characteristics of the absorption spectra of water and carbon dioxide. Perhaps it is an indication that there is always enough water vapor in the lower troposphere to cause the water vapor bands to emit as black bodies. The component of R due to carbon dioxide, because of the intense absorption exhibited by the gas at atmospheric concentrations, will originate at a level close to the surface at a temperature very nearly equal to T_a. Therefore, the contribution of R from water vapor may be conceived as being a function of T_a. The depth of the surface layer that is necessary to contain sufficient water vapor to cause full radiation in the relevant wave bands may be shallow enough so as to differ very little from the surface temperature T_s.

Nevertheless, other observations of γ versus temperature seem to show lower correlations. In Figure 2, γ is plotted as a function of temperature for four sets of observations. There is a large scatter of points, supposedly due to variations in both temperature and humidity near the earth's surface.

It is important to note that relatively few observations were recorded in the vicinity of $0^{o}C$. (This was also true for Swinbank's data.) From this data, one may infer that γ would average about 0.7 for a typical freeze night. During most evenings, γ will gradually increase with decreasing temperature. This is also due to the relatively greater downward radiation as a response to the

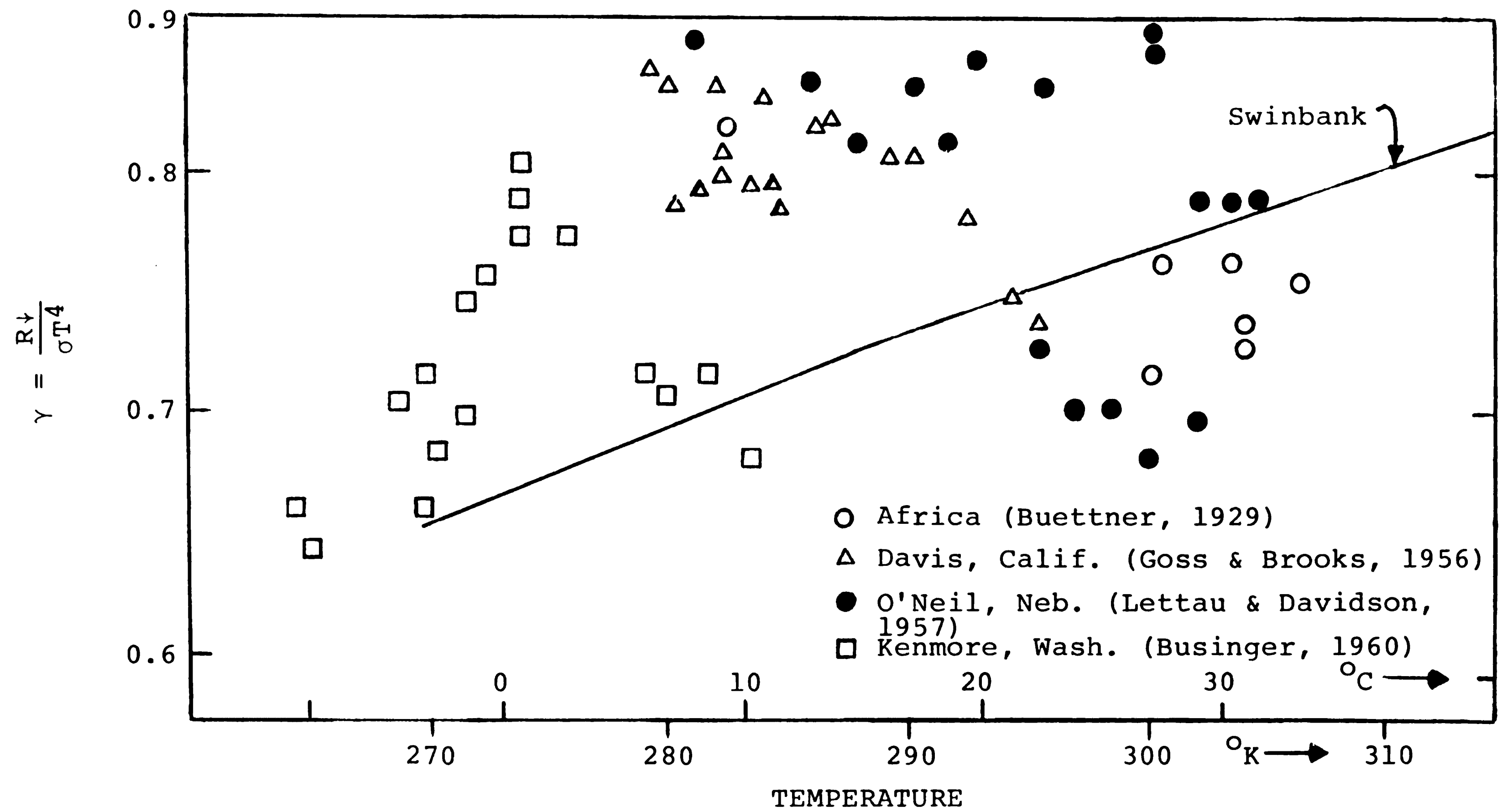


Figure 2. Ratio of long-wave sky radiation (R) to the black-body radiation σT^4 corresponding to air temperature as a function of air temperature at screen height. (Source: Businger, 1965)

vertical temperature gradient in the lower atmosphere.

2. Transfer of sensible and latent heat. Some degree of convection will always occur around leaves, regardless of the prevailing wind conditions. The sensible heat flux density to the air immediately surrounding the leaf may be expressed by:

$$F_h = h_t(T_l - T_a) \qquad (2.10)$$

where h_t is the coefficient of heat transfer, which depends upon wind speed, size, and shape of the leaf, T_a is the air temperature, and T_l is the leaf temperature (Businger, 1965).

The latent heat flux density may be similarly expressed by:

$$F_e = \frac{L\beta}{R_w T_a}(e_l - e_a) \qquad (2.11)$$

where L is the latent heat of vaporization, β is the coefficient of mass transfer, R_w is the specific gas constant for water vapor, e_l and e_a are vapor pressures at the leaf surface and of the surrounding air, respectively (Businger, 1965).

If the surface of the leaf is wet, the vapor pressure at the surface will be equal to the saturation vapor pressure at the leaf temperature. When this happens, both the coefficient of mass transfer β and coefficient of heat transfer h will be a function of wind speed and shape of the leaf. Therefore the ratio β/h will be constant for a range of temperatures and pressures used in the psychrometric equation (6.3×10^{-5} cm^2 $dyne^{-1}C$). The heat transfer coefficient is often incorporated in the dimensionless Nusselt number hd/k, and expressed as a function of Reynolds number vd/ν, where d is the effective leaf diameter, k is the thermal conductivity of the air, v is wind speed, and ν is the kinematic viscosity of the air.

3. Determination of leaf temperature. The energy balance of a leaf requiring freeze protection can be formulated theoretically by considering a single horizontal leaf (Figure 1). The derivation that follows is primarily due to Businger (1965), with additional information from Raschke (1960), Gerber and Harrison (1964), and Gerber and Martsolf (1979). A simple equation for the energy budget of a leaf may be stated by assuming that the temperature of the leaf is uniform, and that the heat capacity per unit horizontal area is C:

$$-(F_n)_{sky} + (F_n)_{surface} - 2F_h - 2F_e = C\frac{dT_l}{dt} \quad (2.12)$$

The leaf temperature has a controlling influence over each of the heat-transfer processes. Convection and conduction are proportional to the temperature difference between plant and environment; radiation loss in the infrared varies with temperature raised to the fourth power. The saturation vapor pressure of water is approximately an exponential function of temperature. Because of these relationships, the energy balance equation is transcendental; i. e., it cannot be solved as it stands.

Raschke (1960) initially solved the energy-balance equation by equating a linear function with a vapor-pressure function (exponential function), and graphically displaying each function in order to find the point of intersection, which gives the temperature of the leaf. Raschke (1960) found a quicker method to obtain the leaf temperature by invoking certain mathematical approximations in considering the temperature difference between the leaf and the air. The key assumption in applying this method is that the curves of the radiation and vapor pressure as a function of temperature (in a small range) can be approximated by their tangents at the T_a. Radiative transfer may be calculated by first assuming that the leaf and air temperatures are equal, and then incorporating a correction factor to account for the difference in leaf and air temperature. This consists of the product of the tangent of the radiation-temperature curve and the difference in leaf and air temperature. For differences in temperature of less than $5^{o}C$, the first term of a Taylor's series may be an adequate approximation to the tangent of the radiation-temperature curve (Gerber and Harrison, 1964):

$$R_N = R_{N(a)} - 2(dR_N/dT)(T_a - T_l) \qquad (2.13)$$

$$R_N = 2h_r(T_a - T_l)$$

$$h_r \equiv dR_N/dT = 4\sigma T_a{}^3$$

where h_r is the derivative of the Stefan-Boltzmann equation for radiative flux, and has the dimensions of a heat-transfer coefficient, and $R_{N(a)}$ is the radiative balance when the leaf temperature equals the air temperature.

Equation 2.12 is usually combined with equations 2.4, 2.5, 2.6, 2.10, and 2.11, yielding:

$$4\sigma T_a^3(\gamma T_a+T_s-2T_l) + 2h(T_a-T_l) + \frac{2L\beta}{R_w T_a}(e_a-e_l)$$
$$= C\frac{dt_l}{dt} \qquad (2.14)$$

The surface temperature is not measured very often; it will be a function of soil type, soil cover, heat capacity of the soil, and sky radiation. If the soil cover insulates well, T_s may be a function of the effective sky temperature, soil temperature, and thickness of the insulator.

4. *Required energy for cold protection.* The energy flux density F_p is the required energy necessary to maintain the leaf temperature at the minimum tolerable temperature T_m, which occurs when $dT_m/dt = 0$. This is expressed by equation 2.14 if we substitute e_m for the vapor pressure at the leaf surface, and T_m for the air temperature T_a. If equation 2.14 is subtracted from such an equation, we obtain:

$$F_p = 2(h_r+h)(T_m-T_l) + \frac{2L\beta}{R_w T_a}(e_m-e_l) \qquad (2.15)$$

Assuming that the vapor pressure of the leaf is saturated at air temperature, the difference between the vapor pressure of the leaf and the actual vapor pressure can be adjusted by adding the product of the temperature difference between leaf and air, and the tangent of the saturated vapor pressure-temperature curve at the average temperature. The Clausius-Clapeyron equation expresses the difference in vapor pressures between T_m and T_l (in approximate form):

$$e_m - e_l = \frac{L\bar{e}}{R_w \bar{T}^2}(T_m - T_l) \qquad (2.16)$$

where $\bar{e}$ is the average of e_m and e_l, and T_m may be used instead of $\bar{T}$. Therefore, equation 2.15 becomes:

$$F_P = 2(h_r + h + h_e)(T_m - T_l) \qquad (2.17)$$

where

$$h_e = \frac{L^2 \bar{e} \beta}{R_w^{\,2} T_m^{\,3}}$$

In the vicinity of $0^{\circ}C$, h_e is approximately equal to 0.46h, and h_r is approximately equal to 1.1×10^{-4} cal cm^{-2} sec^{-1}, and $C = 4.7 \times 10^{3}$ erg cm^{-2} $sec^{-1}C$ (Businger, 1965).

Fuchs and Tanner (1966) describe the method of infrared thermometry for obtaining the leaf temperature. This is one of the most accurate means to measure this parameter, because other methods depend entirely upon contact with the leaf surface. Instruments such as thermocouples, thermistors, and diffusion porometers suffer from the disadvantage that they must make contact with the leaf surface. Because the radiation load on each side of the leaf will be different at different temperatures, you may at best have only an average of the two surfaces, rather than a distinct temperature for the top of the leaf.

It is important to note that the factor 2 appears in equation 2.16 because the leaf has two surfaces. In dealing with a fruit bud which is spherical, the factor 4 should be used, as the surface of a sphere is four times its cross section (Businger, 1965).

Broadly speaking, four processes may be considered to provide the required energy F_p:

1. To prevent radiation loss through the use of man-made fog;

2. To utilize the release of the latent heat of fusion by sprinkling;

3. To heat the air surrounding the plants; and

4. To transport the warmer air available above the fruit crop into the immediate vicinity of the fruit.

The remainder of this section will deal with the last process, which is the action of wind machines to prevent damage to fruit crops.

C. The Action of Wind Machines in Freeze Protection. Wind machines have been used in California since the 1920s (Gerber and Busby, 1959), but have only been reported in Arizona since 1954 (Hilgeman et al., 1964), and in Florida since about 1960 (Reese and Gerber, 1969). They have also seen limited use in Washington and Idaho orchards (Ballard, 1976), Oregon (Bates, 1972), and British Columbia in Canada (Davis, 1977). To date, no studies of their effectiveness in Michigan have been published, although they have been in use since about 1950.

The objective here is to point out the salient features of these studies in order to interpret the results of the experiments at Texas Corners, MI conducted during 1978, 1979, and 1980.

The most crucial factor for the successful performance of a wind machine is the existence of a sufficient temperature inversion in the orchard or vineyard. These values are typically reported in terms of 5-50 foot inversions, or some other comparable range. Wind machines are only effective in the absence of wind (non-advective conditions), and, of course, when the actual temperatures that compose the profile are warm enough to potentially raise the leaf or bud temperatures above critical temperatures.

The primary role of the wind machine in freeze protection is to pull warm air available above the crop down to its growing level. Turbulence induced by the wind machine is also beneficial as it increases the turbulent transfer coefficient (h_t in equation 2.10) for the sensible heat flux towards the leaf or bud (which may be cooled below air temperature during radiative freezes). Although the physiology of freezing damage is beyond the scope of this thesis, it is generally accepted that partially frozen fruit are injured less if they thaw slowly. Therefore, if the wind machine is operated after sunrise, rapid warming that occurs from direct exposure to the sun may be slowed (Crawford, 1965). According to some of the Texas Corners observations, quite often a temperature inversion may exist for at least one-half hour past sunrise. Also, some fruit might not incur freeze damage due to its ability to sub-cool without destructive crystallization. Brooks (1947) speculated that the turbulence would minimize the temperature contrast between the exposed side and the shielded side of the fruit, and that this would enhance the possibility of subcooling without damage.

The protection pattern around a wind machine has often been reported to be roughly circular (Gerber and Busby, 1963; Bates, 1972; Crawford and Brooks, 1959; Crawford and Leonard, 1960). However, other protection patterns similar to a torus have also been reported in the literature (Brooks et al., 1951). This pattern was often observed to be elongated on the downdrift side and shortened on the updrift side.

Reese and Gerber (1969) utilized the most elaborate instrumentation system of any of the wind-machine trials conducted up until that time to study its protection pattern. They observed that the protected area was apparently kidney-shaped in many instances and not isothermal (Figure 3). This hypothesis was also borne out by observations in a Florida citrus grove (Reese and Gerber, 1963) as depicted in Figures 4, 5, and 6. The instrumentation layout in this study was quite unique in that it was designed to simulate the spokes of a wheel, using the machine tower as an axle. Many thermistors were mounted on 28 temperature towers at 5 and 20 feet, and on inversion towers at 5, 20, 35, and 50 feet. Sensitive cup anemometers were used at 5 and 20 feet, and were placed 100, 200, and 300 feet east of the wind machine. Signals from their thermistors were recorded on four Leeds and Northrup 20-point recorders to obtain a complete coverage of the temperature over the entire area every 80 seconds.

The typical air flow pattern was then verified by Reese and Gerber (1969) with the aid of smoke plumes from heaters. They noted an inward air movement immediately prior to the passage of the turning jet, which is where the depression appears in the isotherms. This was accompanied by an inward flow of air that moves parallel but opposite to the outward traveling jet.

Wind machines act to move warm air downward; in a reciprocal manner, it moves colder air inward from the surface in advance of the jet. As it pushes out a small pocket of air in the lower atmosphere, the air pressure

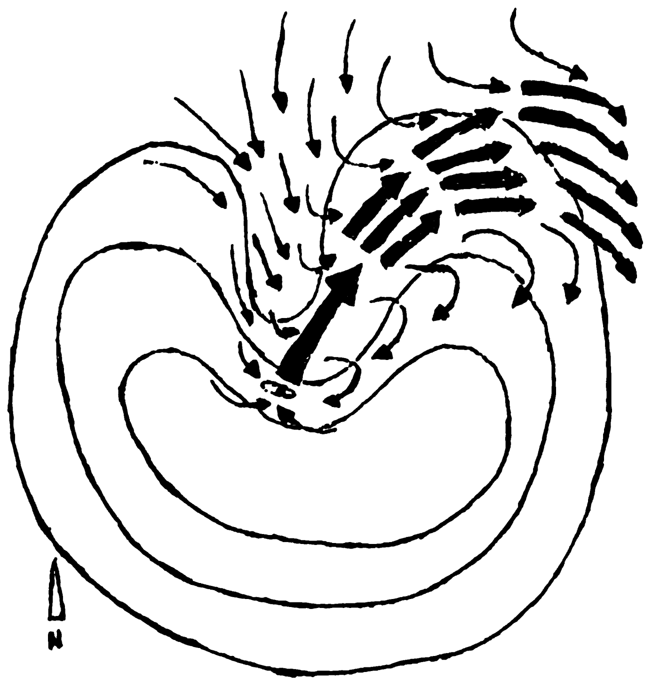
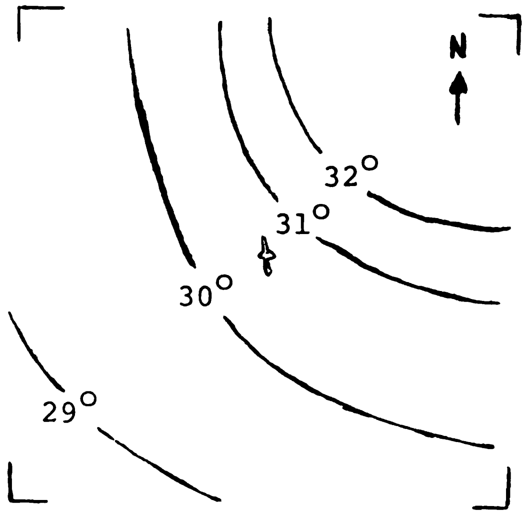


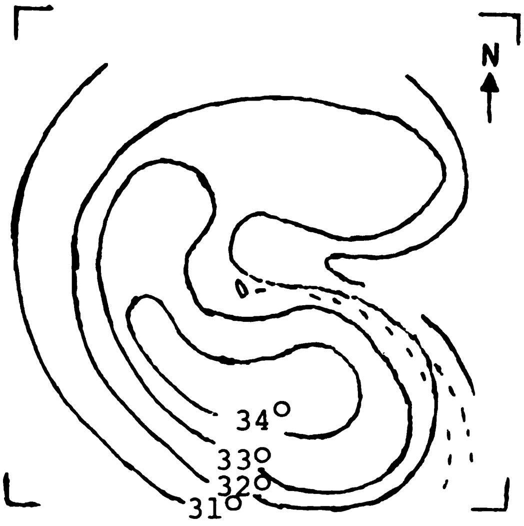
Figure 3. Typical air flow pattern showing direction of air movement around the turning jet based on visual observations and temperature patterns. (Source: Reese and Gerber, 1969)



Meteorological Data

Sky: Clear	Date: January 4, 1963
Wind: NNW 0-2 m. p. h.	Time: 2:25 a. m.
Inversion: 5-20 ft., 2.1°F 5-50 ft., 9.7°F	Square corners indicate boundaries of 10 acre test plot.
Check: 29.5°F	Trees foliated.

Figure 4. Isotherms at the 5-foot level before starting the wind machine. (Source: Reese and Gerber, 1963)



Meteorological Data

Sky: Clear

Wind: NNW 0-2 mph

Inversion: 5-20 ft., 3.1°F
5-50 ft., 6.9°F

Check: 29.0°F

Date: January 4, 1963

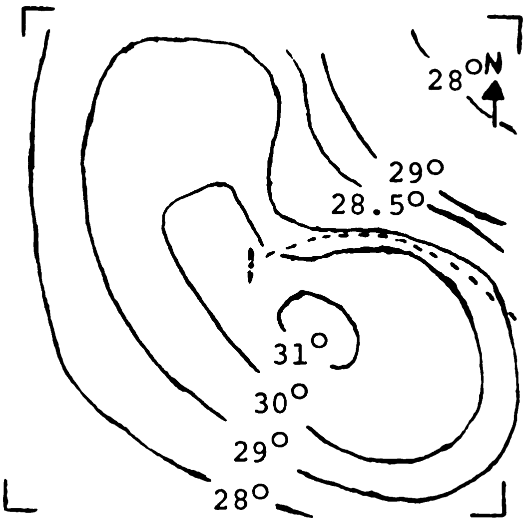
Time: 4:20 a. m.

Square corners indicate boundaries of 10 acre test plot.

Trees defoliated.

Dashed line is edge of turning jet.

Figure 5. Isotherms at the 5-foot level with the wind machine operating. (Source: Reese and Gerber, 1963)



Meteorological Data

Sky: Clear

Wind: W 0-2.5 mph

Inversion: 5-20 ft., 0.5°F
5-50 ft., 5.7°F

Check: 27.5°F

Date: December 11, 1962

Time: 12:20 a. m.

Square corners indicate boundaries of 10 acre test plot.

Trees foliated.

Dashed line is edge of turning jet.

Figure 6. Isotherms at 5-foot level with wind machine operating. (Source: Reese and Gerber, 1963)

is lowered surrounding the wind machine. This allows for warmer, less dense air to move into the area. The thrust of the turning jet was seen to maintain this pocket once it was formed by adding energy with each revolution of the wind machine.

Early attempts to articulate the adequacy of freeze protection by wind machines were mostly in terms of horsepower per acre. Using the micrometeorological aspects of a dry atmosphere, Ball (1956) showed that 1/4 horsepower per acre would mix a 100-foot layer. This estimate differed from some of the prior field data by nearly two orders of magnitude. The inconsistency of the field data may have occurred because the efficiency of the propeller in transmitting horsepower to the air was not taken into account. For a given thrust, the shaft power is inversely proportional to the propeller diameter (see Appendix B).

The most useful characteristic of a wind machine is the thrust. The reach of a wind machine will be determined mainly by its thrust and the pressure exerted by the wall of cold air which is trying to flow back into the protected area (Brooks et al., 1952).

Crawford (1962) discussed the concepts of power and thrust with respect to wind machines, and derived an equation for the area influenced by a slowly turning wind machine. This derivation involves fluid mechanical theory of the free air jet, and considers it to be geometrically and dynamically similar to an air jet produced by a nozzle. An important assumption in deriving the equation was that the lateral velocity profiles in a turbulent, axially-symmetric jet can be closely approximated by a normal distribution. The air jet must attain some minimum velocity before the turbulent mixing created by the wind machine can be effective, so the average cross sectional velocity was incorporated into the equation:

$$A = \frac{25}{u_a^2} \left(\frac{F}{\rho\pi}\right) \quad \text{(acres)} \qquad (2.18)$$

where A is the area influenced, u_a is the minimum value of average cross sectional velocity, and F is the thrust (kg). The constant 25 takes into account the ratio of the average velocity to the centerline velocity of a jet, as well as the decrease of centerline velocity with distance from the nozzle.

The average cross-sectional velocity (u_a) was defined to be the velocity necessary to cause a temperature rise in the orchard of 10 percent of the temperature inversion between five and fifty feet above the ground. Implicit in this definition is the frictional decay of the free-air jet by the ground surface and vegetation.

Table 4 gives the small amount of data available from field tests of wind machines that include the temperature inversion, temperature changes over a given area, and the thrust of a wind machine. Field tests later than 1964 (Reese and Gerber, 1969; Bates, 1972; Davis, 1977) either did not discuss thrust or did not use

TABLE 4

AREA OF OCCURRENCE OF A TEMPERATURE RISE OF AT LEAST 10 PERCENT OF THE INVERSION STRENGTH

Wind Machine Type	Orchard	Thrust, Pounds	Area, Acres	Reference
Under tree	Peaches	320	3.6	Crawford and Leonard, 1960
Under tree	Peaches	320	6.2	Crawford and Leonard, 1960
Under tree	Peaches	250	4.4	Crawford and Leonard, 1960
Under tree	Peaches	390	12.4	Crawford and Leonard, 1960
Under tree	Peaches	470	1.2	Crawford and Leonard, 1960
Tower	Prunes	1100	18.8	Goodall et al., 1957
Tower	Almonds	1050	19.1	Goodall et al., 1957
Tower	Citrus	1050	18.0	Brooks et al., 1952
Tower	Citrus	240	7.2	Brooks et al., 1952
Tower	Almonds	340	4.6	Rhoades et al., 1955

SOURCE: Crawford, 1964.

instrumentation sensitive enough to determine whether adequate mixing was occurring. These data are also summarized in Figure 7. A line of best fit was drawn through the data. Using equation 2.18 and $\rho = 1.29 \times 10^{-3}$ gm per cubic centimeter, a value of 112.8 centimeters per second was found for u_a from the slope of the line in Figure 7.

The amount of temperature rise that a wind machine will provide depends on the strength of the

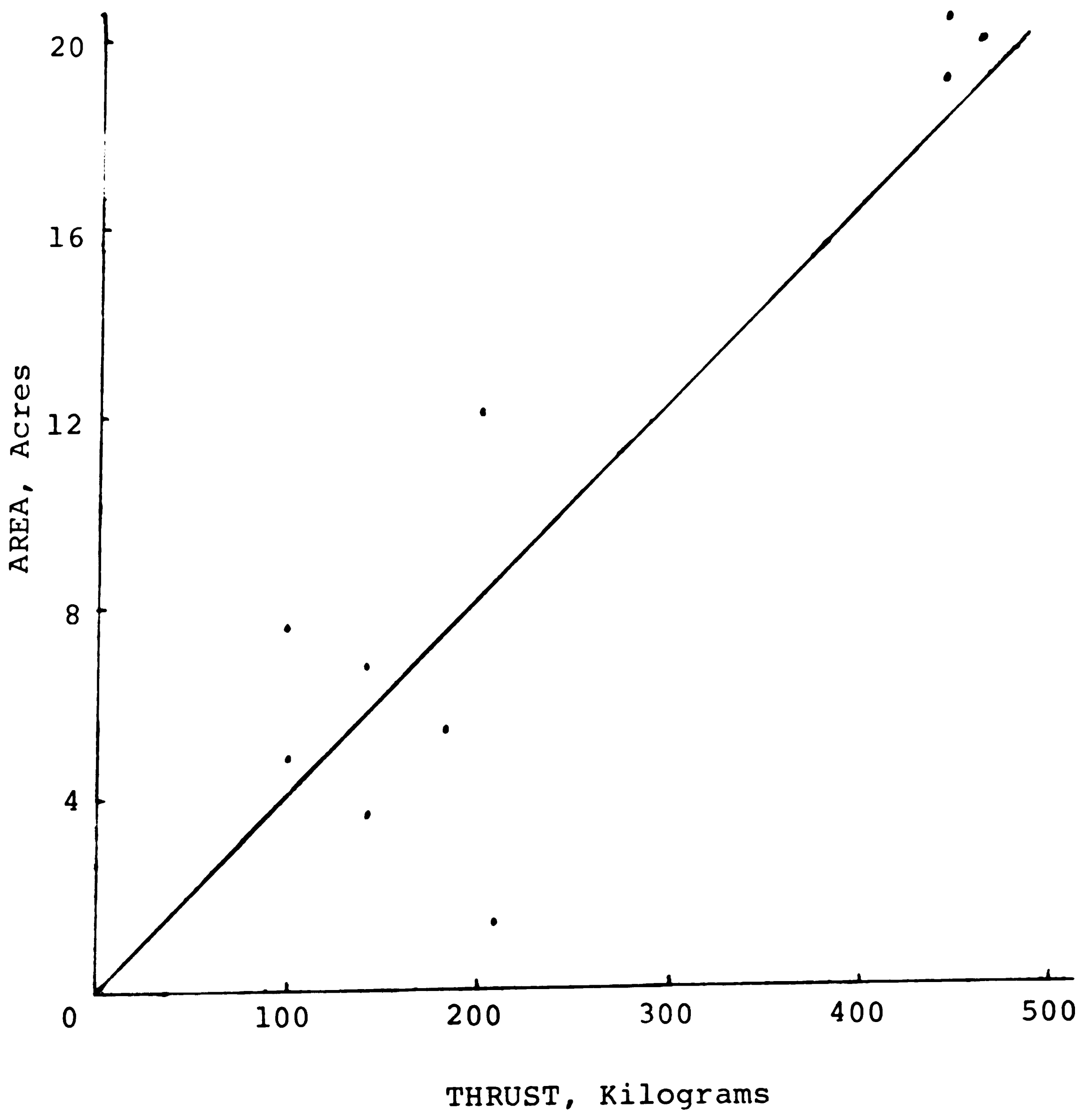


Figure 7. Area influenced by wind machines of different thrusts. (Source: Crawford, 1965)

inversion. The most comprehensive set of measurements relating the area of protection (resulting in a temperature rise of 1 through 4°F) that can be expected at various temperature inversions was discussed by Reese and Gerber (1969). These results are summarized in Figures 8 and 9 according to whether or not leaves were present in the orchard. The area of protection was found to be greater with weak inversions when leaves were absent (Figure 8). (The authors do not give any explanation for this result.) The two sets of curves gradually converged as the inversion strength increased. During the occurrence of large temperature inversions (8°F or more), the area protected in defoliated citrus trees became less than that found when leaves were present on the trees. The two sets of curves reported by Reese and Gerber (1969) differ because the presence of foliage increases the surface roughness, which in turn creates more eddies in the orchard. Although the jet will penetrate further without foliage, the turbulent mixing and therefore the degree of protection will be less.

Although Reese and Gerber (1969) discuss inversion strength as a function of wind speed, they seem to assume calm or very light winds in their figures. Thus, the results of Crawford and Leonard (1960) seem to fit their observations reasonably well, and are summarized in Table 5. Several other studies were reviewed for the purpose of adding data to this table (Crawford and Brooks, 1959; Brooks et al., 1951; Brooks et al., 1952; Brooks

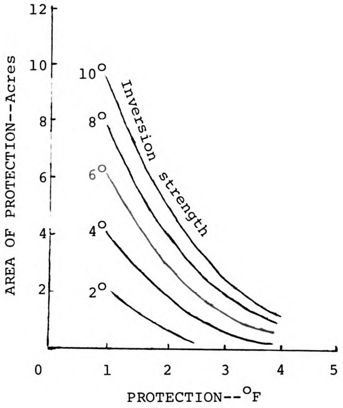


Figure 8. The area of protection of 1, 2, 3, and 4°F that can be expected at the indicated inversion strengths when leaves were not present on trees. (Source: Reese and Gerber, 1969)

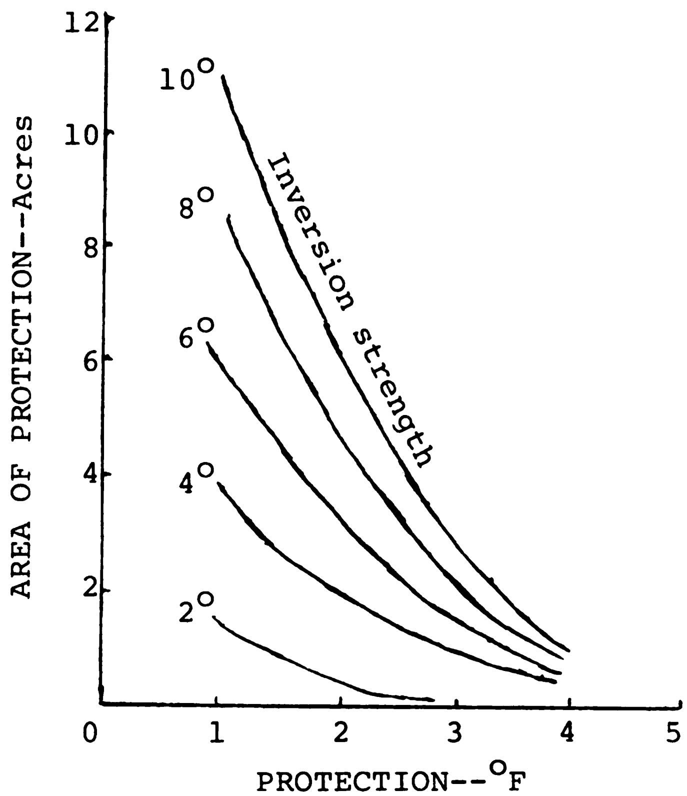


Figure 9. The area of protection of 1, 2, 3, and 4°F that can be expected at the indicated inversion strengths when leaves were present on trees. (Source: Reese and Gerber, 1969)

et al., 1953; Brooks et al., 1954; Rhoades et al., 1955). However, these results were not consonant with Crawford and Leonard's data, either due to the fact that inversions were recorded from 7 to 40 feet, or that the drift was not specified.

In Michigan, Van Den Brink (1968) reported observations of temperature inversions from the 5 to 60 foot level in the vicinity of Peach Ridge, near Sparta, Michigan. Table 6 summarizes the types of freeze, frequency, and associated temperature characteristics for the spring months 1963 through 1966. The magnitude of the temperature inversions that were encountered during radiative-type frrezes throughout the course of this study usually ranged between 4°F and 6°F.

TABLE 5

RESULTS OF SOME FREEZE PROTECTION TESTS IN CALIFORNIA

Date	Inversion 5'-50' (F)	Wind at 50' (mph)	Wind Machine Thrust (lbs)	Temp Rise (°F)	Min Temp (°F)	Areal Coverage (acres)
3/20/59	7.4	2.0	320	1.0	35	2.7
3/25/59	6.1	2.7	320	1.0	34	3.8
12/8/59	8.6	3.3	250	1.0	23	3.8
1/5/60	5.9	1.7	390	1.0	21	7.3

SOURCE: Crawford and Leonard, 1960

TABLE 6

TYPES OF FREEZES, FREQUENCY, AND ASSOCIATED TEMPERATURE CHARACTERISTICS (SPRING MONTHS, 1963 THROUGH 1966)

Minimum Temperature at 5-Foot Level	Factor[a]	Type of Freeze		
		Radiation	Advection	Advection-Radiation
32°F or lower	A	12	6	5
	B	52%	26%	22%
(23 cases)	C	5.3°	2.0°	4.0°
	D	27.9°	29.0°	30.1°
	E≤32°F	7.1	6.0	2.6
	F	53.4°	52.8°	62.0°
30°F or lower	A	8	5	3
	B	50%	31%	19%
(16 cases)	C	5.4°	2.2°	3.7°
	D	26.4°	28.6°	29.2°
	E≤30°F	6.7	3.9	1.8
	F	50.9°	52.8°	63.0°
28°F or lower	A	7	1	0
	B	87%	13%	-
(8 cases)	C	5.4°	0.0°	-
	D	26.1°	26.5°	-
	E≤28°F	4.7	5.0	-
	F	50.4°	51.0°	-
26°F or lower	A	3	0	0
	B	100%	-	-
(3 cases)	C	4.5°	-	-
	D	24.7°	-	-
	E≤26°F	4.7	-	-
	F	47.3°	-	-

[a]Factors:
A = Number of cases
B = Frequency
C = Average maximum inversion (°F), 5-60 ft.
D = Average minimum temperature
E = Average number of hours, temperature shown
F = Average previous day's maximum

SOURCE: Van Den Brink, 1968.

Gerber and Busby (1962) describe the turbulent mixing of a wind machine as observed by a captive balloon on nylon yarn. The duration of the turbulence will be a fraction of the time required for the machine to make one revolution, and was observed to extend 425 feet downwind and 300 feet upwind (Figure 10). From this data they hypothesize that reduced protection around the edge of a protected area is due to the shorter duration of the turbulence. No other observations of the decay of the turbulence with distance appear in the literature, but speculations abound. For example, Bates (1972) claims that a radius of 320 feet will be the limit at which protection should be expected, but that the turbulence was evident to about 650 feet. In an early study, Moses (1938) says that the effectiveness of a small machine decreases rapidly beyond 300 feet. Recommendations by Brooks et al. (1952) for spacing of several wind machines in a 40-acre citrus grove were that they should be 600 to 800 feet apart.

D. Empirical Minimum Temperature Forecasting Formulas. According to Sutton (1953), Kammerman's rule was the predecessor of many rules for forecasting the minimum temperature. This rule appeals to the principle that the amount of water vapor in the air controls the radiative heat loss. The nocturnal minimum temperature is established by subtracting a constant number of degrees from a previously determined wet-bulb temperature.

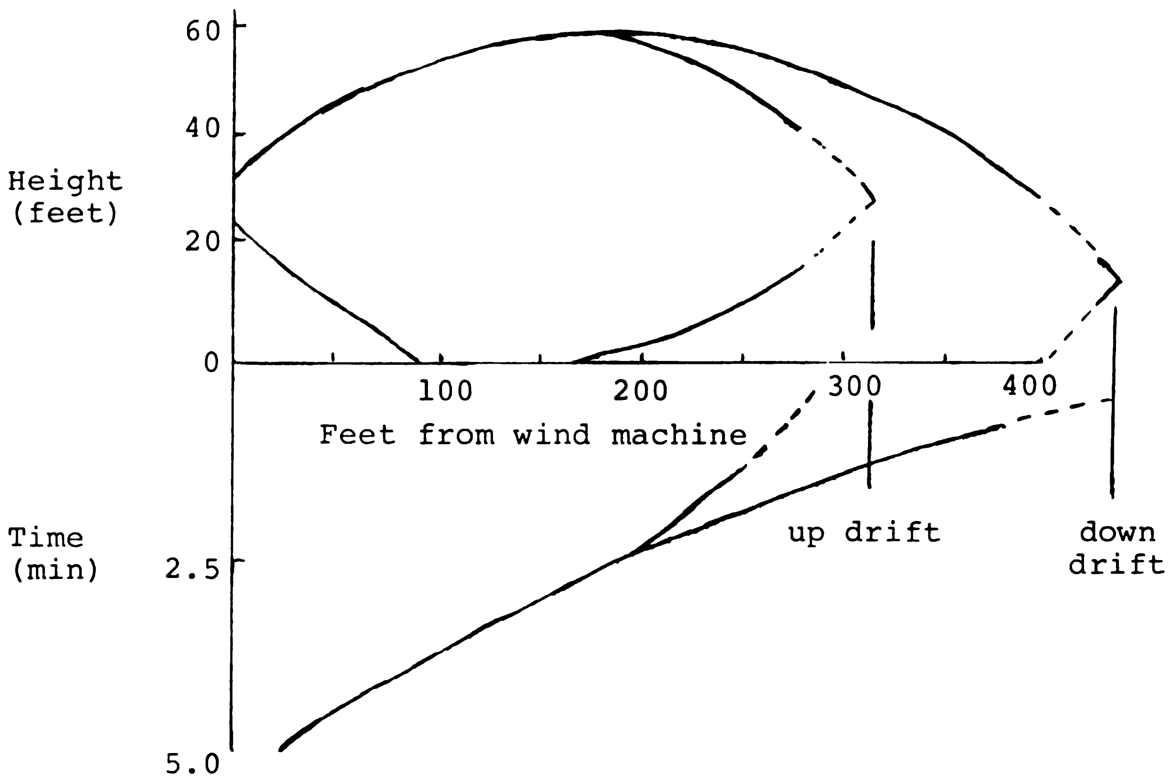


Figure 10. Extent and duration of turbulence created by the wind machine. (Source: Gerber and Busby, 1962)

Subsequent investigations revealed that better results were obtained when both the wet-bulb and dry-bulb temperature were taken into account. The physical parameters that are common to the formulation of these empirical relationships are: dry-bulb temperature, wet-bulb temperature, dew point, wind speed, and cloud cover.

Bagdonas et al. (1978) extensively reviewed many empirical and theoretical techniques of minimum temperature forecasting. Cold damage to fruit and crops in the far western regions of the United States sparked interest in developing local temperature forecasting formulas by analyzing data statistically. After the factors to be correlated have been selected, the actual construction of the minimum temperature formulas is similar. A scatter diagram is prepared by plotting one factor against another, and a line of "best fit" is then determined.

An average moisture content of the soil surface is usually assumed in the construction of these formulas. An extreme condition in soil moisture is an important factor in minimum temperature forecasting, particularly when a hygrometric formula is applied. The minimum temperature will be lowered or raised, depending on whether an abnormally dry or rain-soaked soil exists.

Ellison (1928) discusses empirical formulas which were designed to evaluate the minimum temperature from factors which can be assigned definite values in the early evening. These formulas may be placed into three groups:

Group 1: $y = f(Y)$

Group 2: $y = f(d)$

Group 3: $y = f(d) + f(h)$

The following mathematical conventions will be used throughout the remainder of this discussion:

y is the minimum temperature

d is the dew point at an afternoon observation

n is a number deduced from study of data

V_d is a number depending on d

V_h is a variable depending on h

Formulas in Group 1. The "median-hour" relationship uses the midpoint of the daily temperature range to predict the minimum temperature. The temperature at the time of the median is subtracted from the maximum temperature, and the remainder is the fall that will occur between the median and the minimum temperature (Beals, 1912).

One type of night which often occurs with ideal freeze conditions is when the dew point approaches or reaches the air temperature near the median hour, in which case the median-hour relationship should not be used to predict the minimum temperature.

Another rather infrequent case in which this formula would not apply is the "advective-radiative" freeze. This situation is defined to be the occurrence of frost at night following the passage of a cold front, which is often preceded by a cloudy afternoon.

A rapid drop in air temperature in the early evening is often accompanied by local winds, e. g. mountain and valley winds, and this will cause the temperature to fluctuate over short intervals. This formulation suffers from the fact that the instantaneous temperature at the median hour is affected by local conditions.

The time of occurrence of the median hour in many areas of the country is so late that it is not practical to use the formula in the preparation of forecasts.

The "post-median hour" relationship consists of recording the difference between the maximum temperature and the 10 p. m. air temperature, and taking this to be two-thirds of the difference between the maximum and minimum air temperature (Thomas, 1912). This formula is also not practical because of the lateness of the post-median hour.

The "pre-median hour" method establishes the temperature fall in the early evening. This technique is used by the forecaster to predict the median-hour temperature by extrapolation (Alter, 1920). Although this allows for an earlier approximation of the minimum temperature than by the median-hour method, it is subject to more error.

A "daily temperature range" method was formulated by Smith (1914) in which the mean, greatest, and least daily temperature ranges were compiled for semi-monthly periods. These values are used to forecast the minimum temperature once the maximum temperature is known.

Formulas in Group 2. Humphreys (1914) proposed an "evening dew point" relationship in which the temperature is assumed not to fall below the coincident dew point. The minimum temperature is predicted to equal the evening dew point.

Meteorological records from fruit-frost work show that this relationship will only work consistently for stations that are elevated. The minimum temperature is often 8^{o}F to 10^{o}F lower than the evening dew point (Ellison, 1928).

Keyser (1922) proposed the "wet-bulb minimum temperature" method in which the average difference between the wet-bulb temperature at 5 p. m. and the minimum temperature was subtracted from the current 5 p. m. wet-bulb temperature to establish a forecast minimum. Similarly, Smith (1920) correlated the difference between the evening temperature and dew point with the difference between the evening dew point and ensuing minimum temperature. Nichols (1926) devised the "depression of the dew point below the maximum temperature" method, in which the maximum temperature minus the evening dew point is correlated to the difference between the maximum and minimum temperature.

However, Ellison (1928) points out that all of the formulas in the previous paragraph are in error. Under the assumption of constant dew point, the wet-bulb formula implies constant relative humidity. Also, the depression of the evening dew point is a pure number which may correspond to widely differing values of absolute humidity or air temperature.

Formulas in Group 3. The hygrometric formulas rely upon the concept that the minimum temperature will be greater than or less than the evening dew point by an amount related to the relative humidity. Most of the literature on minimum temperature formulas, especially since 1930, has dealt with formulas of this nature.

Ellison (1928) reports that the first hygrometric relationship was put forward by Donnel in 1910, while working on Boise, Idaho freeze records:

$$y = d - \frac{h - a}{b} \tag{2.19}$$

where a and b are constants derived from the data. Smith (1917) used linear regression, and expressed his hygrometric formula as:

$$Y_{m-d} = a - bh \tag{2.20}$$

where Y_{m-d} is the difference between the minimum temperature and the evening dew point.

The first application of a curvilinear form of the hygrometric formula is due to meteorologist Floyd Young (1920), to whom much fruit-freeze forecasting work can be attributed. His equation was:

$$y = d - \frac{h - n}{4} + V_d + V_h \tag{2.21}$$

where n = 20, 30, or 40 for clear, partly cloudy, or cloudy skies, respectively.

Smith (1920) fit parabolic curves to the hygrometric data, by suggesting an equation of the form:

$$Y = a + bh + ch^2 \tag{2.22}$$

Nichols (1920) felt that it was not necessary to use mathematical curves to fit the hygrometric data, and suggested that:

$$y = d + V_h \tag{2.23}$$

After examining all of the empirical formulas, Ellison (1928) concluded that the hygrometric types were best. This conclusion was more recently borne out by Kangieser (1959), who compared several empirical formulas for clear nights in an arid region. Sutton (1953) remarked that the hygrometric equations worked very well when applied by meteorologists with a good knowledge of local conditions. The Frost Warning Service of the National Weather Service has employed hygrometric formulas very successfully for about 40 years (Bagdonas et al., 1978).

One empirical relationship for forecasting the minimum temperature deviates from the hygrometric, median temperature, and maximum-minimum concepts. Georg (1970) devised the "semi-objective radiometer technique," which implicitly establishes a relationship between the nocturnal net radiation and the air temperature at screen height. The radiating temperatures of two black copper plates, one facing the sky (T_t) and one facing the ground (T_b), are observed two hours after sunset. A scatter diagram of T_b-T_t vs. T_b-T_m is obtained, and two best-fit lines are computed for nights when $T_t \leq 0^oC$ and $T_t \geq 0^oC$. The predictive equations are then used to forecast T_m. It is crucial that instrumental error be minimized to insure the quality of these objective forecasts. The economical net radiometer (Suomi and Kuhn, 1958) was chosen by Georg (1970) because it is shielded from advective heat transport by transparent polyethylene, and is ventilated to prevent dew and frost deposition. Among the assumptions that are made when employing this technique is that cloud cover and wind do not change dramatically throughout the course of the evening, and that the top sensor of the instrument is evaluating the effective radiating temperature of the sky.

E. Semi-Empirical and Theoretical Minimum Temperature Forecasting Formulas. Consideration of heat-transfer laws has shown that the temperature of the earth's surface at night very closely parallels the air temperature in the boundary layer. This assumption has allowed for the development of several semi-empirical and theoretical techniques for predicting the nocturnal minimum air temperature, spanning three decades from 1920 to about 1950.

Brunt's (1941) theoretical solution of the nocturnal cooling of the earth's surface is often quoted in the literature as an approximation of the nocturnal air temperature on clear, calm nights. The equation that he developed, assuming the earth radiates as a black body, is:

$$\Delta T = \frac{2}{\pi} \frac{T_s^{\,4}(1 - a - b\sqrt{e})}{\rho_s \, C_s \, K_s} \quad \sqrt{t} \tag{2.24}$$

where:

ΔT is the fall in temperature at the ground surface from sunset to sunrise (^oK)

σ is the Stefan-Boltzmann constant (7.92×10^{-11} cal $cm^{-2}(^oK)^{-4}$ min^{-1})

T_s is the sunset temperature of the earth's surface (^oK)

e is the vapor pressure in the atmosphere (mb)

t is the time interval in hours and tenths of hours beyond zero on the time scale which is taken as the time of sunset

ρ_s is the density of the soil (1.6 g cm^{-3})

C_s is the specific heat of the soil (0.18 cal g^{-1} $^oC^{-1}$)

K_s is the thermal diffusivity of the soil (cal deg^{-1} cm^{-1} sec^{-1})

a and b are constants derived from the data

This equation essentially models the situation in which the heat flux density outward from the earth's surface by radiation is constant throughout the night, and is equal to the heat flux density from below the surface. Brunt derived his equation by solving the Fourier heat conduction equation

$$\partial T/\partial t = K_s \; \partial^2 T/\partial^2 Z \tag{2.25}$$

with the assumptions:

1. The initial temperature distribution in the soil is isothermal (T (Z,0) = the sunset temperature of the soil surface).

2. The eddy conduction of heat from the air to the earth's surface is equal to zero.

3. The flux of heat to the earth's surface due to condensation processes is equal to zero (assuming no dew or frost).

When developing his equation, Brunt assumed one specific conductivity of heat for the surface layers of the earth.

Reuter (1951) is credited with extending Brunt's equation to include eddy conductivity in the air, and the variation of temperature with depth in the soil. The semi-empirical method that he developed was:

$$\Delta T = \frac{2}{\pi} \frac{R_{n(o)} + \lambda\frac{dT}{dZ} + (\Gamma_s - \Gamma)^{C_a A_e}}{\sqrt{K_s \rho_s C_s} + C_a\sqrt{A\rho}} \sqrt{t} \qquad (2.26)$$

where:

$R_{n(o)}$ is the net radiation from the soil surface (cal cm^{-2} min^{-1})

λ is the coefficient of thermal conductivity of the soil (cal deg^{-1} cm^{-1} sec^{-1})

dT/dZ is the change of temperature with depth in the soil (^{o}K/100 cm)

Γ_s is the lapse rate of temperature in the air at sunset (^{o}K/100 m)

A_e is the coefficient of eddy conductivity in the air (m/sec)

C_a is the specific heat capacity of the air (J g^{-1} $(^{o}K)^{-1}$)

Γ is the dry-adiabatic lapse rate (^{o}K/100 m)

and all other symbols are as defined for equation 2.18

Several other modifications of the Brunt formula endeavor to create a theoretically more vigorous solution. They have addressed the effect of wind on nocturnal cooling, net radiation as an explicit function of time, and the contributions of both the air and soil to the heat radiated from the earth's surface. To include wind in models of nocturnal cooling, eddy transfer coefficients were defined whose magnitude varied with height above the ground. However, it is not a sound practice to establish values of the eddy conduction of heat in an airflow characterized by an unpredictable degree of turbulence. Cooling formulas in which net radiation is not constant do not give significantly different results for time periods on the order of a night (Georg, 1971). Finally, equations that have included a conductivity parameter involving properties of both air and soil are so complex that they have no practical meaning.

The constants in forecasting formulas are affected by local conditions, such as topography, cultural practices, nature of the vegetation, and stage of plant growth. Thus, the constants will vary with respect to time for any location.

The theoretical formulas, in addition to the above limitations, are particularly sensitive to the type and condition of the soil. Georg (1971) states: "The soil constants in formulas of the Brunt-Groen type vary both spatially and temporally because of the nature and state of the soil surface layers and changes in the water content of the soil." Assuming average values of the soil constants, i. e., thermal conductivity, is not practical because it will change dramatically with small changes in water content.

F. Current Techniques of Minimum Temperature Prediction. Bagdonas et al. (1978) discuss minimum temperature forecasting formulas that are currently being used in 14 nations. References will be cited mainly from this survey to discuss some of the present-day forecasting techniques, according to the following categories: hygrometric, graphical, Brunt-Reuter, and multiple regression.

Hygrometric approach. The Mendoza area in Argentina is an important growing region. The central forecast station in Buenos Aires uses a hygrometric formula to predict the minimum temperature throughout this region. Linear regression was employed to develop a predictive equation for T_m from T_w, which is the 1800 GMT wet-bulb temperature:

$$T_m = a + bT_w \tag{2.27}$$

where a and b are constants derived from the data.

A correction factor was developed by segregating data into five different synoptic patterns known to produce frost in the Mendoza area. (An important criterion in distinguishing between the different synoptic patterns is the expected wind speed.) Data were then analyzed separately for each pattern, with the end result being a total correction C_1:

$$C_1 = \overline{\Delta T} - \sigma_y\sqrt{1 - r^2} \tag{2.28}$$

where $\overline{\Delta T}$ is the difference between the mean value for a given location and the reference forecast point, σ_y is the standard deviation of T_m, and r is the correlation coefficient between T_m at the reference forecast point and the given location.

Graphical approach. The Canadian Department of Transportation (Meteorological Branch, Toronto) has developed a technique to forecast the minimum temperature on clear nights in Hamilton, Ontario, during May. The focal point of this technique is an indirect quantitative measure of the soil heat flux in the nocturnal cooling process. This is accomplished by assuming that the difference between maximum air temperature (T_x) and the normal temperature of western Lake Ontario is roughly analogous to the difference between temperatures at the soil surface and several centimeters below. They gathered data to construct a scatter diagram of:

$$(T_x - T_{LAKE}) \text{ vs. } (T - T_d)_{1330 \text{ EST.}} \tag{2.29}$$

Values of ΔT (maximum minus minimum temperatures) were then marked beside each point and plotted, and best fit isopleths constructed. Predictions from these graphs were then modified by adding a wind correction factor based upon estimated surface wind speed at 0730 EST.

Brunt and Reuter's formulas. These formulas have received wide use in the prairie areas of Canada. Eley (cf. Bagdonas, 1978) applied some simplifying assumptions in Reuter's formula, and gathered historical data to construct nonograms for a graphical solution:

$$\Delta T_o = \frac{2}{\pi} \frac{E}{\sqrt{C_s \rho_s K_s} + C_p\sqrt{A}} \sqrt{t} = F \cdot E\sqrt{t}$$

An empirically derived equation for net-outgoing radiation (E) as a function of surface temperature and vapor pressure was found, and Reuter's assumption of $A = 65\ \bar{U}$, where $\bar{U}$ is the mean wind speed (mph), was applied. The quantity $\sqrt{C_s \rho_s K_s}$ was also determined empirically by observing ΔT_o for radiative nights. This quantity averaged 0.290 cal C^{-1} cm^{-2} $min^{-½}$. One nonogram of F•E corresponding to relative humidity and sunset temperature, and another nonogram to obtain ΔT_o from F•E for any date from April through September were constructed.

Kagawa (cf. Bagdonas, 1978) rearranged Brunt's formula to make $C = \sqrt{C_s \rho_s K_s}$ the dependent variable, and recorded values for C from field studies. The mode in the distribution of C was chosen, since the quantity exhibited a wide range. He followed Reuter's procedure to calculate $S(O)_n$, the flux of terrestrial radiation with n tenths of clouds:

$$S(O)_n = S(O)_o\ (1-K_n) \qquad (2.31)$$

where K_n is a constant according to cloud type: 0.031 for cirrostratus, 0.063 for altostratus, 0.085 for stratus, and 0.099 for nimbostratus.

The assumption of constant soil parameters for any locality allowed Kagawa to simplify Brunt's formula:

$$T = C \cdot S(O)_o \cdot 2.03\sqrt{t} \qquad (2.32)$$

Brunt's formula has been used in the Florida peninsula for at least 10 years. Recently, researchers in this region have sought to improve this method by determining the thermal diffusivity for soils of varying water content. Where this is inconvenient, an approximate thermal diffusivity may be determined graphically from soil temperature profiles and the classical heat conduction equation, where $K = K_s/\rho_s C_s$.

Multiple-regression equations. Wallis and Georg (cf. Bagdonas et al., 1978) derived multiple-regression equations for 300 fruit-frost temperature survey stations in groves and fields on the Florida peninsula. The procedure was to correlate the minimum temperature at each fruit-frost station with the minimum temperature at three "key" stations, using 40 nights over a three-year period during winter. The minimum temperature for the nights chosen was 2.2°C or lower somewhere on the peninsula. A total of 14 "key" stations are maintained by the National Weather Service or Agricultural Experiment Station of Florida.

In Canada, Yacowar (cf. Bagdonas et al., 1978) derived a complex set of multiple-regression equations where maximum and minimum temperature were dependent variables, e. g. atmospheric parameters at the surface, 850 mb, and 500 mb. This procedure is limited to use at the larger meteorological centers, which would disseminate the information to local forecasters.

Jensensius et al. (1978) of the Techniques Development Laboratory, National Oceanic and Atmospheric Administration, also derived multiple linear regression equations to forecast maximum and minimum air temperature out to 132 hours, and probability of precipitation amount out to 84 hours for agricultural weather stations in Michigan (see Table 7). Minimum relative humidity and maximum and minimum soil temperatures 4 inches beneath bare and grassy surfaces were also projected for stations in Indiana. The prediction equations were developed by determining statistical relationships (i. e., how much each included parameter reduced the variance) between local weather observations and the output from the six-layer Primitive Equation (PE) model. The predictors in the maximum/minimum air temperature equation are: 1000-850 mb thickness, 1000-700 mb thickness, 1000-500 mb thickness, 850 mb temperature (the best predictor for minimum air temperature), 500 mb height and temperature, boundary layer and mean relative humidities, number of hours of sunshine, and daily insolation at the top of the atmosphere. The mean absolute errors for the resulting minimum temperature forecasts in Michigan are included in Table 8.

Soderberg (1969) devised a minimum temperature forecasting scheme for agricultural weather stations in

TABLE 7

AGRICULTURAL WEATHER STATIONS IN MICHIGAN
USED IN TDL* AGRICULTURAL FORECAST GUIDANCE

1. Arcadia (Beulah)
2. Belding
3. Coldwater
4. Edmore
5. Empire
6. Fennville
7. Fremont
8. Glendora
9. Graham
10. Grand Junction
11. Grant
12. Holland
13. Hudsonville
14. Kent City
15. Kewadin
16. Lake City
17. Lake Leelanau
18. Ludington
19. Mapleton
20. Mears
21. Michigan State University Hort. Farm
22. Nunica
23. Onekama (Bear Lake)
24. Paw Paw
25. Peach Ridge
26. Sodus
27. Watervliet

SOURCE: Jensensius et al., 1978

*Techniques Development Laboratory, NOAA, U. S. Department of Commerce

TABLE 8

MEAN ABSOLUTE ERRORS FOR THE MINIMUM AND MAXIMUM AIR TEMPERATURE MODEL OUTPUT STATISTICS EQUATIONS WHEN TESTED ON ONE GROWING SEASON OF INDEPENDENT DATA (APRIL-OCTOBER, 1976)

Type of Equation	Approximate Forecast Projection (hours from 0000 GMT)											
	12-36				36-60				60-84			
	MOS[a]	Pers[b]	Clim[c]	Mod[d]	MOS[a]	Pers[b]	Clim[c]	Mod[d]	MOS[a]	Pers[b]	Clim[c]	Mod[d]
Maximum Air Temp.	3.14	5.99	7.22	3.37	3.70	8.07	7.22	3.98	4.42	8.30	7.22	4.80
Minimum Air Temp.	3.88	6.38	7.17	4.00	4.37	8.48	7.17	4.61	5.25	8.77	7.17	5.45

SOURCE: Jensensius et al., 1978

NOTE: Also included are the mean absolute errors for persistence, climatology, and a modified forecast based on the mean error of the past three 12-36 hour. The minimum air temperature equations are valid from late afternoon until approximately 7 a.m. local time the next morning. All of the errors for temperature equations are in ^{o}F.

[a]Model Output Statistic

[b]persistence

[c]climatology

[d]modified forecast based on past three 12-36 hour forecasts

western Michigan. This method combines a graphical and hygrometric approach in which mid-afternoon air temperature, dew point, and cloud cover were used to predict the nocturnal minimum temperature at Grand Rapids, Michigan. Using Grand Rapids as a reference point, minimum temperature predictions were made for 25 agricultural weather stations in Michigan by adding or subtracting the average minimum temperature difference. (This data is grouped according to radiative and advective nights.) The mean absolute error in forecasting the Grand Rapids minimum temperature was 2.5^{O}F.

METHODS AND DATA COLLECTION

1. Freeze Climatology

Of the 27 agricultural weather stations used in the TDL agricultural forecast guidance (Jensensius et al., 1978), several of the agricultural weather stations were rejected for this study on the basis that they had to be moved to significantly different microclimates. For each of the 17 agricultural weather stations that were selected, the mean dates for each of the temperature thresholds were generated over the period 1950 through 1979. A computer program developed by the National Climatic Center (NCC) and modified by Dr. F. V. Nurnberger of the Michigan Weather Service, Michigan Department of Agriculture, was utilized in computing dates of 5, 10, 25, 50, 75, 90, and 95 percent chance of temperature occurrence. The normal frequency distribution was chosen to compute the dates of these events (Thom and Shaw, 1958).

The density function for a normal random variable Y is

$$f(Y) = \frac{1}{\sqrt{2\pi}\ \sigma} \exp\left[-\tfrac{1}{2}\left(\frac{Y-\mu}{\sigma_n}\right)^2\right] \qquad -\infty \leq Y \leq +\infty \quad (3.1)$$

where μ and σ_n, the two parameters of the normal distribution, are the mean and standard deviation, respectively. The sample mean and sample standard deviation are

$$\overline{Y} = \frac{\sum_i Y_i}{n} \qquad (3.2)$$

$$S = \left[\frac{\sum_i (Y_i - \overline{Y})^2}{n - 1}\right]^{1/2} \qquad (3.3)$$

where n is the number of observations in the sample. These two parameters were computed for each station for the spring and fall, as well as the estimated standard deviation of the sampling distribution of $\overline{Y}$,

$$S(\overline{Y}) = \frac{S}{\sqrt{n}} \qquad (3.4)$$

As previously reported in Michigan Freeze Bulletin (1965), the sample variances (S^2) for long-term climatic stations in Michigan were assumed to be equal for all stations. To obtain dates for the various probability levels at the different temperature thresholds, the authors used the 50 percent probability level (mean date) in conjunction with the average standard deviation, 11.48 days for spring and 12.86 days for fall. The freeze program that was employed in this study, however, calculated the individual sample variances.

The confidence interval for μ (the mean frost date), with a confidence coefficient of $1 - \alpha$ (probability level), is

$$\overline{Y} - Z(1 - \alpha/2;n - 1)\ S(\overline{Y}) \leq \mu \leq$$
$$\overline{Y} + Z(1 - \alpha/2;n - 1)\ S(\overline{Y}) \qquad (3.5)$$

In order to establish the 30-year climatology of the chosen agricultural weather stations, it was necessary to estimate freeze dates from the established climatic network. The statistical technique of linear regression was employed to compare agricultural stations to nearby long-term climatic stations. In this manner, predictive equations for minimum temperatures were obtained in order to establish the appropriate freeze dates. The slope and the y-intercept of the resulting regression equations were computed, along with the sample correlation coefficient r:

$$r = \frac{\Sigma(x_i - \overline{x})(y_i - \overline{y})}{[\Sigma(x_i - x)^2][\Sigma(y_i - \overline{y})^2]} \qquad (3.6)$$

In many instances, several correlations were attempted with surrounding stations, and the station exhibiting the best correlation was chosen.

The average length of the growing season was also computed for each station at the various temperature thresholds. This statistic represents the average number of days between the last date of a given temperature occurrence in the spring and the first date of that same temperature occurrence in the fall.

2. Vineyard Data Collection

The primary objective of this field study was to establish the existence and magnitude of nocturnal temperature inversions in southwestern Michigan vineyards. Two vineyards in Texas Corners were chosen because they are relatively flat in comparison with others in the area, e. g. Paw Paw, Lawton, or Mattawan. Temperature inversions were recorded during the springs of 1978 and 1979 in the vineyard formerly owned by Mr. Del Kellogg, and were also recorded during the spring of 1980 in the vineyard owned by Mr. Peter Dragecivich and maintained by Mr. Max Miller. Both vineyards are located on South 6th Street about 10 km southwest of downtown Kalamazoo.

Copper-constantan thermocouples were mounted at six different heights on an instrumentation tower. Temperatures in degrees Fahrenheit were recorded by a null balance self-balancing Leeds and Northrup potentiometer in the Kellogg vineyard, and by a Kaye Instruments digital potentiometer in the Miller vineyard.

Temperature inversions were monitored because their existence is essential to the successful operation of wind machines. Ground truth data were gathered during a wind machine trial which included ambient temperatures within the Miller vineyard before and during the wind machine operation, bud temperatures, and wind drift within the Miller vineyard before the wind-machine operation.

Temperatures were monitored within the vineyard by 14 minimum temperature thermometers mounted on wooden blocks which were mounted on posts at approximately the 1½ meter level. Bud temperatures were periodically monitored during the wind-machine trial by a Precision Readout Thermometer (PRT), an instrument which utilized optical pyrometry. A hot wire anemometer was used to record the wind drift.

On the morning of May 16, 1979, wind-machine gusts were timed in the Bob Kellogg orchard in Mattawan and in the Del Kellogg vineyard in Texas Corners. A watch with a second hand and a hand-held digital thermometer were the only materials that comprised these wind-machine trials. The purpose of these experiments was to determine the temperature fluctuations during the cycle of the wind machine. A secondary objective was to judge (by visual observation) the distance of the influence of the wind machine.

3. Minimum Temperature Forecasting

The method employed was developed by Marshall Soderberg of the National Weather Service, Kent County Airport Office, in Grand Rapids, Michigan (Soderberg, 1969). The Soderberg technique is an objective scheme for forecasting nocturnal minimum temperatures during possible frost nights from April 15 through June 15 at 24 agricultural weather stations and 4 airport locations in western Michigan, and segregates the data into radiative and advective nights. Soderberg assumed that the critical temperature for frost formation was 40°F at the standard instrument shelter height. The temperature observations at the agricultural weather stations were all at approximately the same height above the ground.

The Soderberg technique is essentially a hygrometric and graphical approach, where isopleths of the minimum temperature are plotted from 4 p. m. air temperature and dew point measurements at the Kent County Airport. Once this has been done, a line that most closely fits the data is drawn. These parameters were chosen to take into account moisture and radiative characteristics of the prevailing air mass, assuming that the absorption of incoming solar radiation, and hence maximum air temperature, occurred at 4 p. m.

The occurrence of cloud cover will modify the nocturnal radiation balance a great deal (excluding high-level cirrus clouds), which brings a third parameter into the scheme. Two graphs are required for nights of radiational cooling, one for evenings when the 4 p.m. Grand Rapids cloud cover is clear to partly cloudy (corresponding to zero to five-tenths cloud cover), and the other for evenings when it is mostly cloudy to overcast (six-tenths to ten-tenths cloud cover).

Finally, a parameter which depends on the forecaster's expertise is included to determine whether significant advection will be occurring during the forecast period. This correction is only applied to the forecast when the passage of a warm or cold front is anticipated, i. e., an evening when an advective type freeze is expected. A predictive equation for the correction to the Grand Rapids forecast (to the nearest ^{o}F) is obtained from the anticipated 24 hour 850 mb temperature change ending at 7 a. m. (to the nearest ^{o}C). Soderberg chose to neglect 850 mb temperature changes of $-3^{o}C$, $-2^{o}C$, $-1^{o}C$, $0^{o}C$, and $1^{o}C$. No justification was given for this assumption.

Once the forecast for Grand Rapids is obtained, the average minimum temperature difference between the agricultural weather station and Grand Rapids (^{o}F) is added or subtracted, according to whether radiational cooling, warm advection, or cold advection is occurring. Following Soderberg, only nights when the Grand Rapids minimum temperature was less than or equal to $45^{o}F$ were used in gathering data for the study.

RESULTS

1. Freeze Climatology of Selected Agricultural Weather Network Stations in Michigan

The 50% probabilities of the last occurrence of 20°F, 24°F, 28°F, and 32°F in the spring and the first occurrence of 20°F, 24°F, 28°F, and 32°F in the fall, the length of the growing season (28°F and 32°F), as well as the 5% and 95% probabilities of the last occurrence of 28°F and 32°F in the fall for selected agricultural network stations (generated for the period of record 1950-1979), were chosen for presentation (see Figures 11 through 29). In order to distinguish "spring" and "fall" dates, July 31 was assumed to be the last day of "spring." This did not affect the freeze statistics for the agricultural weather stations. However, for the climatological stations throughout the state, especially in the Upper Peninsula (see Figure 27), freezing temperatures have been reported in all months of the year. This assumption can affect the freeze statistics.

The resulting freeze dates were compared with an isopleth analysis of the climatological network, which contains the stations listed in Table 9. This comparison reveals Grand Junction to be the station that deviates

TABLE 9

CLIMATIC NETWORK STATIONS USED IN THE CONSTRUCTION OF 30 YEAR FREEZE CLIMATOLOGY FOR MICHIGAN

1. Adrian
2. Allegan
3. Alma
4. Alpena WSO AP
5. Alpena Sewage
6. Ann Arbor
7. Atlanta
8. Bad Axe
9. Baldwin
10. Battle Creek
11. Bay City
12. Benton Harbor
13. Big Rapids
14. Bloomingdale
15. Cadillac
16. Caro
17. Charlotte
18. Chatham
19. Cheboygan
20. Coldwater
21. Detroit City WSO AP
22. Detroit Metro WSO AP
23. East Jordan
24. East Lansing
25. East Tawas
26. Eau Claire
27. Escanaba
28. Fayette
29. Fife Lake
30. Flint WSO
31. Frankfort
32. Gladwin
33. Grand Haven
34. Grand Marais
35. Grand Rapids WSO AP
36. Grayling
37. Greenville
38. Gull Lake
39. Hale Loud Dam
40. Harbor Beach
41. Harrisville
42. Hart
43. Hastings
44. Higgins Lake
45. Hillsdale
46. Holland
47. Houghton
48. Houghton Lake
49. Ionia
50. Iron Mountain
51. Ironwood
52. Ishpeming
53. Jackson FAA AP
54. Kalamazoo St. Hospital
55. Lake City Experiment Farm
56. Lansing WSO AP
57. Lapeer
58. Luddington
59. St. Ignace-Mackinac Bridge
60. Manistee
61. Manistique
62. Marquette WSO
63. Midland
64. Milford GM Proving Ground
65. Mio Hydro Plant
66. Monroe
67. Mount Clemens AF Base
68. Mt. Pleasant University
69. Munising
70. Muskegon WSO AP
71. Newaygo
72. Newberry St. Hospital
73. Onaway State Park
74. Ontonagon
75. Owosso Wastewater Plant
76. Paw Paw
77. Pellston FAA AP
78. Pontiac St. Hospital
79. Port Huron
80. Saginaw FAA AP
81. Saint Johns
82. Sandusky
83. Sault Ste. Marie WSO
84. Seney Nat'l WLR
85. South Haven Exp. Farm
86. Stambaugh
87. Standish
88. Three Rivers
89. Traverse City FAA AP
90. Vanderbilt
91. Watersmeet
92. West Branch
93. Willis

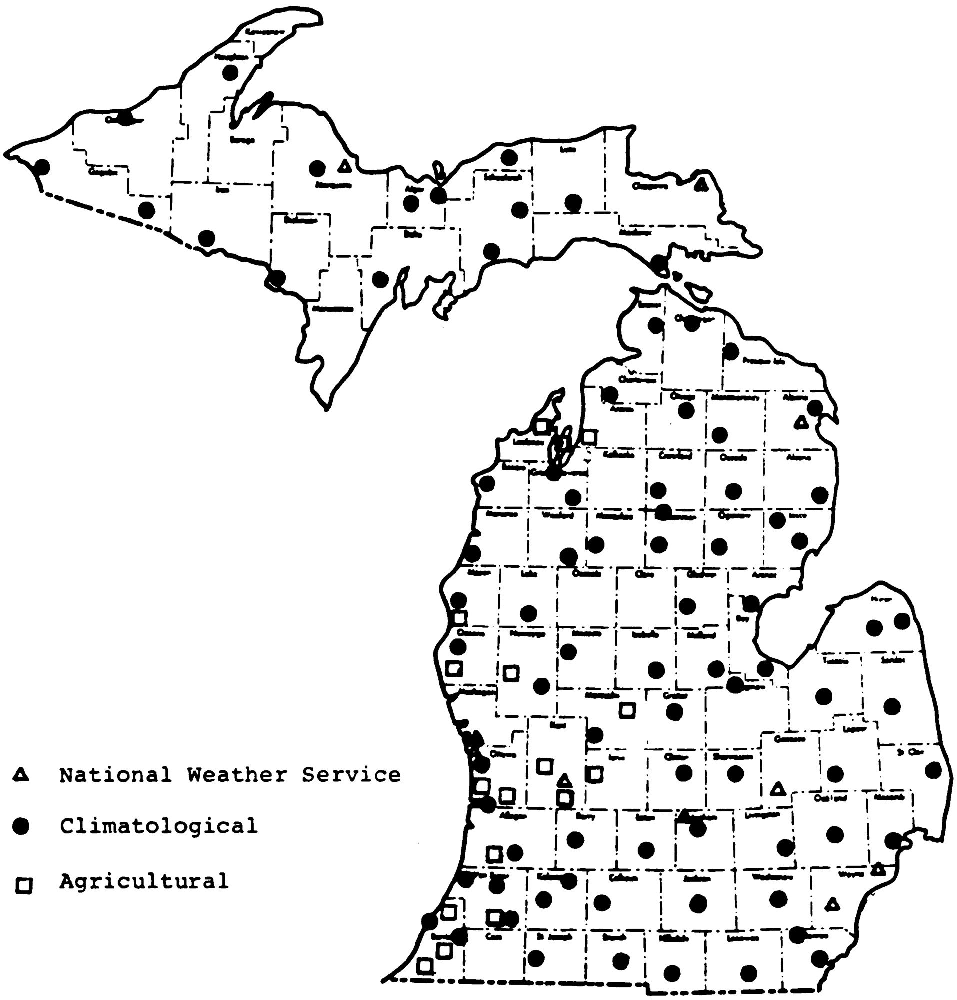


Figure 11. Locations of stations used in freeze climatology study (1950 through 1979).

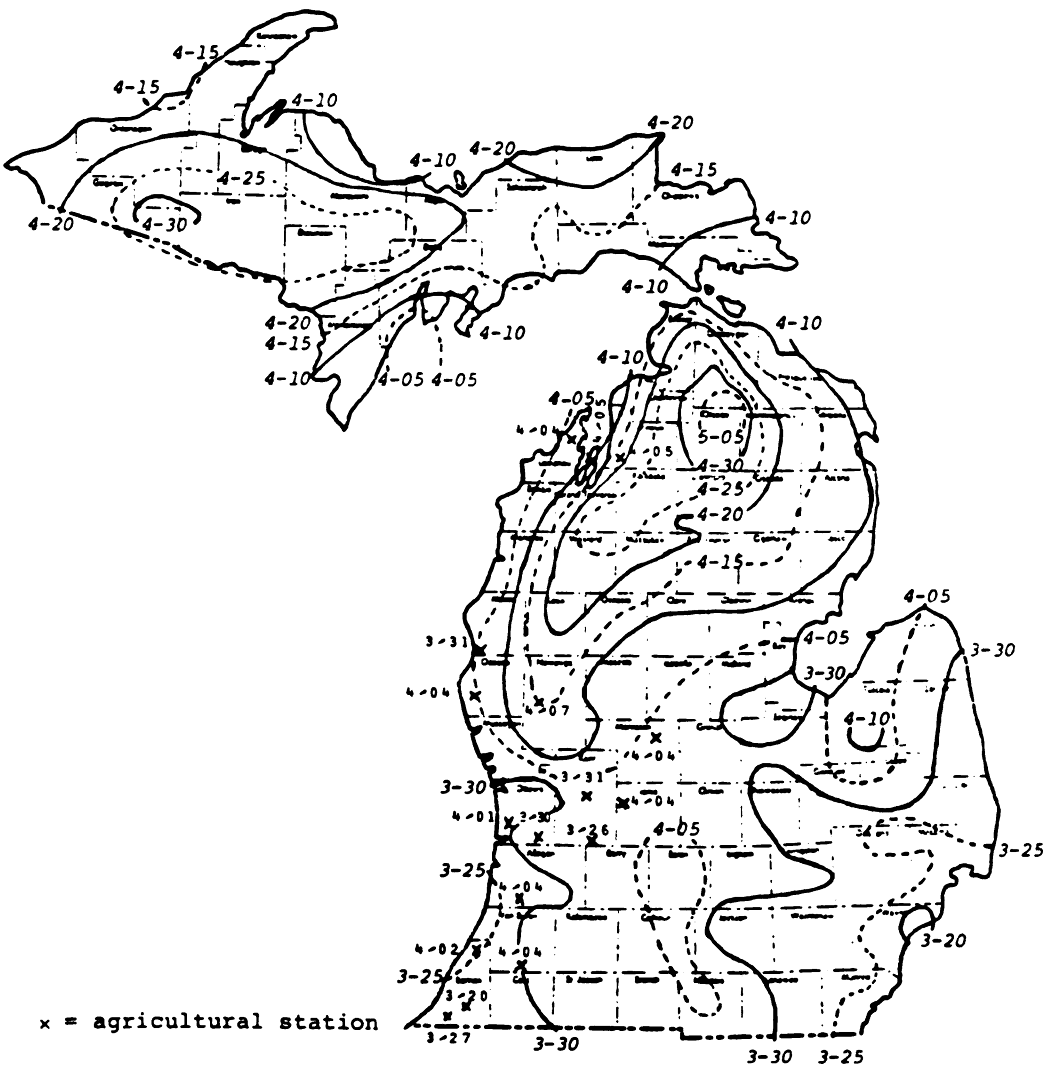


Figure 12. 50% probability date of last 20°F in the spring (1950 through 1979).

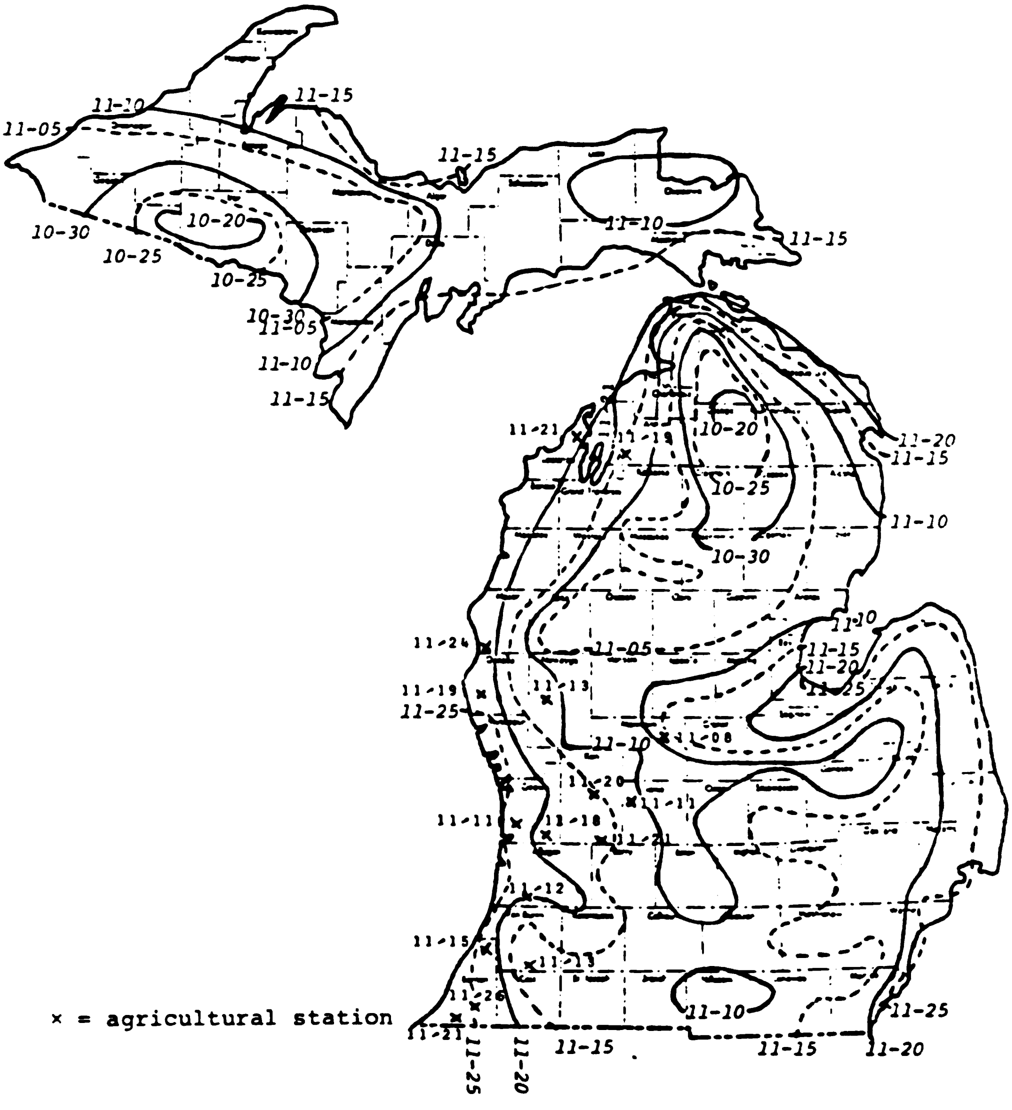


Figure 13. 50% probability date of first 20°F in the fall (1950 through 1979).

Figure 14. 50% probability date of last 24°F in the spring (1950 through 1979).

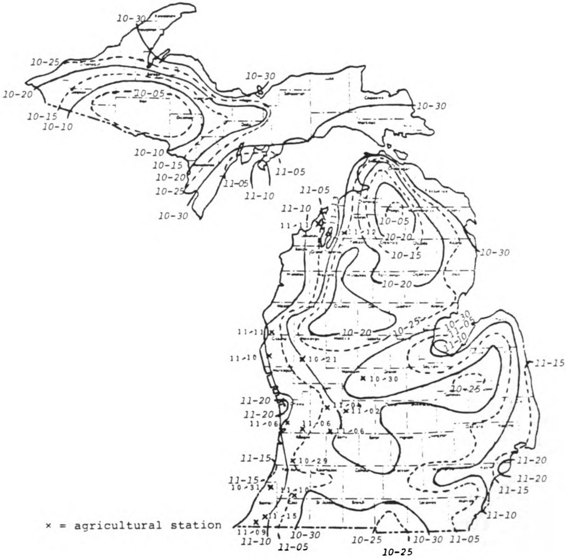


Figure 15. 50% probability date of first 24°F in the fall (1950 through 1979).

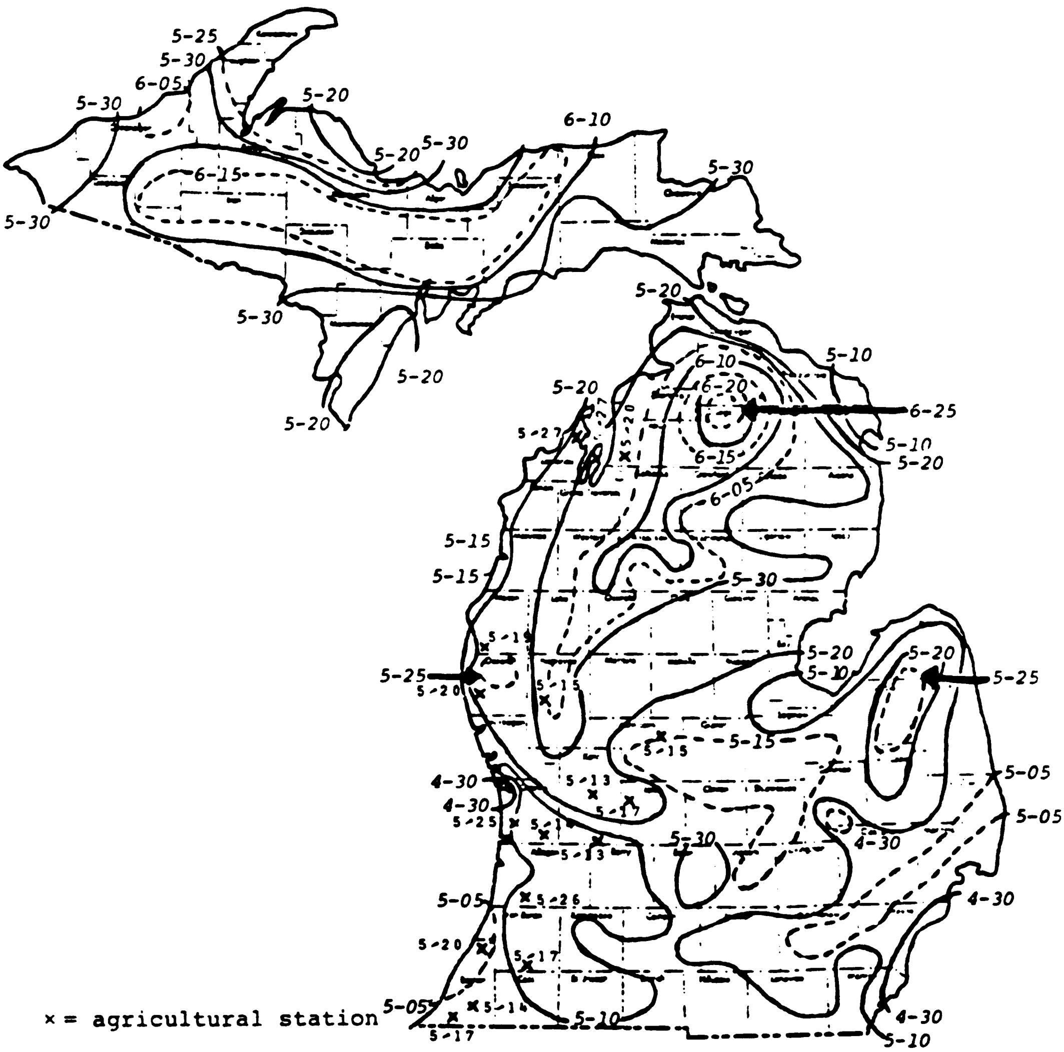


Figure 16. 5% probability date of last 28°F in the spring (1950 through 1979).

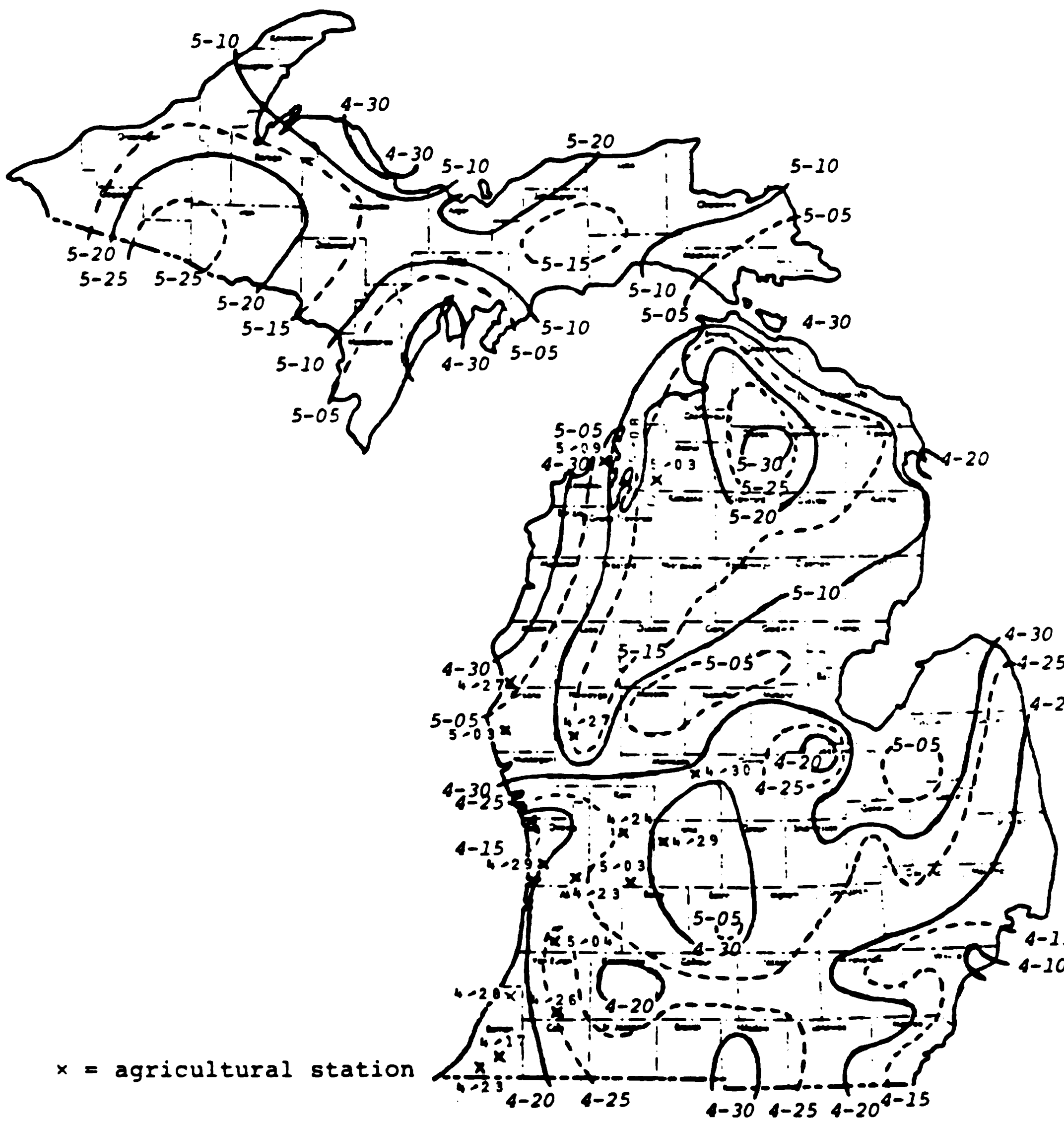


Figure 17. 50% probability date of last 28°F in the spring (1950 through 1979).

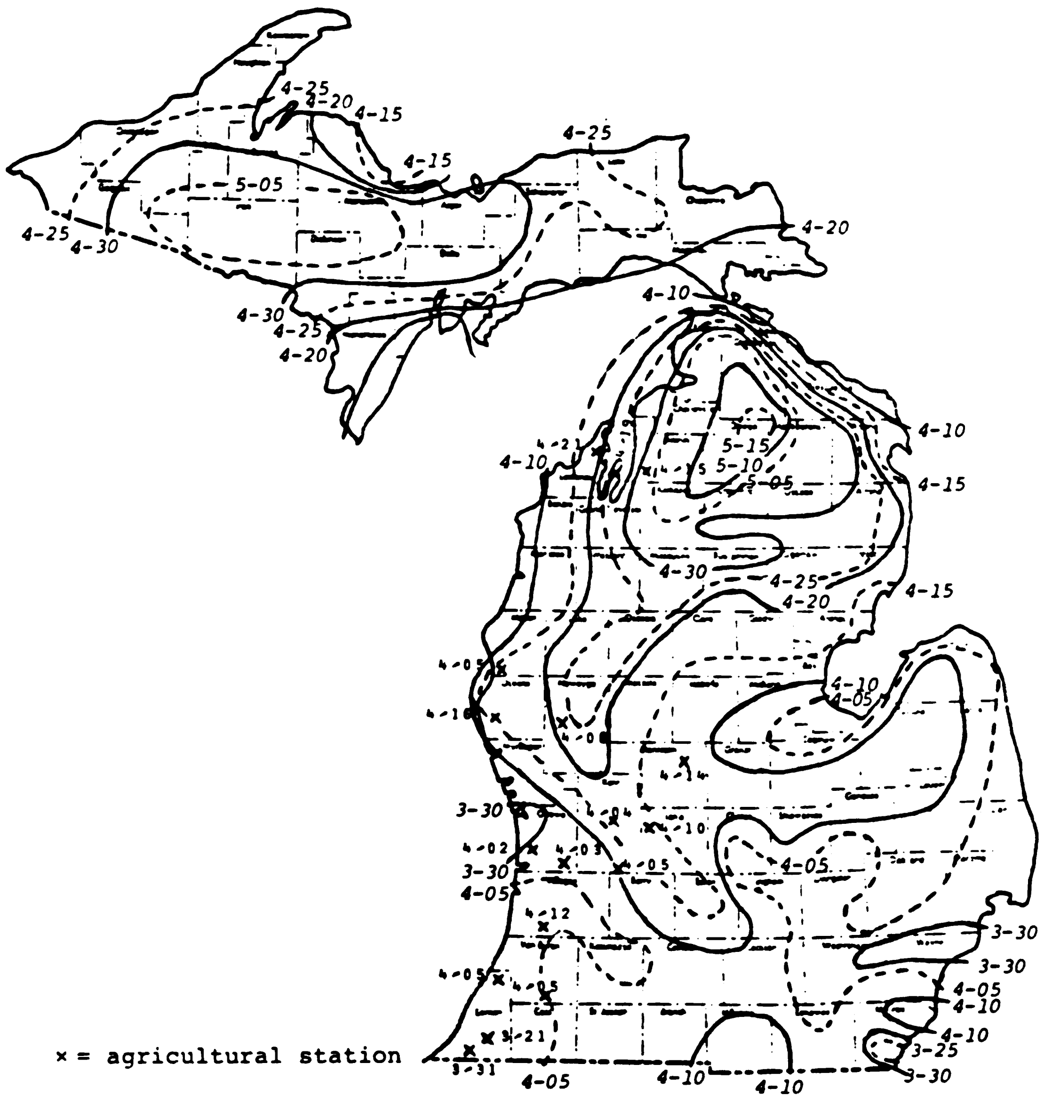


Figure 18. 95% probability date of last 28°F in the spring (1950 through 1979).

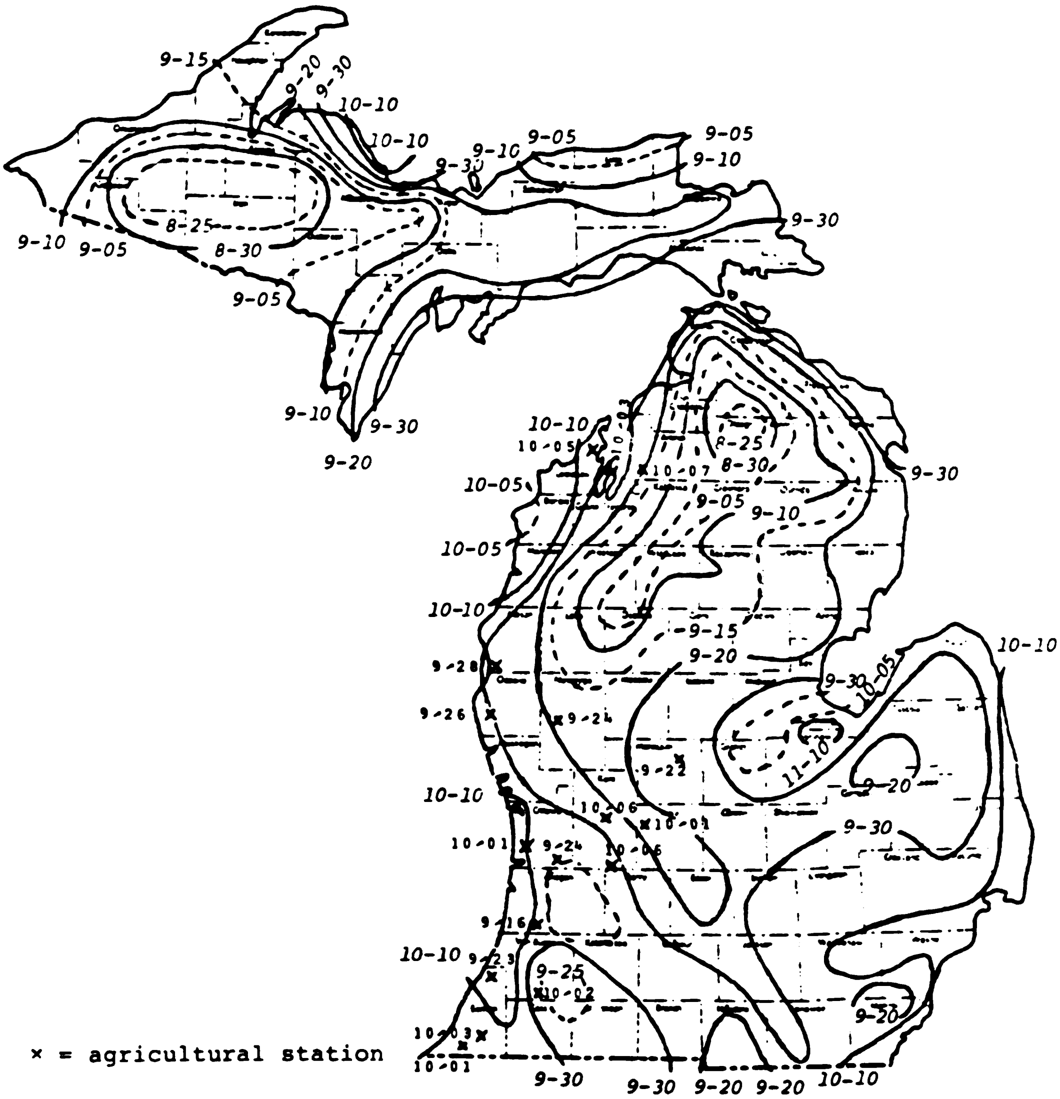
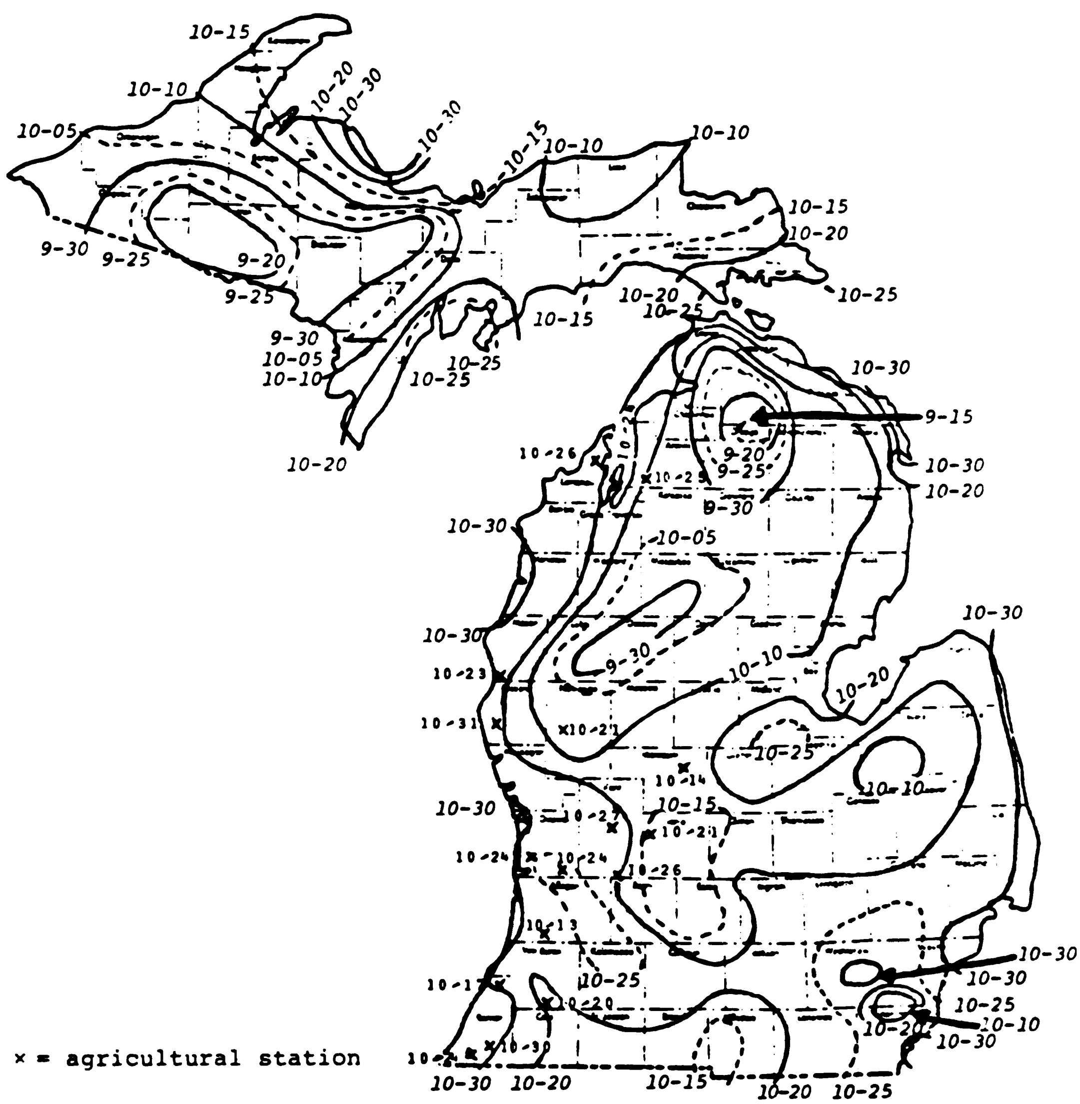


Figure 19. 5% probability date of first 28°F in the fall (1950 through 1979).



× = agricultural station

Figure 20. 50% probability date of first 28°F in the fall (1950 through 1979).

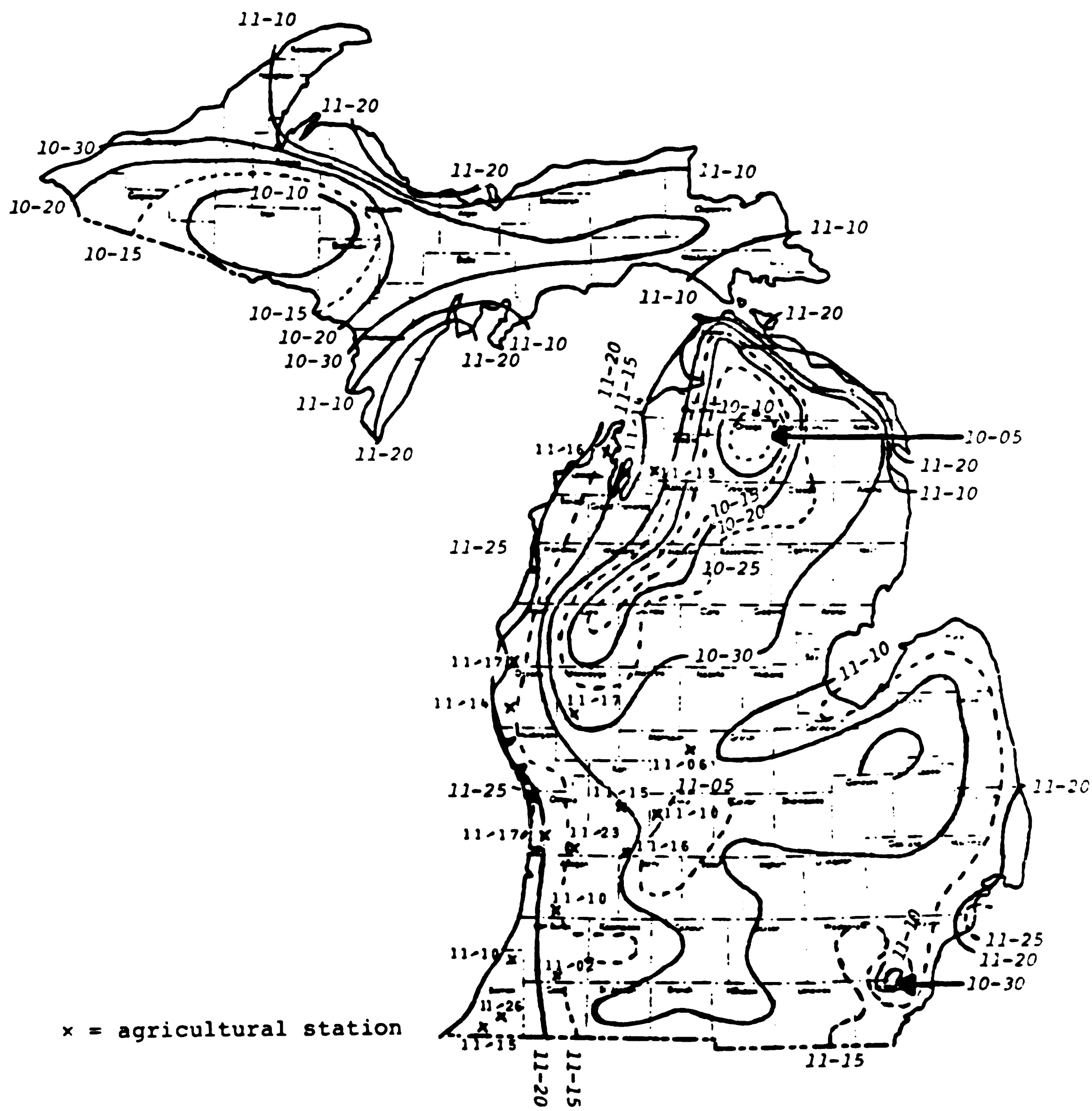


Figure 21. 95% probability date of first 28°F in the fall (1950 through 1979).

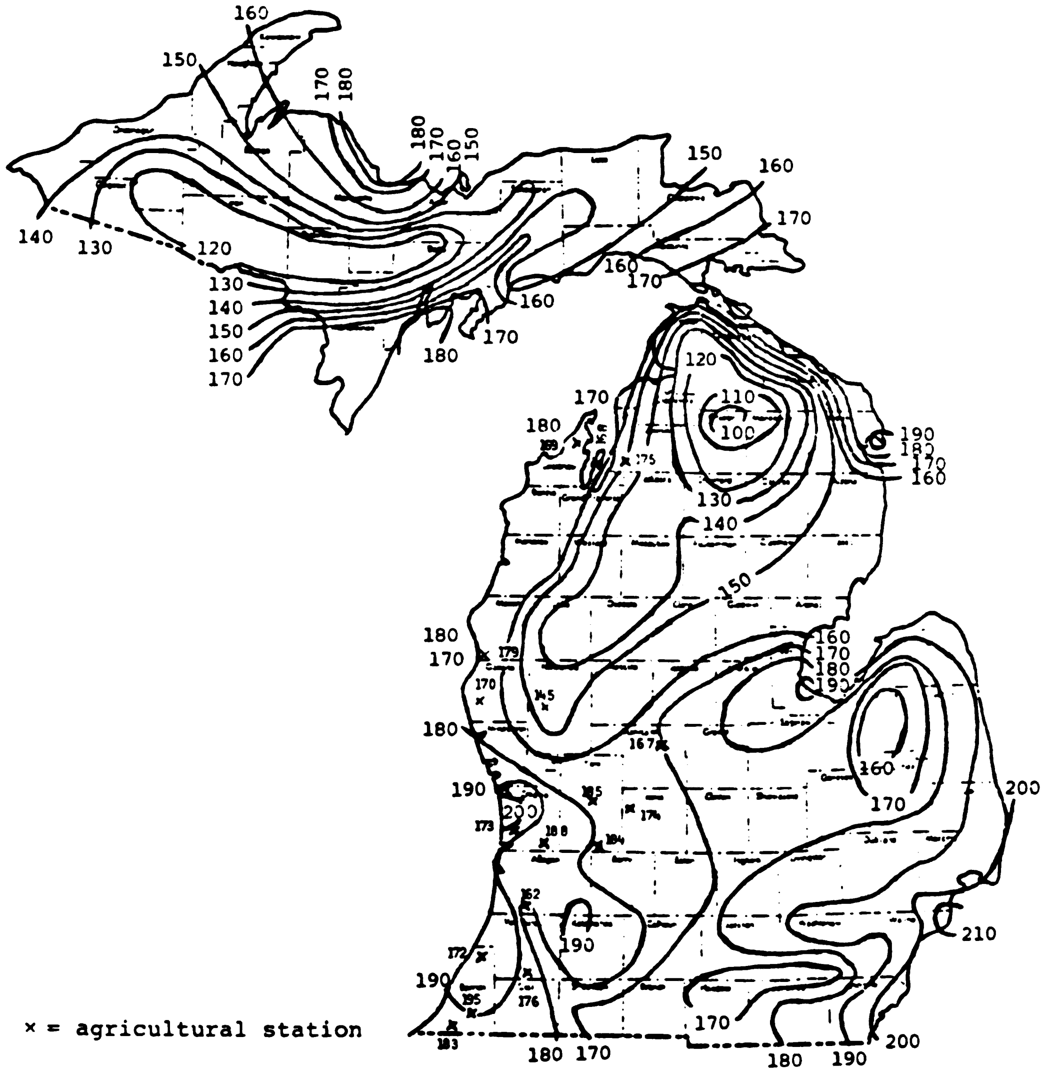


Figure 22. Length of 28°F growing season, days (1950 through 1979).

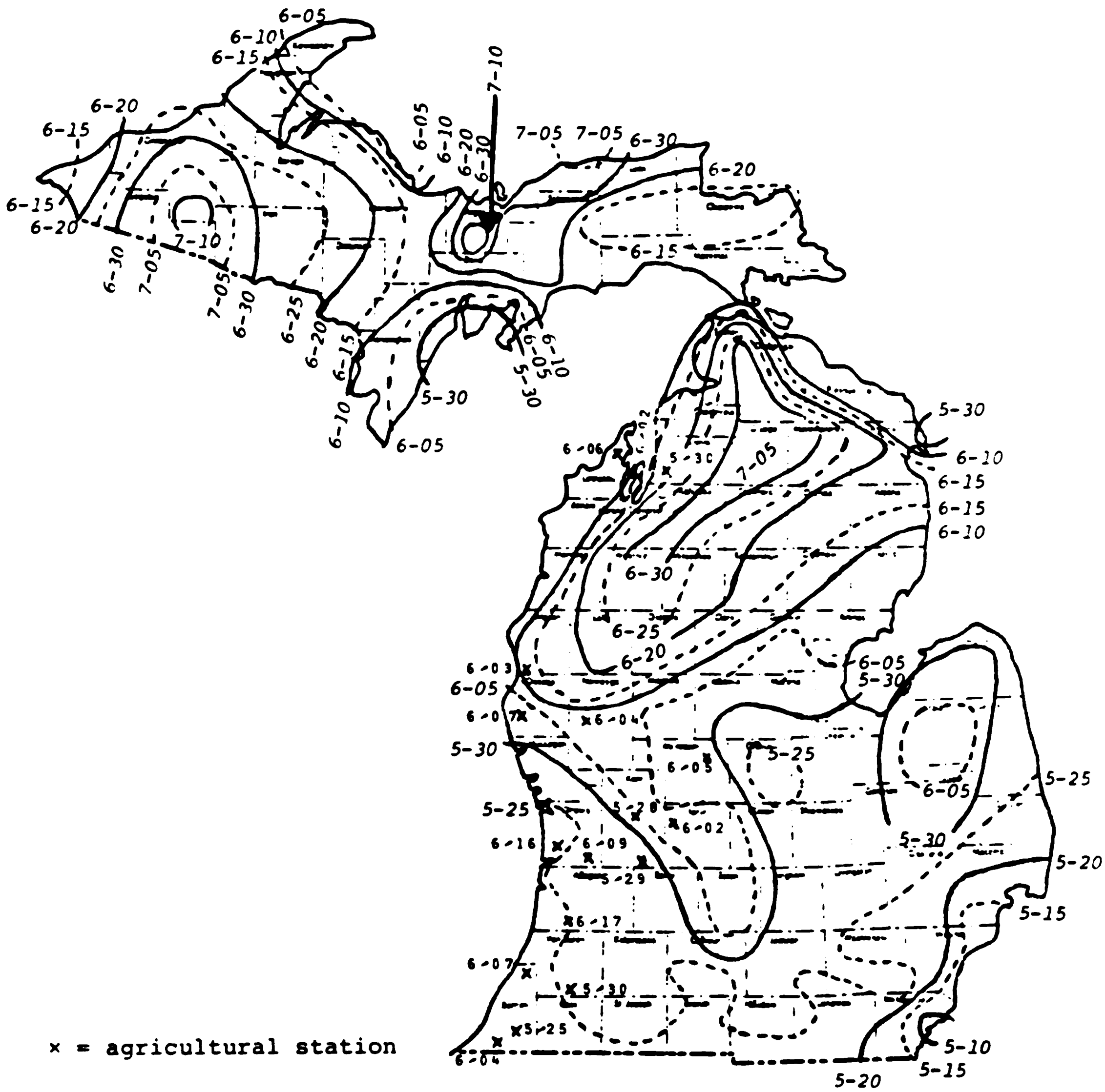


Figure 23. 5% probability date of last 32°F in the spring (1950 through 1979).

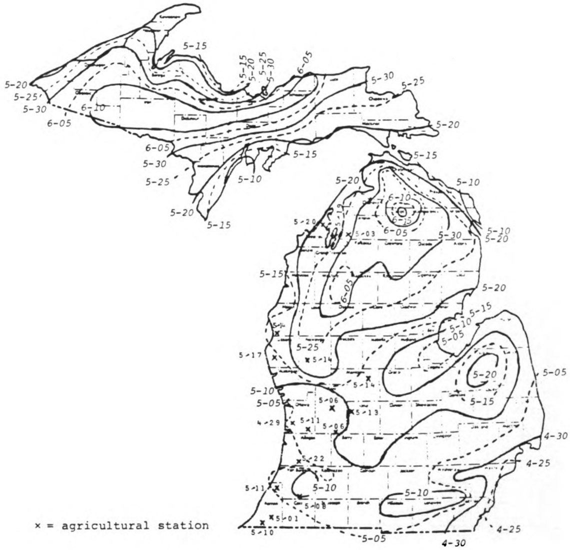


Figure 24. 50% probability date of last 32°F in the spring (1950 through 1979).

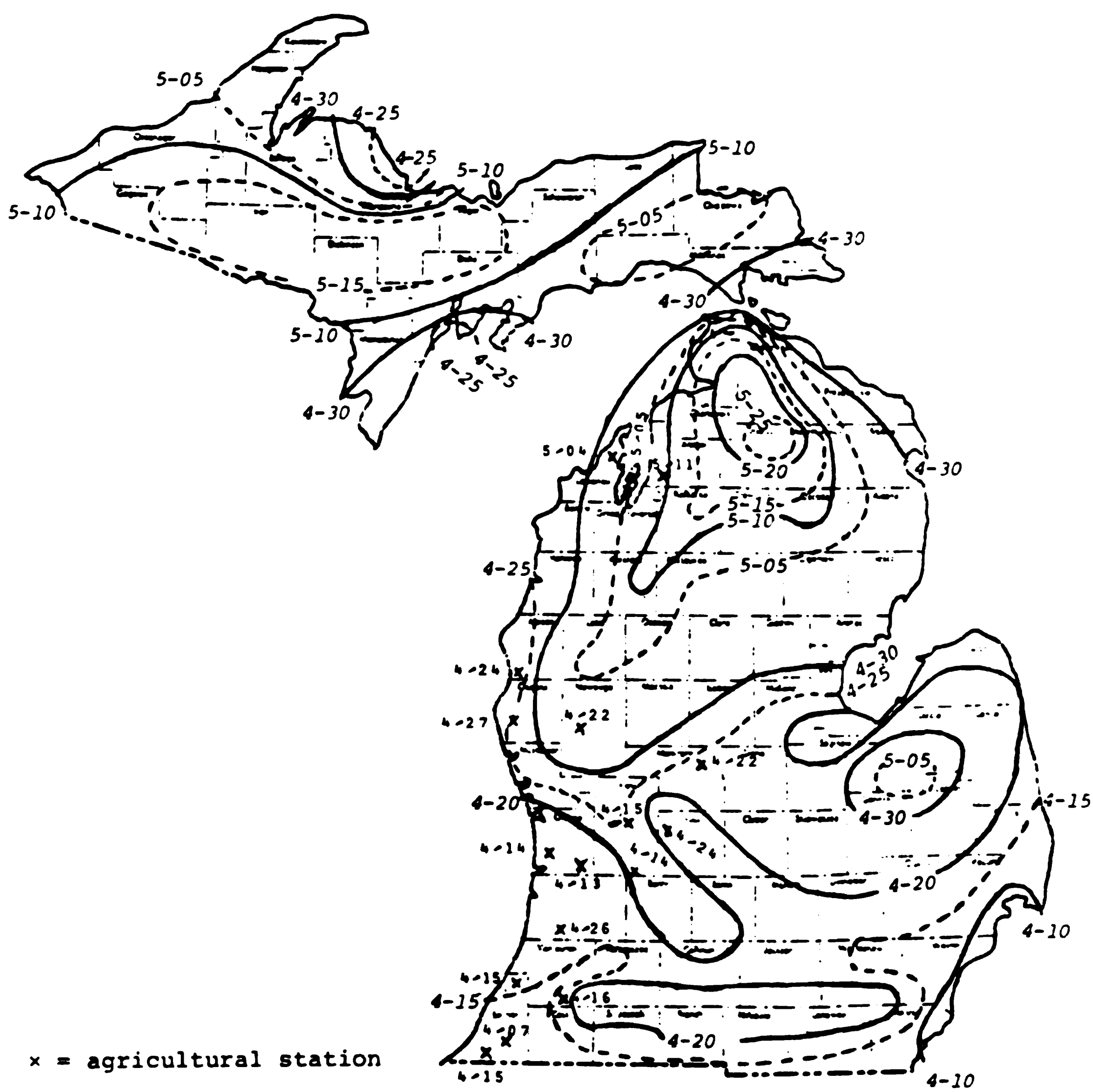


Figure 25. 95% probability date of last 32°F in the spring (1950 through 1979).

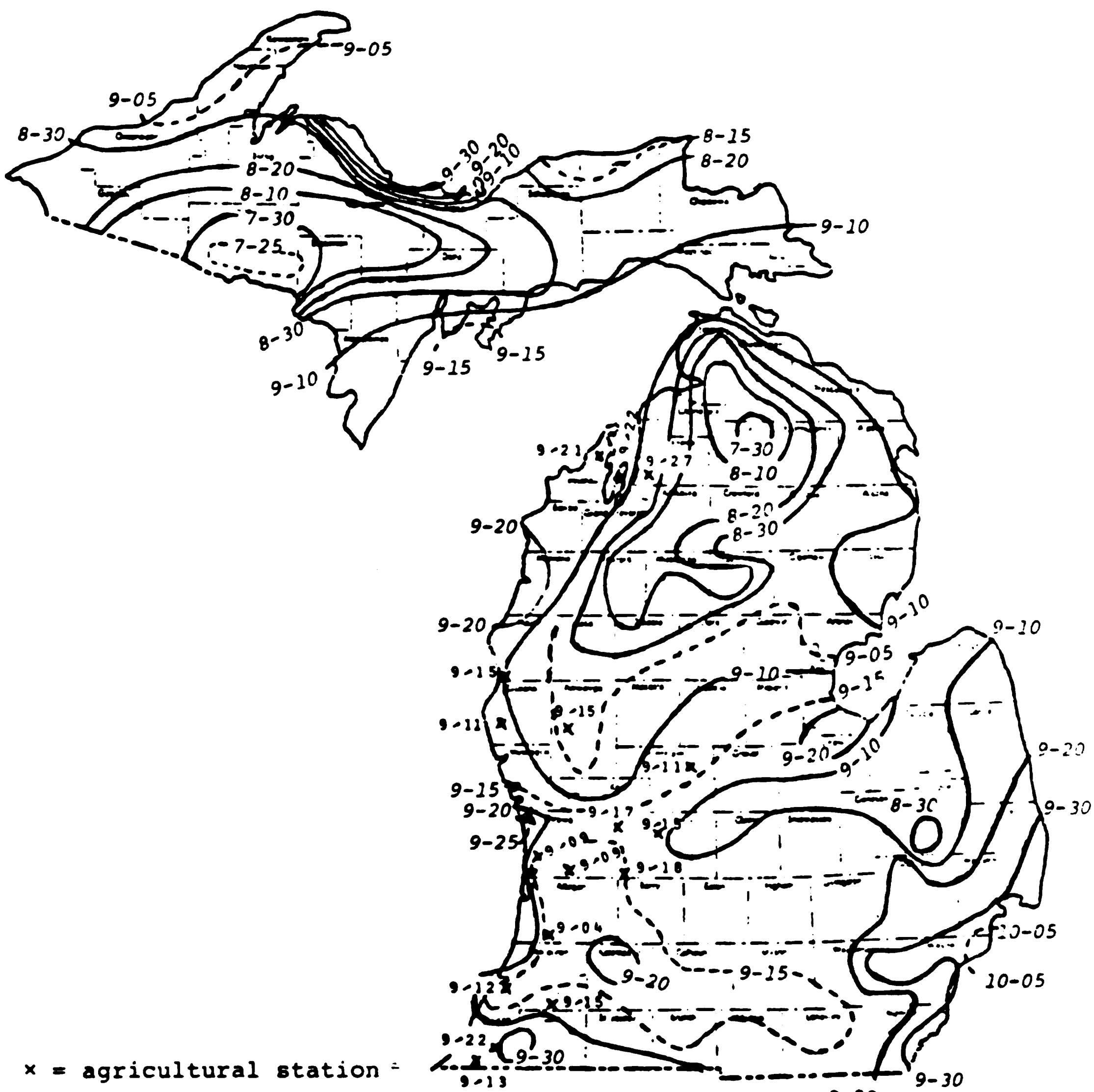


Figure 26. 5% probability date of first 32°F in the fall (1950 through 1979).

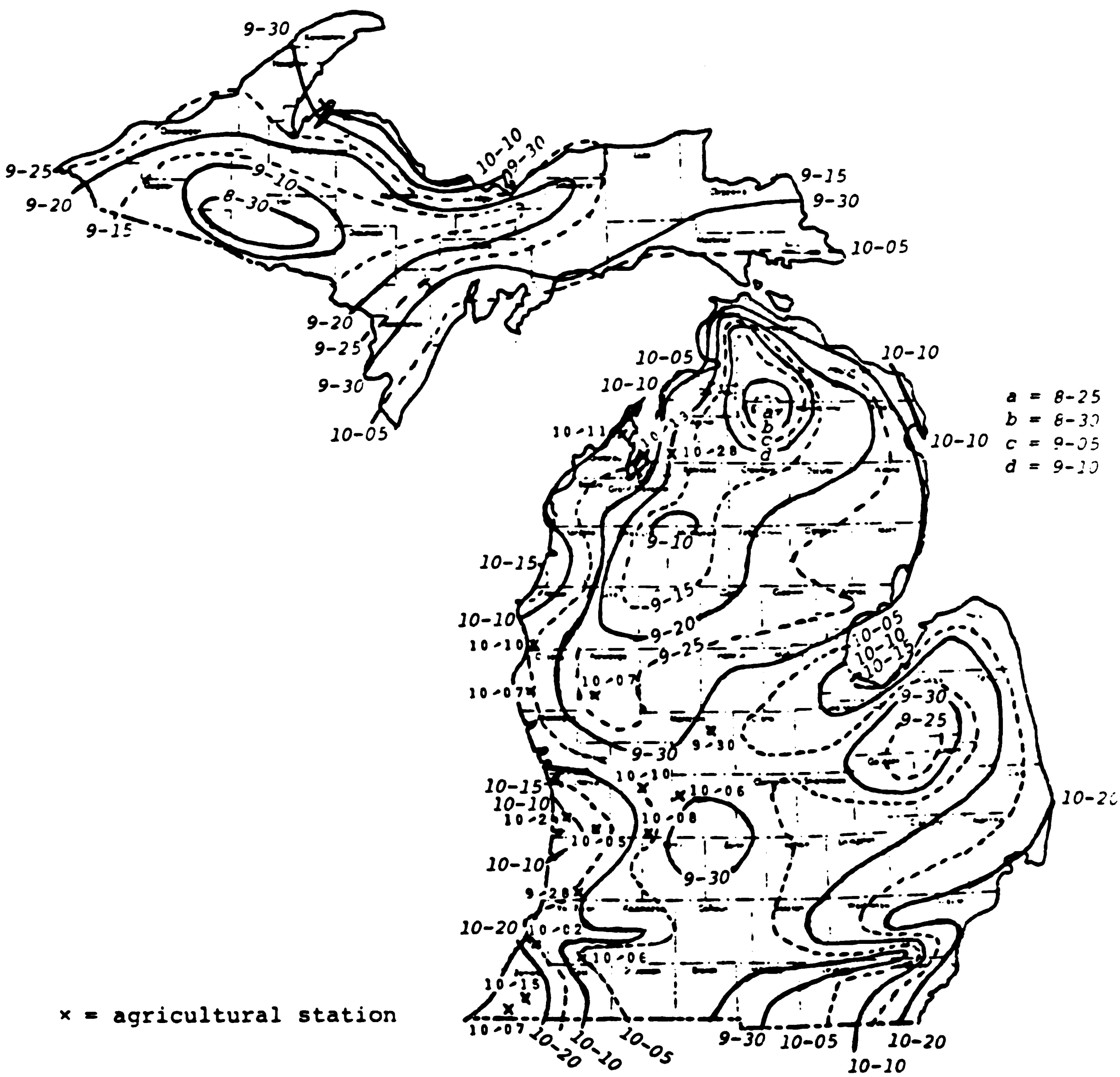


Figure 27. 50% probability date of first 32°F in the fall (1950 through 1979).

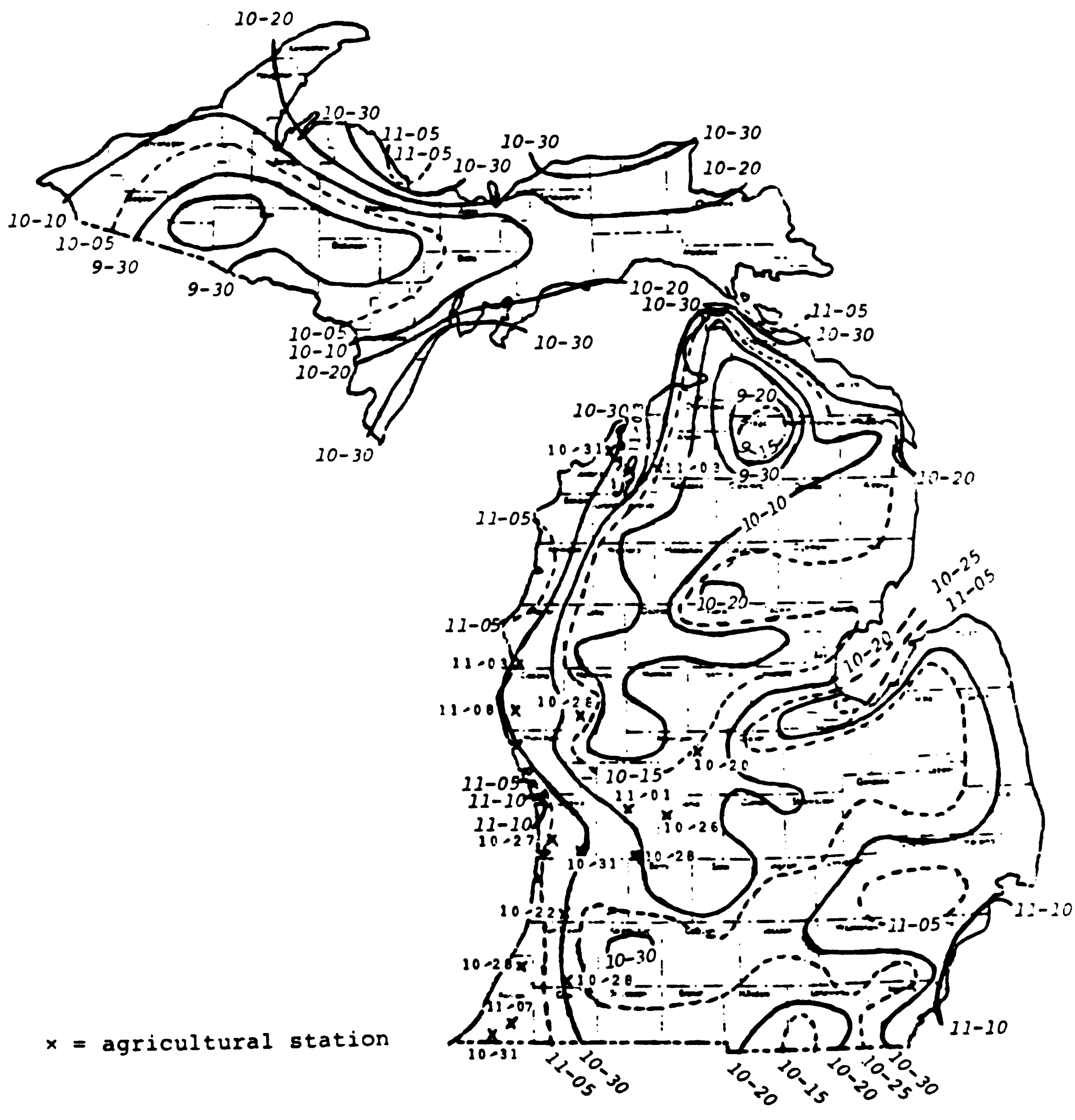


Figure 28. 95% probability date of first 32°F in the fall (1950 through 1979).

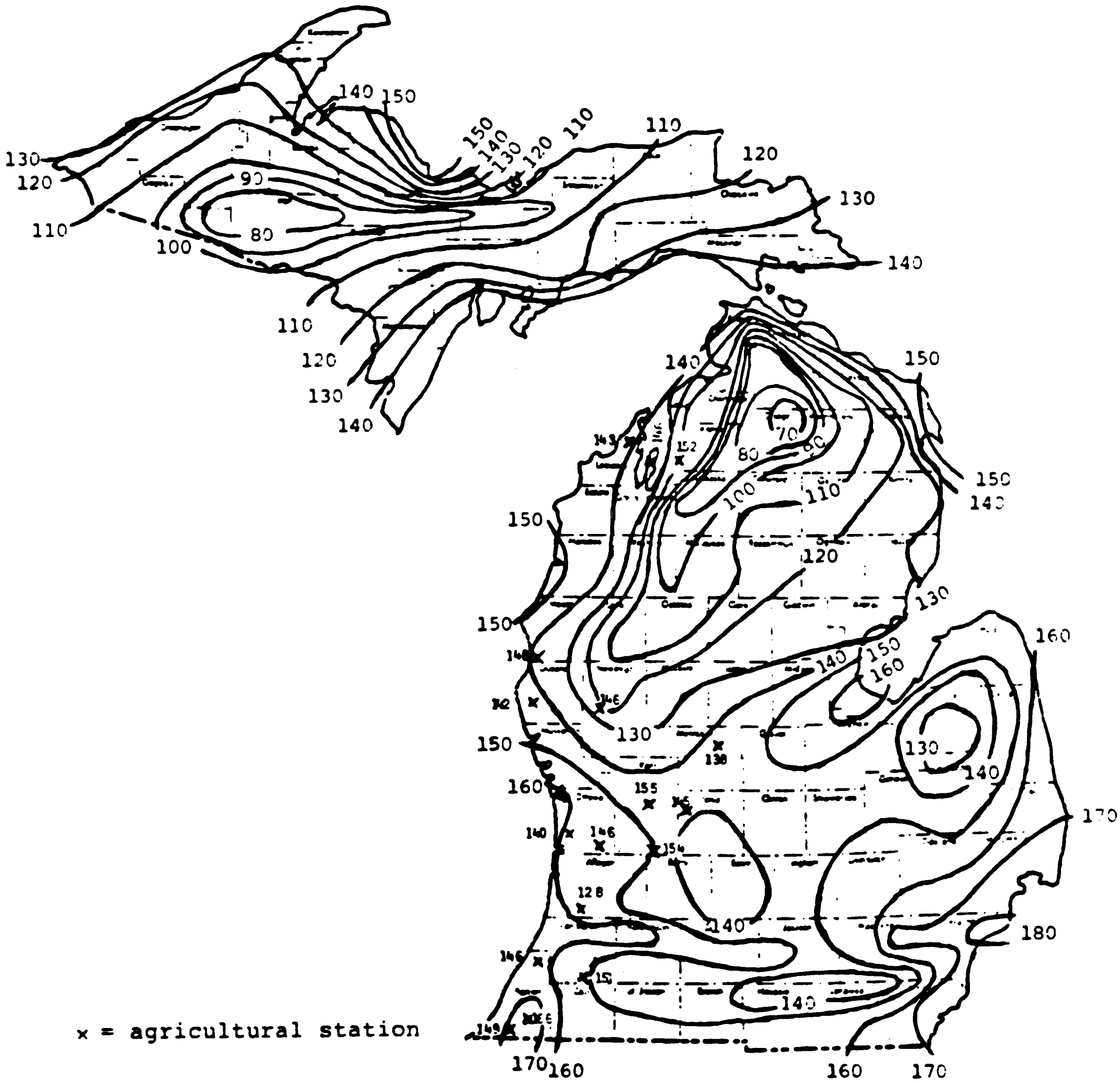


Figure 29. Length of 32°F growing season, days (1950 through 1979).

most from the climatological network analysis. The explanation for this result is that Grand Junction temperatures are recorded in a low-lying area, where cold soils of low thermal conductivity predominate. The analysis of the freeze dates for the climatological network shows that the two coldest areas in Michigan are the northern Lower Peninsula (Ostego County and inland parts of Antrim, Montmorency, and Cheboygan counties that surround it), and the central western Upper Peninsula (in particular Iron County). The warmest areas are extreme southwestern Michigan (Berrien County) and southeastern Michigan (Monroe, Wayne, Macomb, and St. Clair counties). The length of the 32°F growing season (see Figure 29) varies from 70 to 180 days. The 130 to 140 day growing season in the inland area of the "thumb" (Tuscola and Lapeer counties) is a bit shorter than many stations located along a lakeshore further to the north, e. g., Manistee County in the northwest Lower Peninsula, Alpena County in the northeast Lower Peninsula, and the region in Marquette County that is part of the northern shore of the Upper Peninsula.

The agricultural weather network was established in 1962, making it necessary to estimate the remaining freeze dates prior to 1962 by linear regression. Table 10 contains a list of the agricultural weather stations (Y), the climatological station(s) that it was correlated with (X), the intercept, the correlation coefficient (r), the correlation

TABLE 10

COMPLETE LISTING OF PREDICTIVE EQUATIONS
CALCULATED TO ESTIMATE MINIMUM TEMPERATURES
FOR SELECTED AGRICULTURAL WEATHER STATIONS IN MICHIGAN
(Y = mx + b)

	Y	X	Slope (m)	Intercept (b)	r*	r^2	n**
1.†	Belding	Alma	1.07	-2.46	.95	.90	212
2.	Belding	Greenville	1.03	- .18	.95	.91	225
3.	Edmore	Alma	1.02	-2.33	.95	.91	212
4.†	Edmore	Greenville	.99	- .43	.95	.90	225
5.†	Fremont	Newaygo	1.00	5.34	.86	.73	284
6.	Glendora	Benton Harbor	1.01	-1.60	.84	.70	180
7.†	Glendora	Dowagiac	.81	7.32	.86	.74	196
8.	Glendora	Eau Claire	.92	2.16	.78	.61	196
9.	Glendora	South Bend	.88	2.39	.79	.63	179
10.†	Graham	Grand Rapids	1.06	- .38	.92	.85	227
11.	Grand Junction	Allegan	1.03	-2.15	.76	.58	227
12.	Grand Junction	Benton Harbor	1.19	-10.47	.81	.65	180
13.	Grand Junction	Bloomingdale	.91	.40	.82	.66	236
14.†	Grand Junction	South Haven	1.21	-10.41	.83	.70	216
15.†	Holland	Holland	.95	1.41	.91	.83	223
16.†	Hudsonville	Grand Rapids	1.02	1.19	.90	.81	227
17.	Kewadin	Frankfort	1.17	-5.47	.86	.74	268
18.	Kewadin	Mackinaw City	1.01	2.18	.75	.57	311
19.†	Kewadin	Traverse City	.93	3.85	.88	.78	266
20.	Lake Leelanau	Frankfort	1.13	-4.87	.82	.67	268
21.	Lake Leelanau	Mackinaw City	1.00	3.25	.72	.52	311
22.†	Lake Leelanau	Traverse City	.88	4.23	.87	.75	266
23.†	Ludington	Ludington	.96	3.49	.86	.73	256
24.	Mapleton	Frankfort	1.13	-4.81	.82	.71	268
25.	Mapleton	Mackinaw City	.98	2.41	.71	.51	311
26.†	Mapleton	Traverse City	.92	3.25	.89	.79	266
27.†	Mears	Hart	1.01	.26	.91	.83	236
28.	Paw Paw	Kalamazoo	.54	14.89	.68	.46	183
29.†	Paw Paw	Three Rivers	1.03	- .92	.88	.77	199
30.†	Peach Ridge	Grand Rapids	1.00	1.42	.90	.82	227
31.	Sodus	Eau Claire	.94	4.27	.77	.59	196
32.†	Sodus	Dowagiac	.83	9.17	.82	.67	196
33.	Sodus	Benton Harbor	.95	3.30	.75	.57	180
34.	Sodus	South Bend	.85	6.09	.74	.54	179
35.	Watervliet	Benton Harbor	1.07	-4.49	.83	.69	180
36.†	Watervliet	Dowagiac	.90	3.17	.89	.80	196
37.	Watervliet	Eau Claire	.99	- .82	.79	.62	196
38.	Watervliet	South Bend	.95	- .98	.79	.62	179

*correlation coefficient **number of observations

†predictive equations chosen

coefficient squared (r^2), and the number of observations (n). The observations used to develop these relationships cover a 5-year period, 1972-1976, for the months April, May, and June. Only nights when the minimum temperature was less than or equal to 45°F were chosen. The freeze statistics for the selected agricultural weather stations are contained in Appendix C, Tables C1 through C17. The freeze statistics for the 36°F threshold **were not mapped.**

The predictive equations chosen to estimate the minimum temperatures for selected agricultural weather stations were characterized by correlation coefficients that ranged between .86 and .95, except for Sodus and Grand Junction, which were lower. Belding and Edmore each showed correlation coefficients of .95, regardless of whether Greenville or Alma was chosen to construct the regression line. Glendora, Sodus, and Watervliet, which are located in the extreme southwestern area of the state, presented some problems as a set. Eau Claire, Dowagiac, Benton Harbor, and South Bend were all tried as predictors for these stations. Dowagiac was finally chosen because it showed the highest correlation coefficients for each of these stations. Frankfort, Mackinaw City, and Traverse City were each correlated with the three agricultural network stations in the northwest Lower Peninsula: Kewadin, Lake Leelanau, and Mapleton. Traverse City was subsequently chosen as the predictor for these agricultural network stations. Finally, Grand Junction was the single most difficult station for which to predict, and South Haven was selected over Allegan, Benton Harbor, or Bloomingdale.

Table 10 lists the predictive equations for estimating minimum temperatures for selected agricultural weather stations from climatological stations, and their correlation coefficients show a wide range. Belding's correlation of minimum temperatures with Alma, and Grand Junction's correlation of minimum temperatures with South Haven were the best and worst correlations, respectively. The individual sample variance of each of these stations was compared to the sample variance of the climatological station that it was correlated with. The decision rule for testing the equality of the variances (Neter and Wasserman, 1974) is if

$$F(\alpha/2;n_1-1,n_2-1) \leq s_1^2/s_2^2 \leq F(1-\alpha/2;n_1-1,n_2-1) \tag{3.10}$$

conclude C_1: $\sigma_1^2 = \sigma_2^2$; otherwise conclude C_2: $\sigma_1^2 \neq \sigma^2$, where

s_1^2 = sample variance of the agricultural station

s_2^2 = sample variance of the climatological station

σ_1^2 = population variance of the agricultural station

σ_2^2 = population variance of the climatological station

n_1 = number of observations at the agricultural station

n_2 = number of observations at the climatological station

Choosing the level of significance (α) to be .01, the appropriate F-statistics are $F(.005,29,29) = .038$, and $F(.995,29,29) = 2.63$. For spring and fall, $32^{o}F$, the variances for all four pairs of stations were found to be equal.

The assumption that the variances of the freeze dates were homogeneous was tested by using Bartlett's χ^2 test (Bethea et al., 1975). Let $s_1^2, s_2^2, \ldots, s_k^2$ be k independent sample variances corresponding to k normal populations with means μ_i and σ_i^2, $i = 1, 2, \ldots, k$. Suppose $n_1 - 1, n_2 - 1, \ldots, n_k - 1$ are the degrees of freedom.

$$\chi^2 = \left[(\ln V) \sum_{i=1}^{k} (n_i - 1) - \sum_{i=1}^{k} (n_i - 1) \ln s_i^2 \right] \Big/ L \tag{3.7}$$

where

$$V = \sum_{i=1}^{k} (n_i - 1)\, s_i^2 \Big/ \sum_{i=1}^{k} (n_i - 1) \tag{3.8}$$

and

$$L = 1 + \frac{1}{3(k - 1)} \left(\sum_{i=1}^{k} \frac{1}{n_i - 1} - \frac{1}{\sum_{i=1}^{k} (n_i - 1)} \right) \tag{3.9}$$

The test statistic (3.7) has an approximate χ^2 distribution with $k - 1$ degrees of freedom when used as a test statistic for

$$H_o: \sigma_1^2 = \ldots = \sigma_k^2$$

Given k random samples of sizes $n_1, n_2, \ldots, n_k$, from k independent normal populations, the statistic χ^2 can be used to test H_o. The rejection region for testing H_o is

TABLE 11

RESULTS OF CALCULATING THE χ^2 STATISTIC FOR USE IN BARTLETT'S χ^2 TEST FOR THE HOMOGENEITY OF THE VARIANCES, FOR THE CLIMATOLOGICAL NETWORK, THE AGRICULTURAL WEATHER NETWORK, THE COMBINED CLIMATOLOGICAL AND AGRICULTURAL SET, A CLIMATOLOGICAL SUBSET, AND THE COMBINED AGRICULTURAL AND CLIMATOLOGICAL SUBSET (α = .01)

Data Set	Degrees of Freedom	χ^2 Statistic	32°F		28°F		24°F		20°F	
			Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
Climatological	92	126.50	282.09	224.74	140.66	85.73	445.92	97.50	164.78	282.70
Agricultural	16	32.00	39.85	9.60	22.67	19.01	27.41	18.39	21.59	20.88
Combined*	109	145.54	335.70	235.73	173.74	110.28	481.97	116.80	186.61	304.25
Climatological Subset	23	43.00	28.78	19.33	19.55	12.92	34.82	17.62	29.78	24.51
Combined Agric. & Climat. Subset	40	63.69	76.23	30.24	49.57	36.32	73.43	38.80	51.10	47.21

*To calculate the χ^2 statistic for degrees of freedom > 100, the formula $\chi^2_{(k-1),0.99}=\frac{1}{2}(h+2.33)^2$ (Kreyszig, 1970) was used, where $h \equiv \sqrt{2m-1}$, and m is the degrees of freedom.

$\chi^2 > \chi^2_{(k-1),1-\alpha}$.

The χ^2 statistic was calculated using 3.7 through 3.9 for the 93 climatological stations, the 17 agricultural stations, and the combined set (110 stations), at 4 different temperature thresholds for both spring and fall. The individual variances of the freeze dates were obtained from the computer output of the freeze statistics. If the calculated value for χ^2 is greater than the tabled value of χ^2 given in column 1 of Table 11, then the hypothesis of homogeneous variances is rejected. For the 17 agricultural stations, the hypothesis of homogeneous variances is accepted for all but one of the 8 data sets (32°F, spring). For both the climatological stations and the combined data set, the hypothesis of homogeneous variances is rejected for six of the 8 data sets. This result supports inclusion of the individual variances in the freeze program. However, by selecting 24 climatological stations that are in closest proximity to the agricultural weather network (referred to as "climatological subset" in Table 11), the hypothesis of homogeneous variances is accepted at all temperature thresholds. Combining the agricultural network and the climatological subset, the hypothesis of homogeneous variances is accepted at all but two temperature thresholds (32°F and 24°F, spring).

The number of agricultural network stations that "fit" the climatological analysis (i. e., the inclusion of this data would not have altered the analysis) was typically between 8 and 10. The agricultural stations that exhibited the largest deviations from the climatological analysis were Grand Junction, Watervliet, Fremont, and Kewadin.

Referring to the 5% probability dates of the 28°F in the fall, Grand Junction's date was 3 weeks earlier and Watervliet's date was 2 weeks earlier than the climatological analysis would otherwise indicate. (Both of these stations are colder in the spring as well as the fall.) The three agricultural stations in Berrien County are all nearly equidistant from Lake Michigan. Perhaps Watervliet's proximity to Paw Paw Lake accounts for it being cooler than Sodus or Glendora.

Fremont apparently was warmer in both spring and fall, which may reflect the fact that Newaygo (the station with which it was correlated) is located in a low-lying area, in the vicinity of a reservoir. As an extreme example, the 95% probability date of the first 28°F in the fall is more than 2 weeks later than would be expected in comparison with the climatic analysis.

Kewadin is also warmer in both spring and fall. The 5% probability date for the last 32°F in the spring was nearly 3 weeks earlier than the climatological analysis would indicate. It is nearly surrounded by water, with Grand Traverse Bay to the west, Elk Lake and Birch Lake to the south, and Torch Lake to the east. Its proximity to water in conjunction with its elevation (710 feet compared with 580-foot datum at Grand Traverse Bay) that allows for cold-air drainage moderates the temperature decrease during freeze nights.

2. Vineyard Observations

A. Temperature Profiles. An important contribution to the grape industry of Michigan in this multi-faceted study is the characterization of the nocturnal microclimate in two vineyards. Results of this three year study are summarized in Table 12, in which the approximate 1 to 15 meter temperature inversions are reported. To depict the range in the data, the average 1 to 15 meter inversion ($\overline{X}$), the standard deviation (SD), and the number of

TABLE 12

DISTRIBUTION OF APPROXIMATE 1 TO 15 METER TEMPERATURE INVERSIONS ACCORDING TO 1 METER TEMPERATURE (1978-1980) (TEXAS CORNERS, MICHIGAN)

Temp. (°F)	$\overline{X}$	SD	n	Frequency (% of Total)	Frequency (excluding 46°F)
24-25	5.5	1.4	4	1	2
26-27	7.1	3.8	9	3	4
28-29	10.6	3.3	15	5	7
30-31	6.0	4.0	26	9	12
32-33	4.4	3.9	12	4	6
34-35	7.7	3.8	14	5	7
36-37	4.0	3.3	10	3	4
38-39	5.6	3.0	41	14	19
40-41	5.8	3.0	23	8	10
42-43	4.2	2.0	32	10	15
44-45	4.8	2.9	30	10	14
≥ 46	4.2	2.9	84	28	

observations in each category (n) are reported. Two visual summaries in the form of cumulative distribution functions (CDF) were then constructed from this table. Figure 30 is the CDF of inversion strength with respect to 1 meter temperature, neglecting the occurrence of inversions when the 1 meter temperature is above 45°F. Figure 31 is also a CDF which shows the distribution of 1 meter temperatures when inversions of greater than 1°F were occurring.

The resolution of the two instrumentation systems, the Leeds and Northrup potentiometer in the 1978-1979 data (Kellogg vineyard), and the Kaye Instruments digital potentiometer for the 1980 data, were quite different. All 24 channels of the Leeds and Northrup potentiometer were used to record temperatures of six heights: surface, 1.0, 3.7, 8.0, and 15.2 meters. Six sets of four dots that corresponded to the temperature at each height were recorded on a Fahrenheit strip chart every half hour. Based upon the location of these dots, the most-likely temperature to the nearest 0.5°F was noted. The digital instrument, however, was specifically programmed to record temperatures (°F) at the six heights to the nearest 0.1°F: 1.0, 2.9, 6.4, 9.8, 12.8, and 17.4 meters once each hour. The inversions that were obtained from this set of data were rounded off to the nearest 0.5°F to be consonant with the resolution of the Leeds and Northrup potentiometer.

Figures 32 through 46 are 15 graphs of temperature

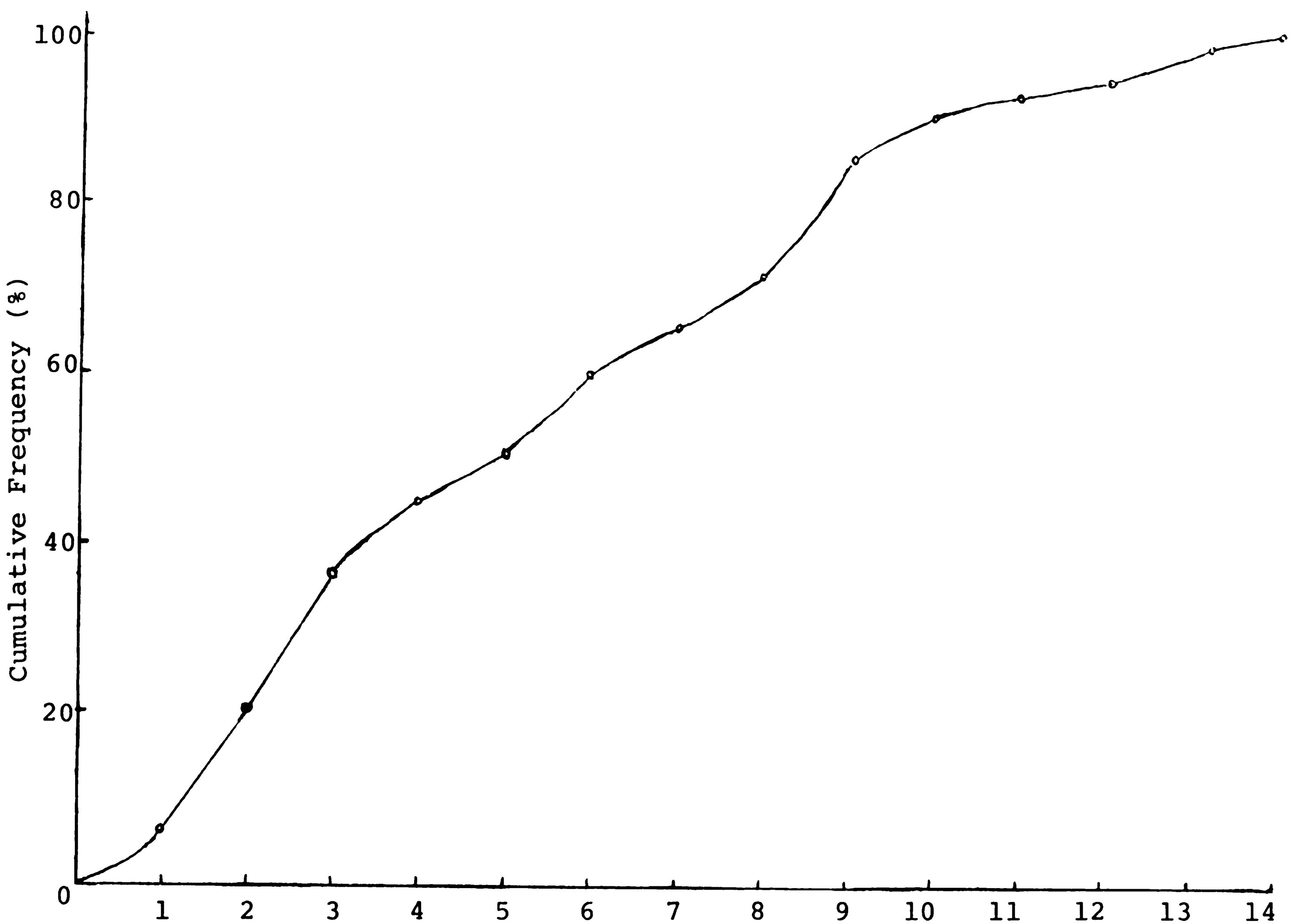


Figure 30. Inversion Strength (°F) When 1 m Temp ≤ 4 5°F

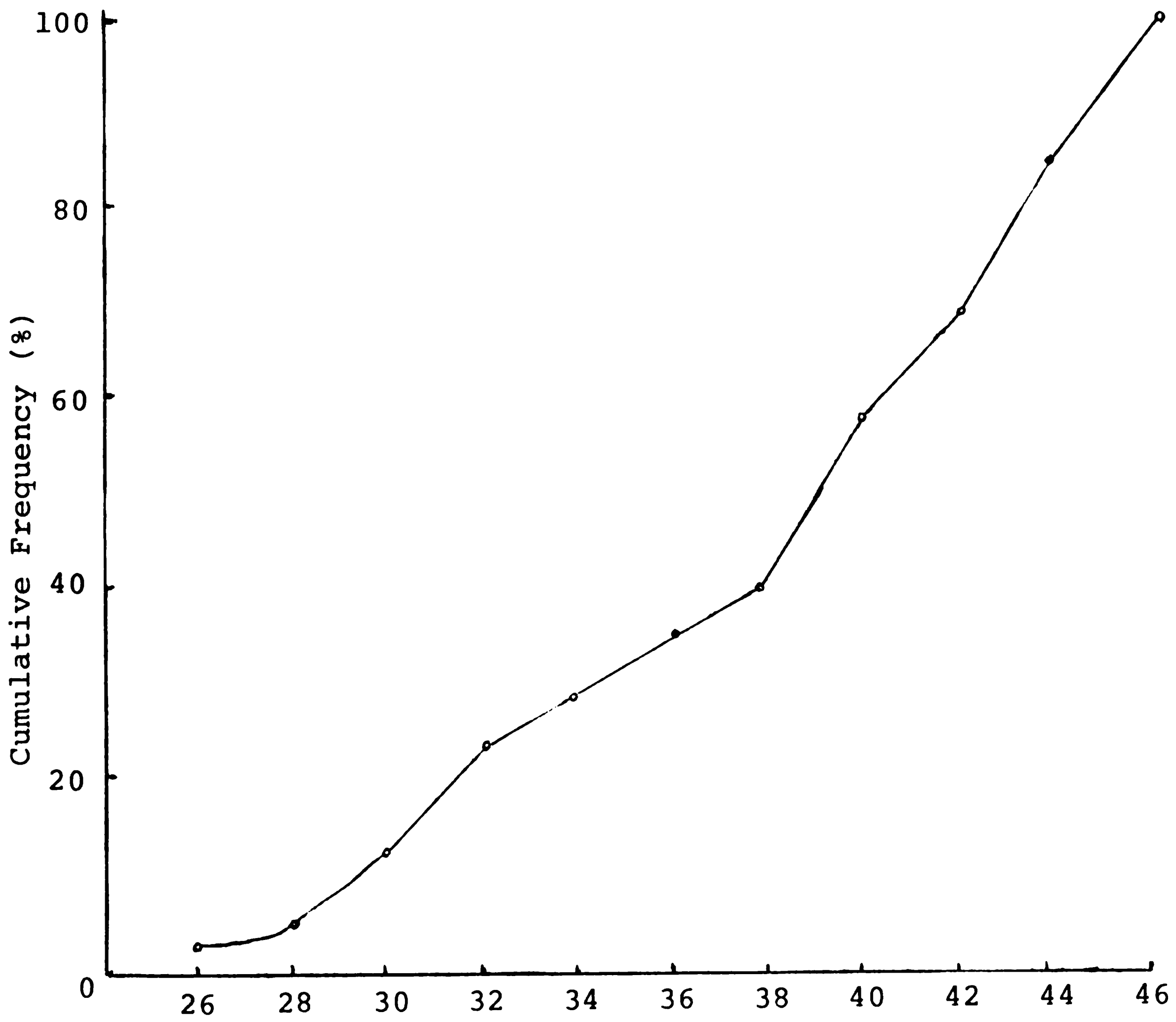


Figure 31. Temperature (^{O}F) at 1 m when inversions of $\geq$ 1^{O}F were occurring.

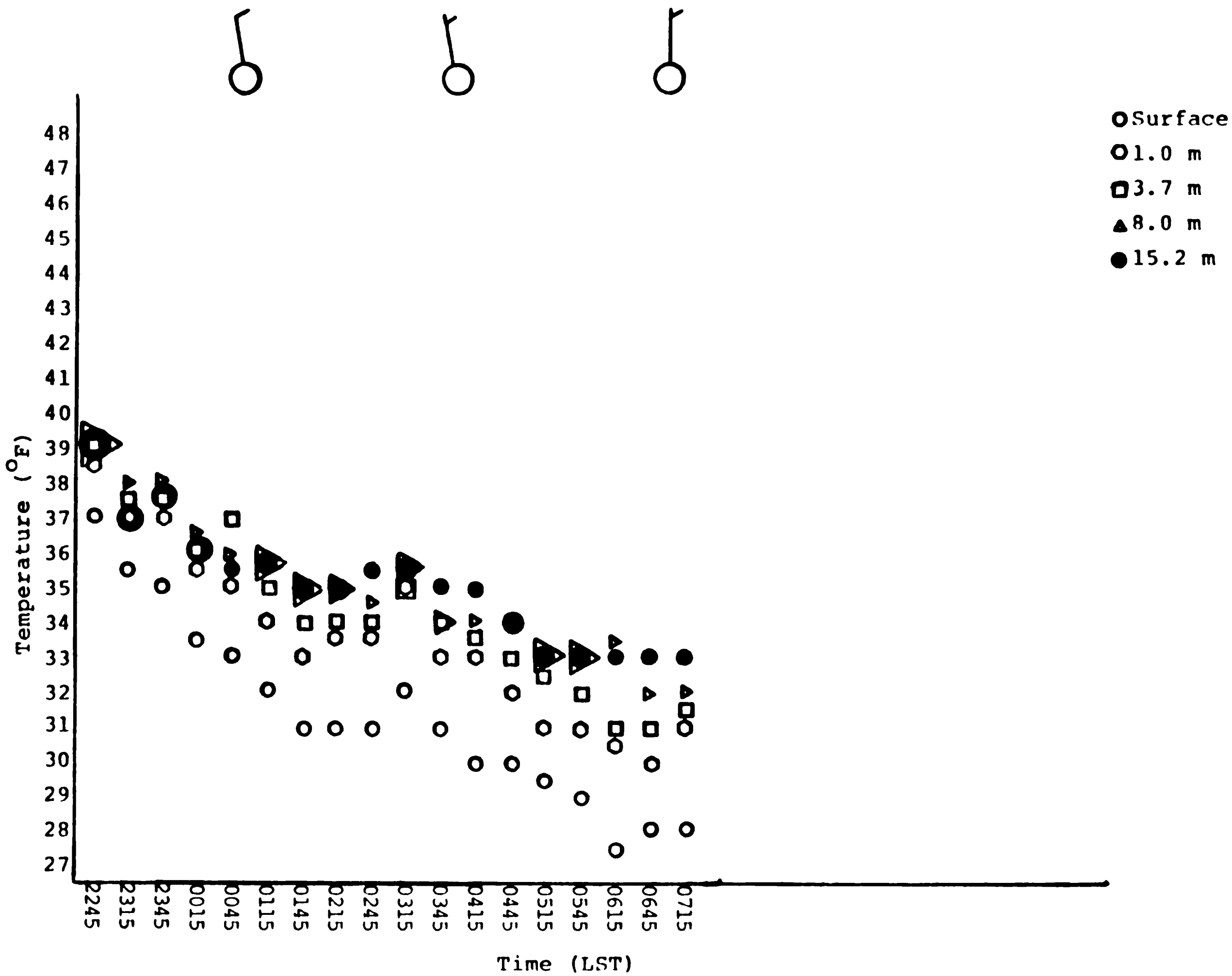


Figure 32. Vineyard temperature profile on April 16-17, 1979 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

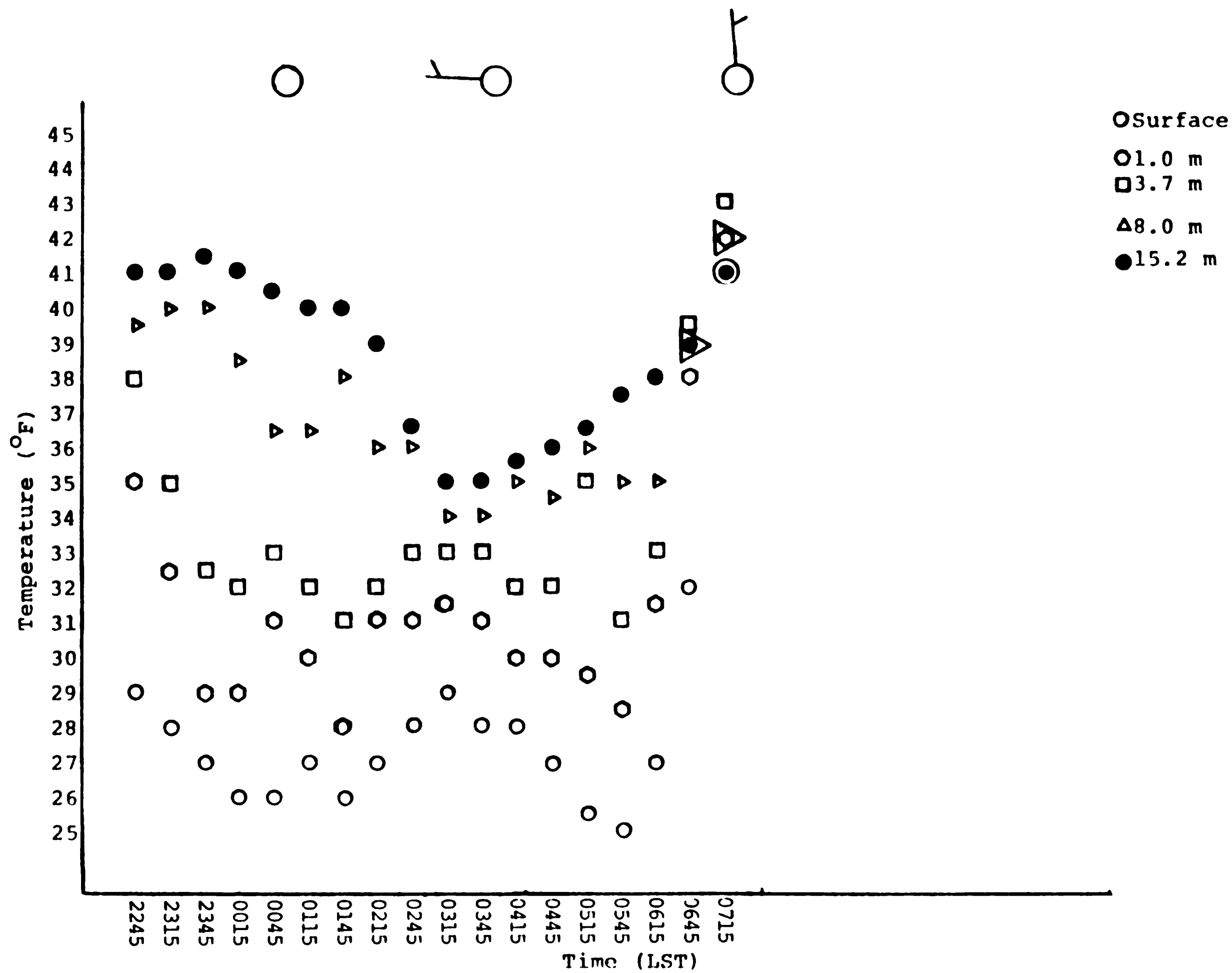


Figure 33. Vineyard temperature profile on April 17-18, 1979 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

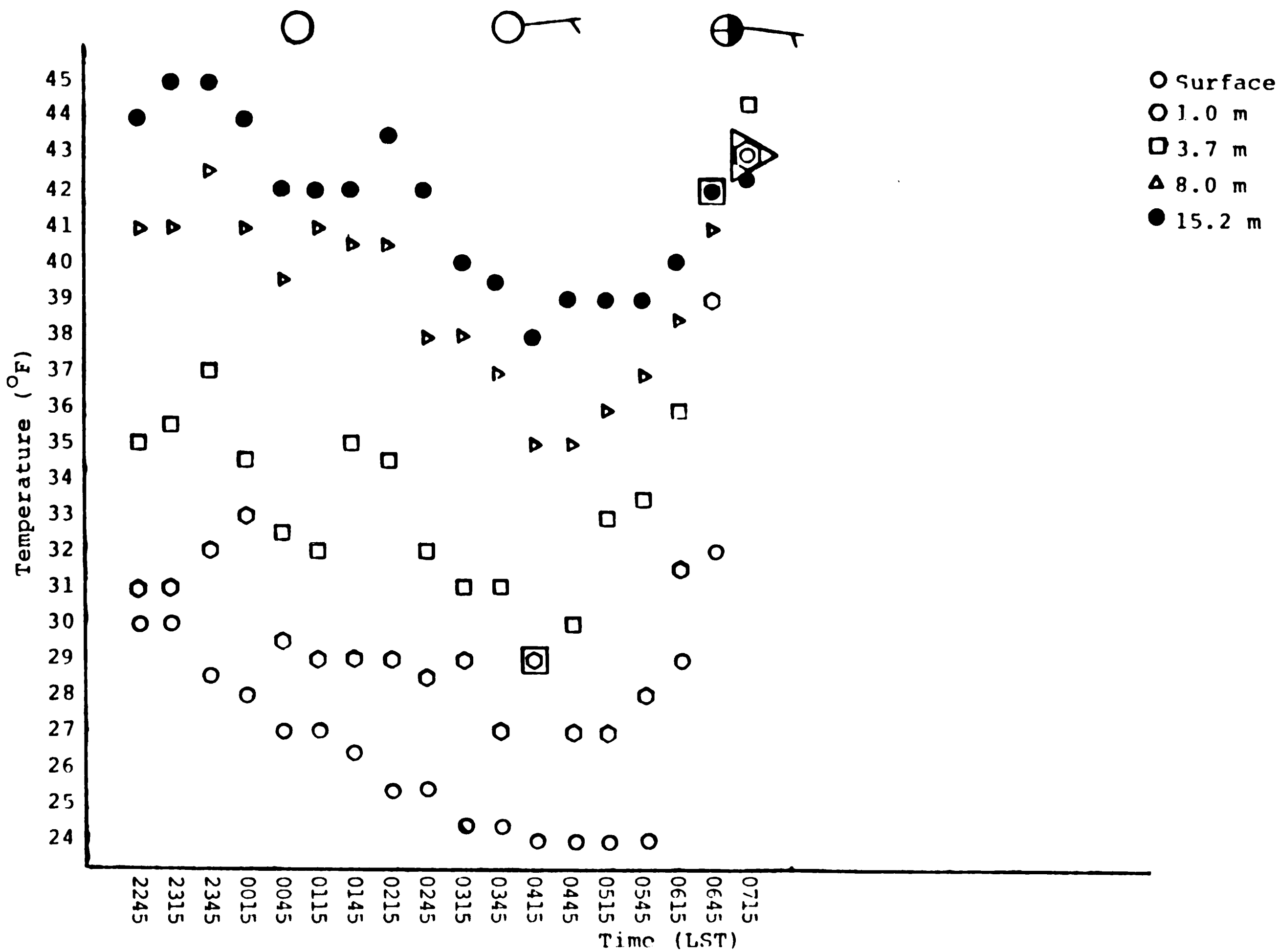


Figure 34. Vineyard temperature profile on April 18-19, 1979 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

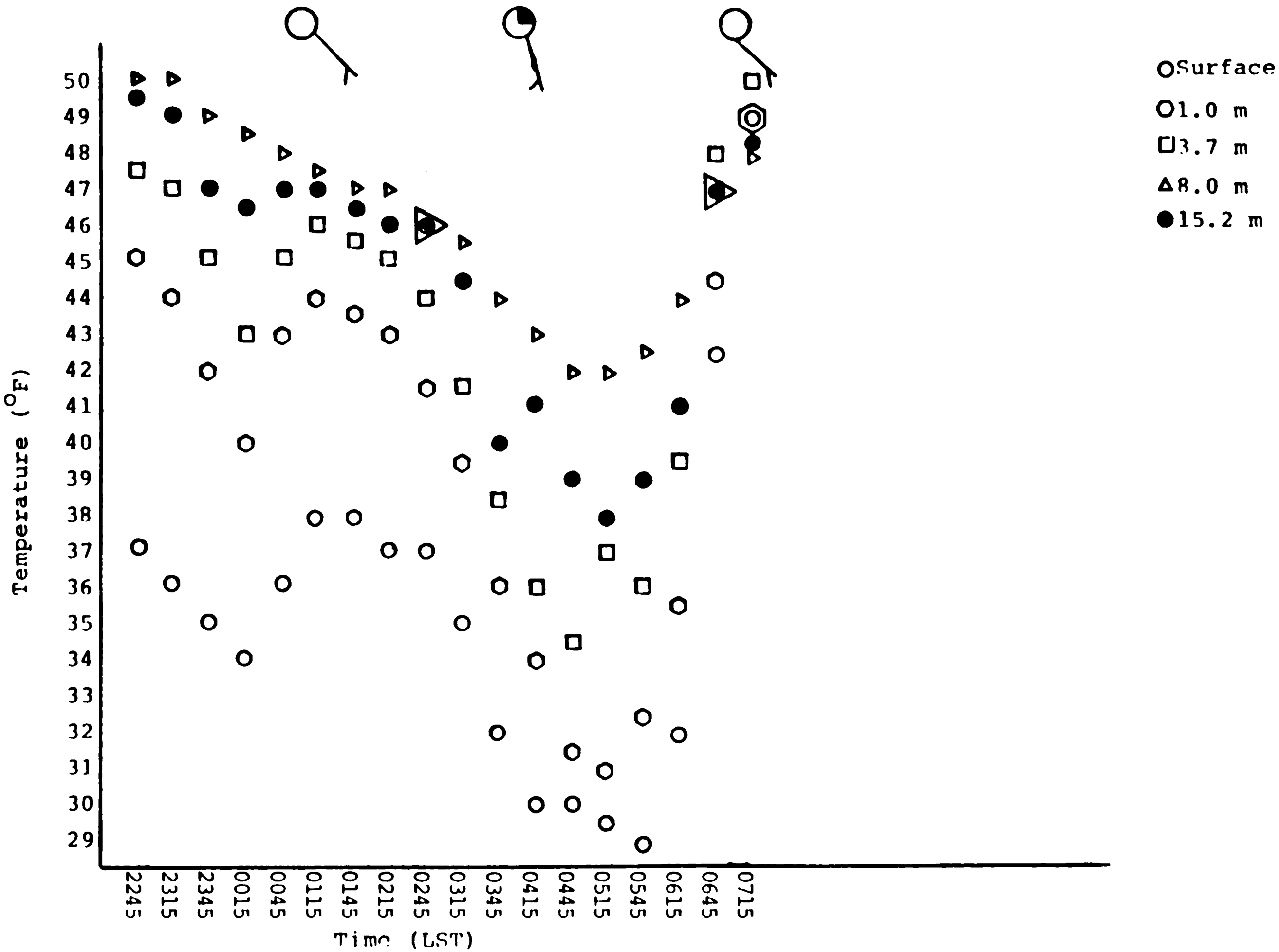


Figure 35. Vineyard temperature profile on April 19-20, 1979 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

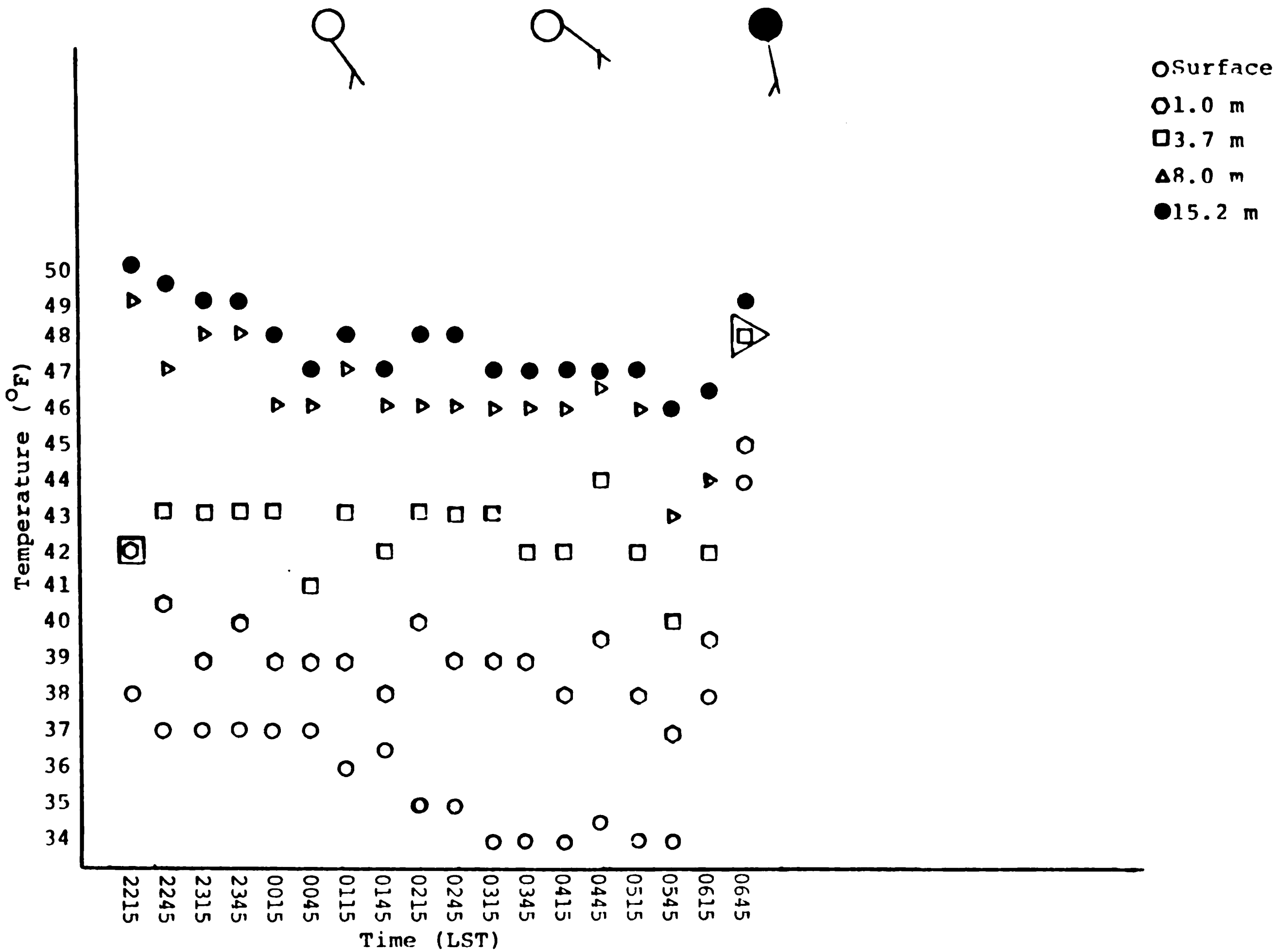


Figure 36. Vineyard temperature profile on April 22-23, 1979 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction and cloud cover indicated at top.

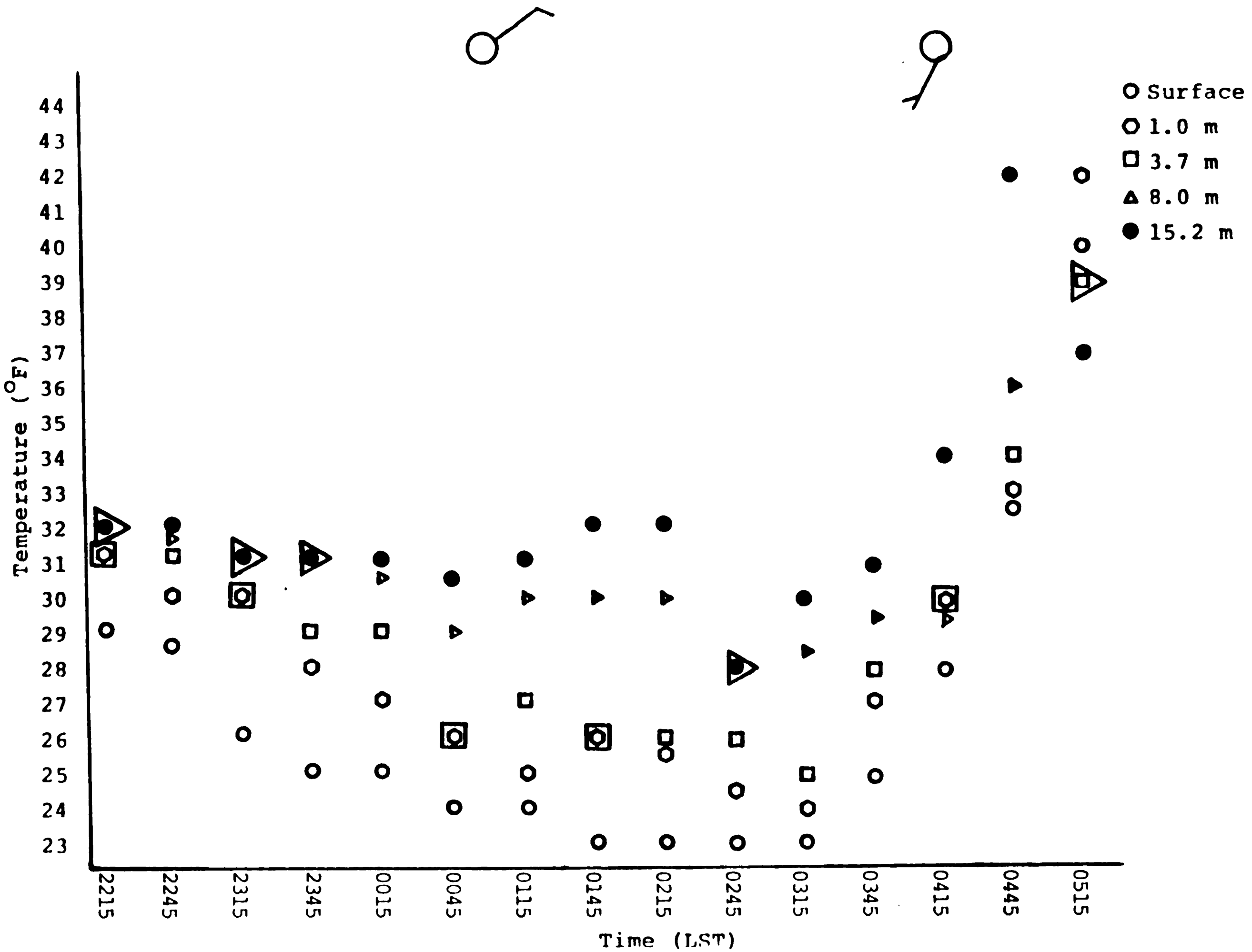


Figure 37. Vineyard temperature profile on April 30-May 1, 1979 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

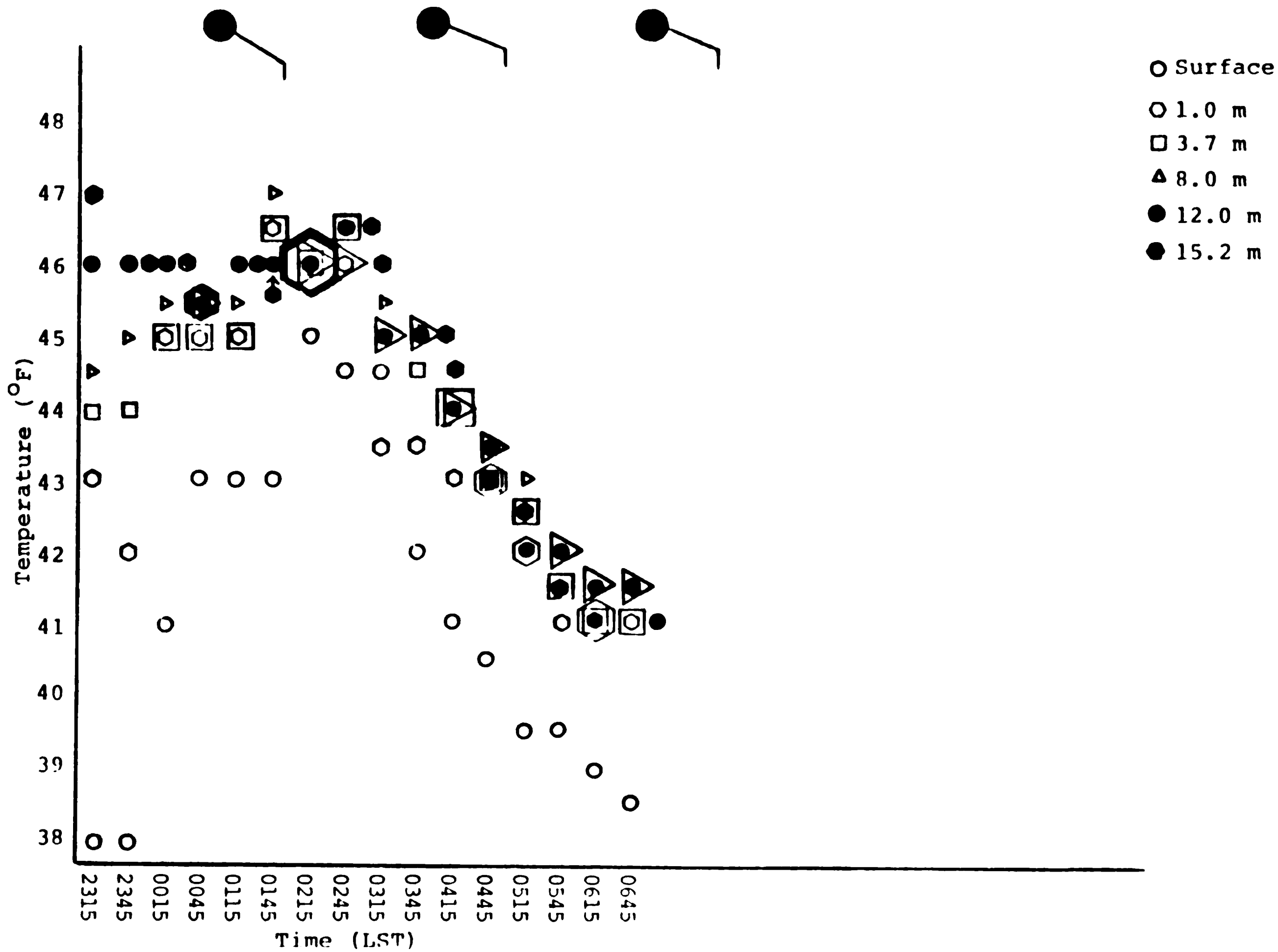


Figure 38. Vineyard temperature profile on May 1-2, 1979 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction and cloud cover indicated at top.

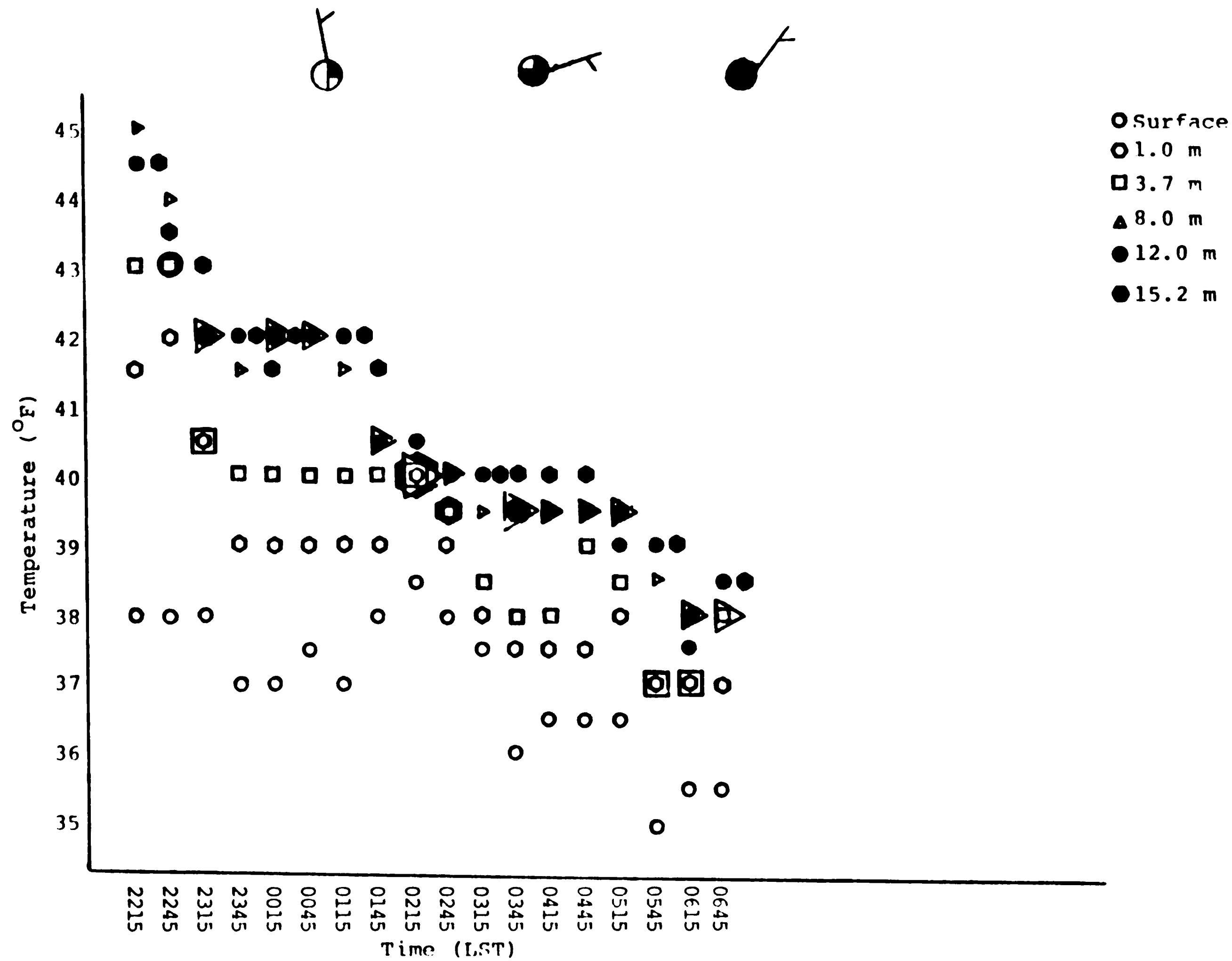


Figure 39. Vineyard temperature profiles on May 3-4, 1979 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

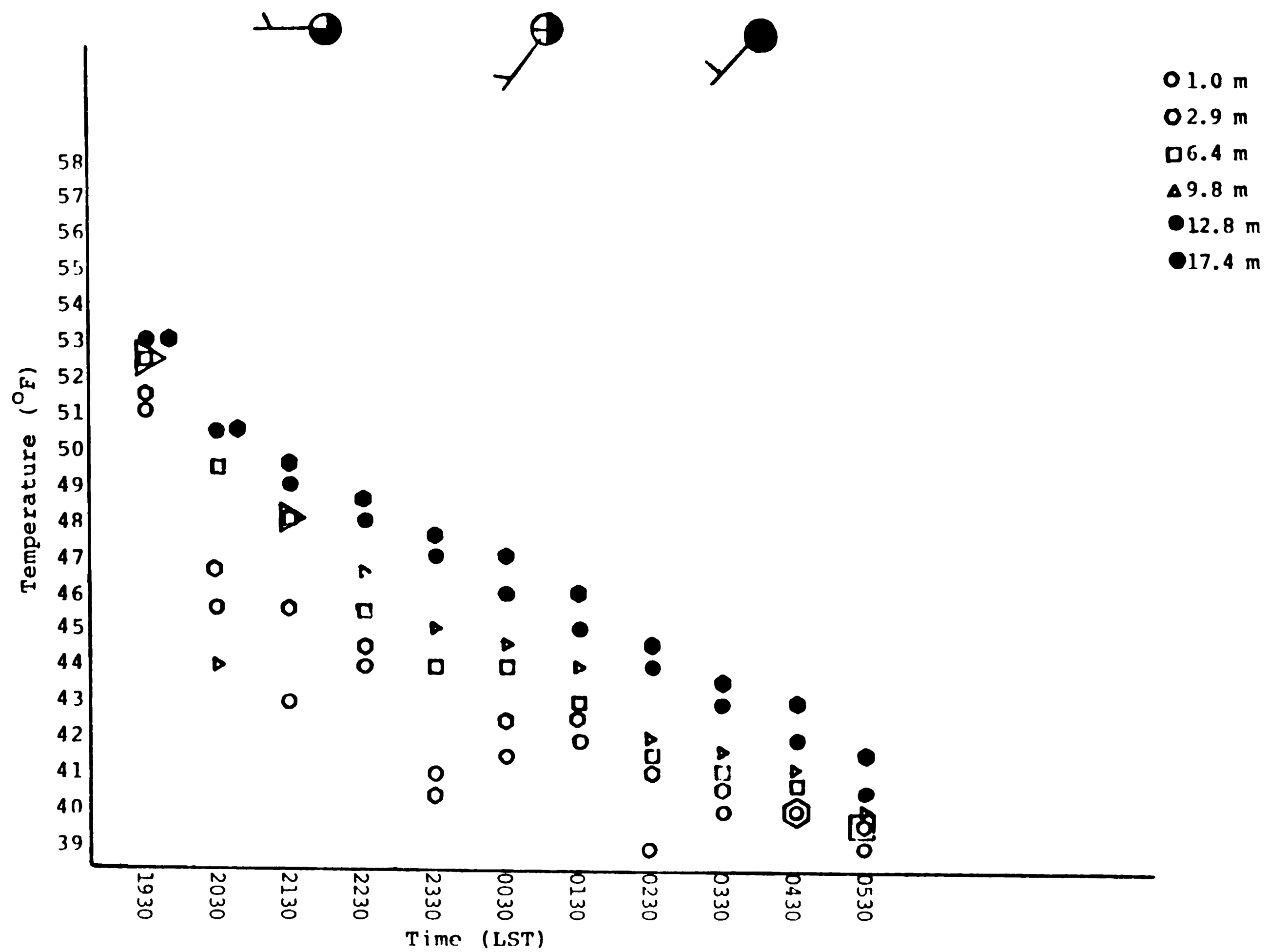


Figure 40. Vineyard temperature profile on April 30-May 1, 1980 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

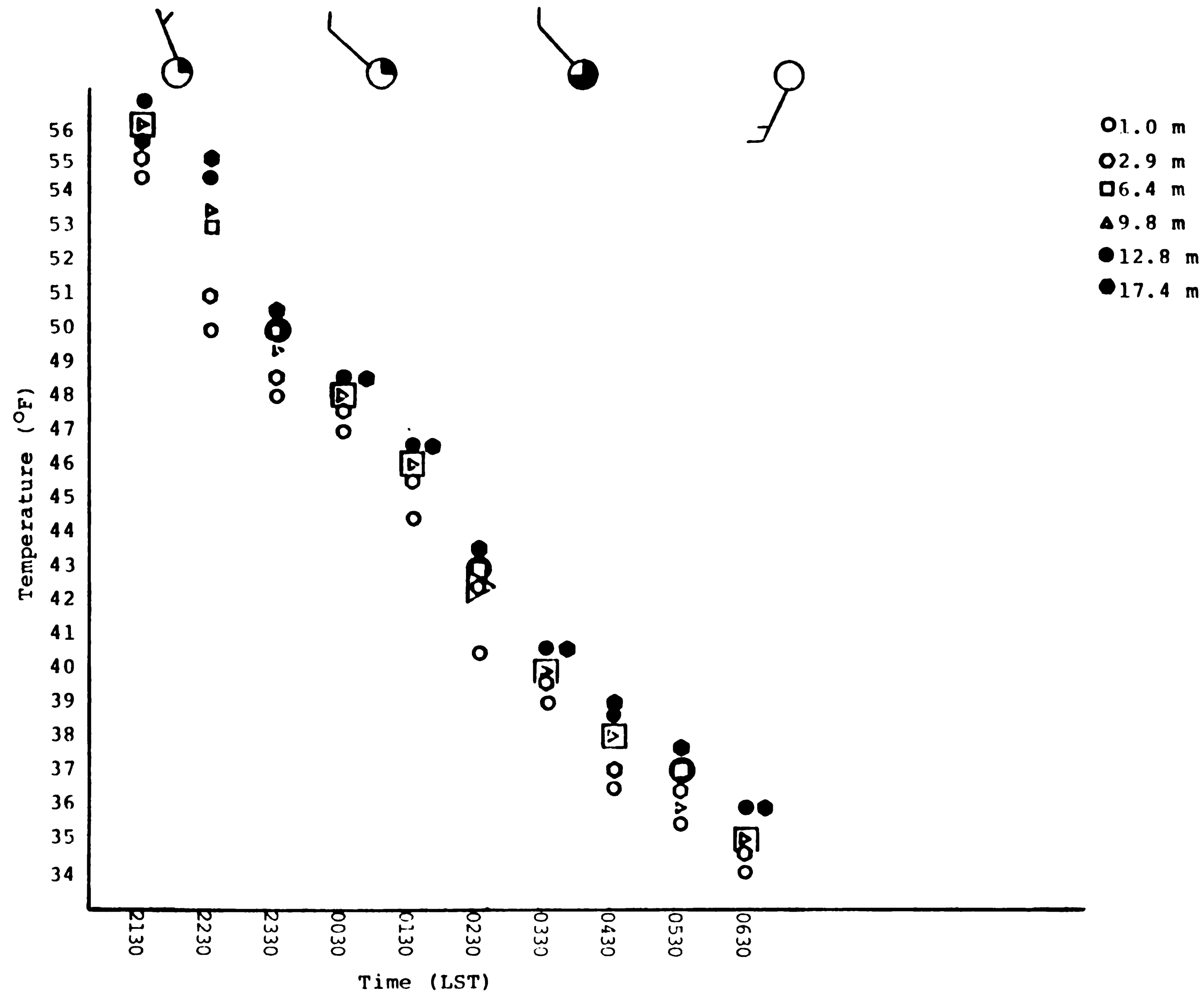


Figure 41. Vineyard temperature profile on May 6-7, 1980 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

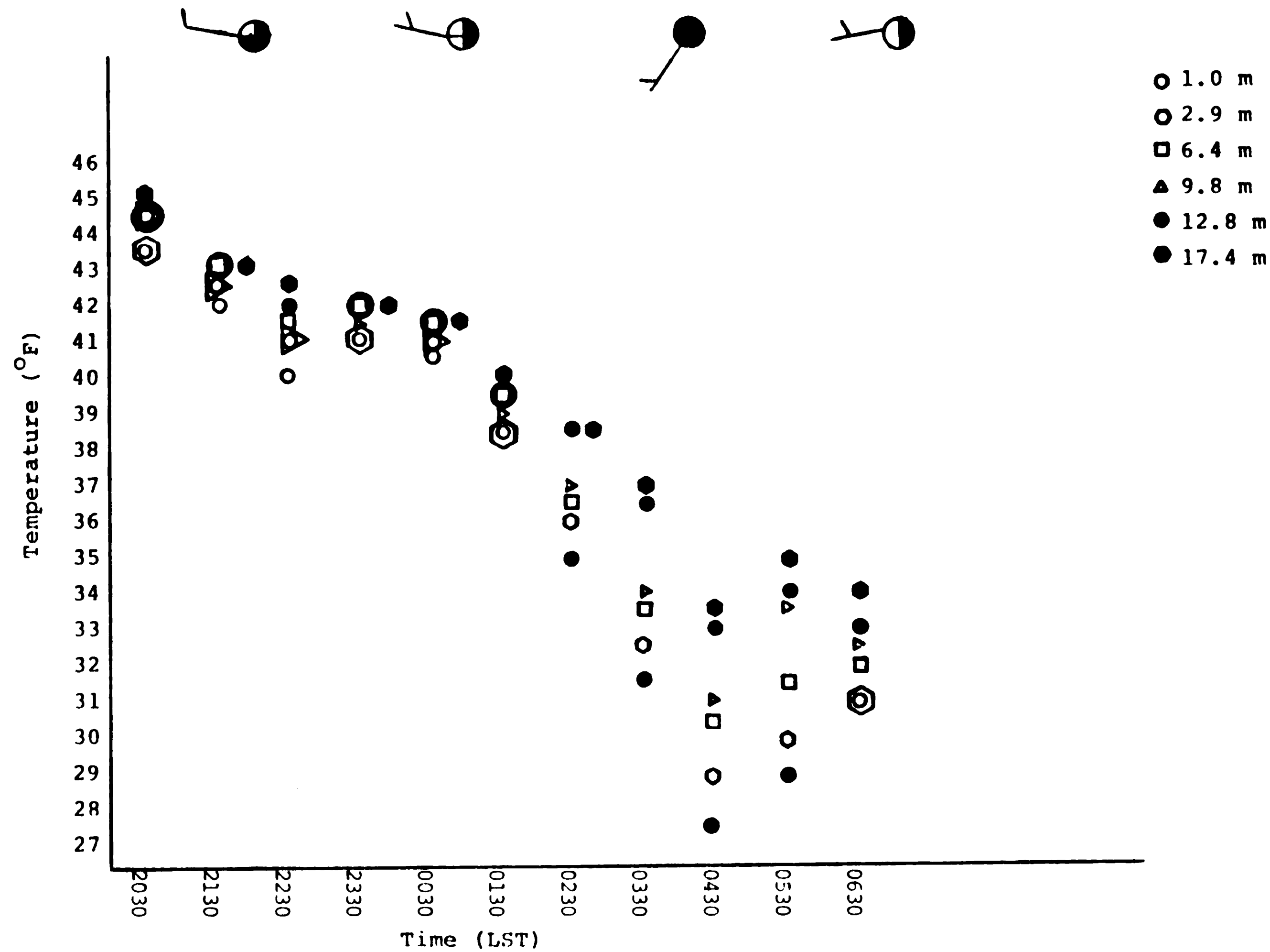


Figure 42. Vineyard temperature profile on May 8-9, 1980 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

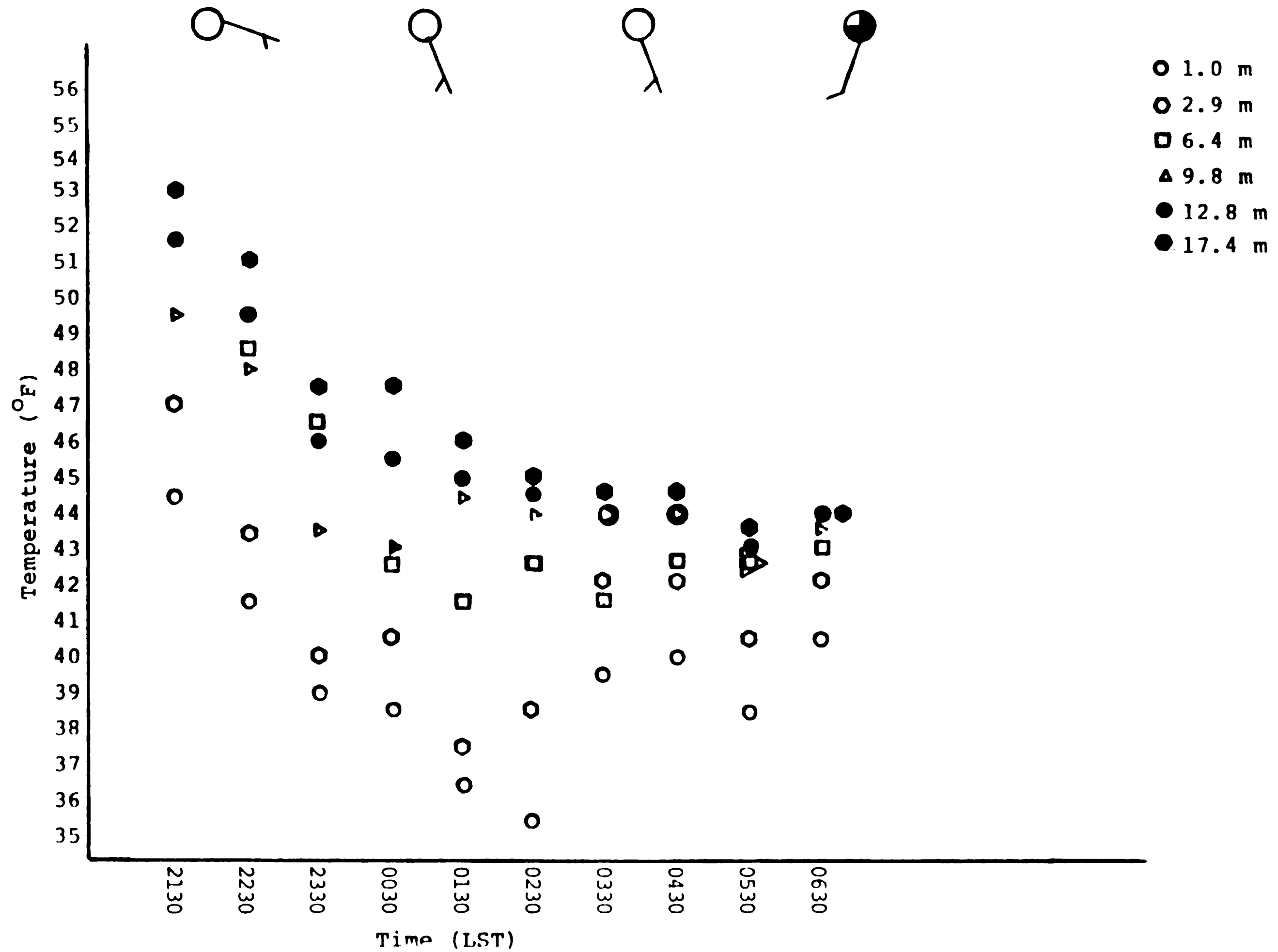


Figure 43. Vineyard temperature profile on May 9-10, 1980 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

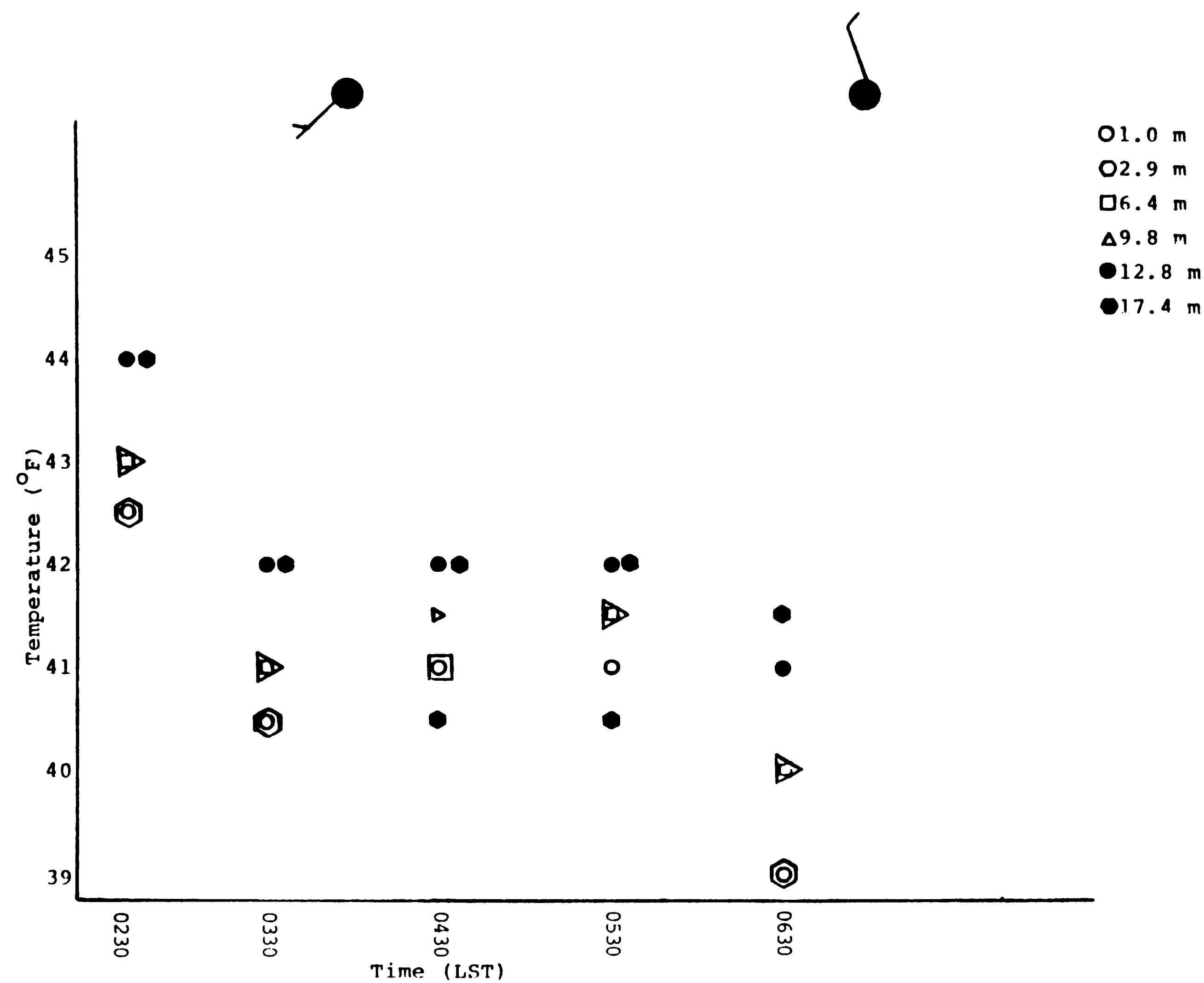


Figure 44. Vineyard temperature profile on May 14, 1980 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

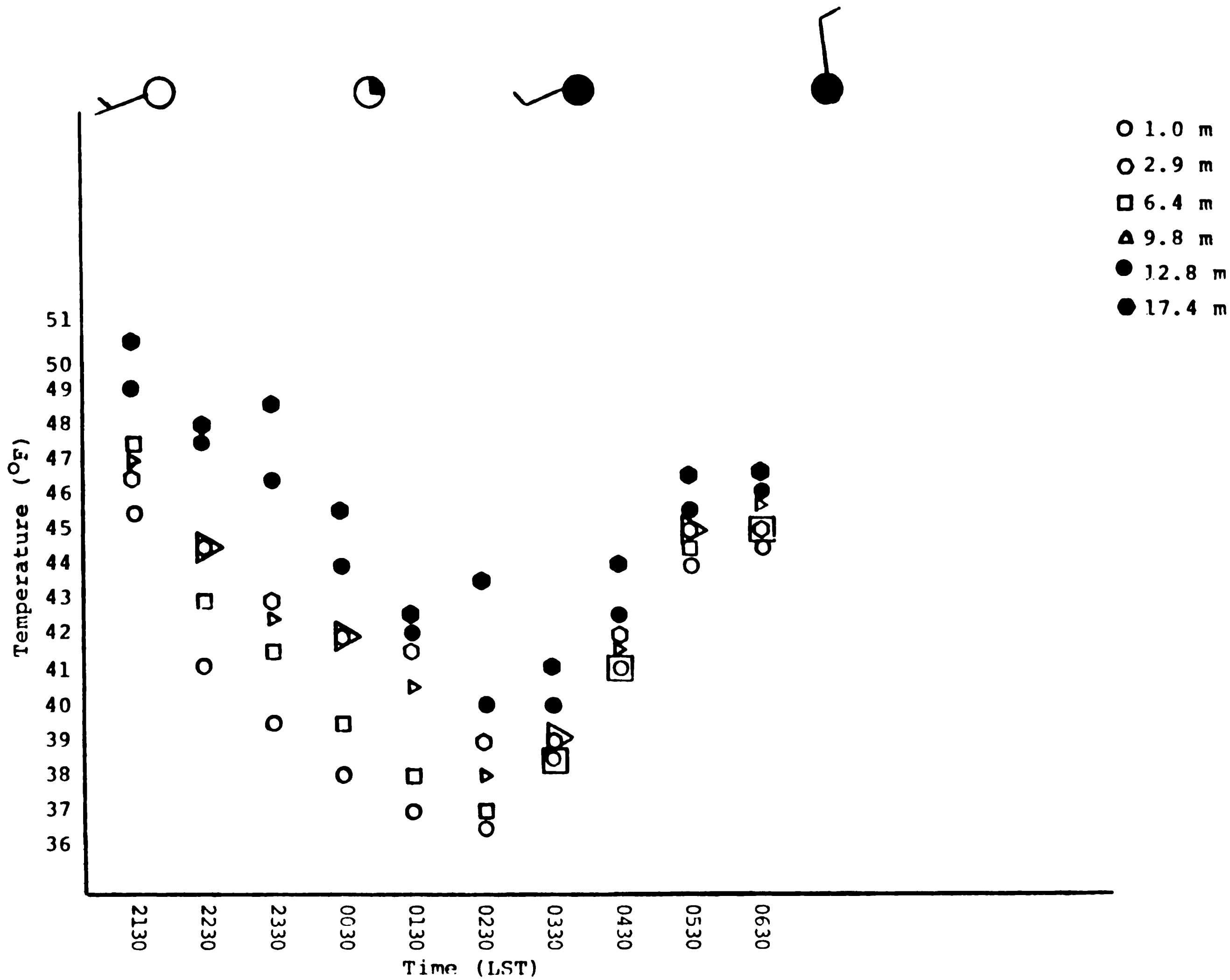


Figure 45. Vineyard temperature profile on May 14-15, 1980 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

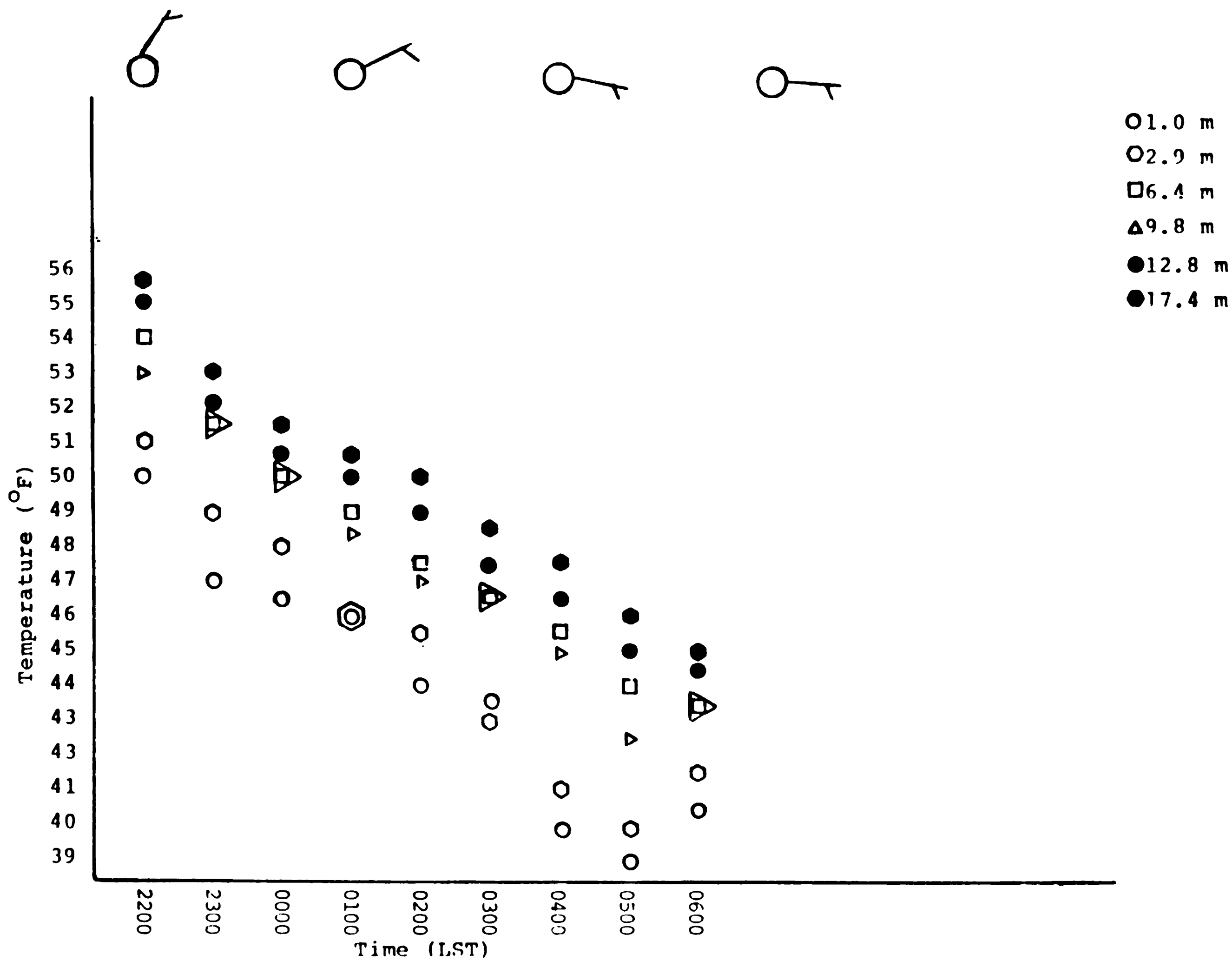


Figure 46. Vineyard temperature profile on May 15-16, 1980 at Texas Corners, Michigan. Grand Rapids wind speed, wind direction, and cloud cover indicated at top.

versus time for each height during selected evenings. The criteria for selecting the evening were that the minimum temperature at the 1-meter level was 45°F or less, and that inversions greater than 1.0°F were consistently occurring. As a source of information for the prevailing weather conditions during the chosen evenings, the "Local Climatological Data" for the National Weather Service office at the Kent County Airport at Grand Rapids was consulted. The data available from this publication are listed in Tables 13 and 14, and contain the following information: hour, sky cover (tenths), ceiling (hundreds of feet), temperature and dew point (°F), relative humidity (percent), wind direction (tens of degrees from true north) and wind speed (knots).

For the time period 10 p. m. through 4 a. m. for 8 of the 15 nights, the cloud cover at Grand Rapids was 3/10 or less. Most of the cloud cover observations during these nights were reported as clear skies. The first four graphs were the consecutive nights April 16 through April 19, 1979, when data were collected during the passage of a particularly strong high pressure system. Calm winds were reported during three of these nights.

The night of April 30, 1979 was the coldest recorded at Grand Rapids for the 15 nights in the case study. The 4 a. m. temperature was 24°F (which was also the minimum temperature), and the 15.2 m temperature was

TABLE 13

WEATHER CONDITIONS AT GRAND RAPIDS FOR SELECTED NIGHTS DURING THE SPRING OF 1979

Date (1979)	Hour	Sky Cover (Tenths)	Ceiling (100s of ft.)	Temp.	Dew Point	Rel. Hu-midity	Wind Dir.	Speed
Ap. 16	10 p.m.	0	Unlim.	44	36	74	33	8
17	1 a.m.	0	Unlim.	40	34	79	35	9
17	4 a.m.	0	Unlim.	36	31	82	33	7
17	7 a.m.	0	Unlim.	34	30	85	36	6
Ap. 17	10 p.m.	0	Unlim.	42	28	58	01	6
18	1 a.m.	0	Unlim.	39	27	62	00	0
18	4 a.m.	0	Unlim.	34	27	76	28	4
18	7 a.m.	0	Unlim.	35	28	76	35	4
Ap. 18	10 p.m.	0	Unlim.	43	30	60	17	5
19	1 a.m.	0	Unlim.	41	30	65	00	0
19	4 a.m.	0	Unlim.	34	30	85	08	4
19	7 a.m.	6	Unlim.	37	30	76	10	3
Ap. 19	10 p.m.	3	Unlim.	50	34	54	00	0
20	1 a.m.	0	Unlim.	44	35	71	13	5
20	4 a.m.	2	Unlim.	44	33	65	16	4
20	7 a.m.	0	Unlim.	41	33	73	15	6
Ap. 22	10 p.m.	0	Unlim.	50	40	69	28	4
23	1 a.m.	0	Unlim.	46	40	80	15	4
23	4 a.m.	0	Unlim.	42	39	89	12	3
23	7 a.m.	10	Unlim.	59	40	50	16	5
Ap. 30	10 p.m.	0	Unlim.	37	30	76	30	7
May 1	1 a.m.	0	Unlim.	32	29	89	05	10
1	4 a.m.	0	Unlim.	29	26	89	21	4
1	7 a.m.	3	Unlim.	31	29	92	00	0 (GF)
May 1	10 p.m.	7	Unlim.	44	37	76	11	6
2	1 a.m.	10	150	46	35	66	13	9
2	4 a.m.	10	150	46	35	66	12	10
2	7 a.m.	10	120	45	34	65	12	9
May 3	10 p.m.	0	Unlim.	46	33	61	33	5
4	1 a.m.	4	Unlim.	41	33	73	35	6
4	4 a.m.	8	Unlim.	38	33	82	07	4
4	7 a.m.	10	250	38	32	79	05	7

SOURCE: Local Climatological Data for Grand Rapids, published by the USDC/NOAA/EDIS National Climatic Center

TABLE 14

WEATHER CONDITIONS AT GRAND RAPIDS FOR SELECTED NIGHTS DURING THE SPRING OF 1980

Date (1980)	Hour	Sky Cover (Tenths)	Ceiling (100s of ft.)	Temp.	Dew Point	Rel. Hu-midity	Wind Dir.	Speed
Ap. 30	10 p.m.	8	50	50	48	93	27	3
May 1	1 a.m.	6	90	45	45	100	22	3
1	4 a.m.	10	90	48	48	100	23	5
1	7 a.m.	10	45	49	49	100	25	5
May 6	10 p.m.	3	Unlim.	51	32	48	33	7
7	1 a.m.	2	Unlim.	44	35	71	30	10
7	4 a.m.	7	32	40	33	76	31	11
7	7 a.m.	0	Unlim.	41	33	73	29	15
May 7	10 p.m.	2	Unlim.	40	29	65	28	7
8	1 a.m.	10	100	38	33	82	25	6
8	4 a.m.	10	110	39	34	82	23	5
8	7 a.m.	10	44	40	33	76	34	8
May 8	10 p.m.	8	60	42	32	68	28	9
9	1 a.m.	6	Unlim.	34	30	85	29	5
9	4 a.m.	10	30	37	33	85	23	4
9	7 a.m.	5	Unlim.	39	34	82	26	4
May 9	10 p.m.	0	Unlim.	44	34	68	11	4
10	1 a.m.	0	Unlim.	41	33	73	16	6
10	4 a.m.	0	Unlim.	43	33	68	16	7
10	7 a.m.	8	Unlim.	49	34	56	19	9
May 14	10 p.m.	0	Unlim.	42	37	83	25	5
15	1 a.m.	2	Unlim.	39	36	89	00	0
15	4 a.m.	10	60	43	40	89	25	5
15	7 a.m.	10	40	45	42	89	35	8
May 15	10 p.m.	0	Unlim.	51	43	74	02	4
16	1 a.m.	0	Unlim.	45	40	83	06	3
16	4 a.m.	0	Unlim.	42	38	86	11	4
16	7 a.m.	0	Unlim.	49	42	77	10	6

SOURCE: Local Climatological Data for Grand Rapids, published by the USDC/NOAA/EDIS National Climatic Center

30^{O}F, indicating a 6^{O}F inversion. The 7 a. m. Grand Rapids wind speed was reported as calm.

The ceiling values recorded in Tables 13 and 14 were pertinent to the interpretation of vineyard temperature profiles. A four-degree inversion was initially recorded in the vineyard while the 10 p. m. Grand Rapids cloud cover was 7/10. Subsequent Grand Rapids observations were overcast skies, accompanied by lower ceilings as middle-level clouds (altostratus) moved in. The inversions after midnight were all very weak.

Wind-machine trials were performed on the night of May 3, 1979 and the results of these trials will be discussed in the next section. The Grand Rapids LCD listed 0 and 4/10 cloud cover at 10 p. m. and 1 a. m. respectively. Vineyard temperature inversions were approximately 3^{O}F until 2:15 a. m., when the 1.0 m and 15.2 m temperatures coincide. Visual observations in the vineyard confirm that skies became overcast at about this time. The sky condition retrogressed to partly cloudy in the early morning hours, and the temperatures returned to modest inversions.

Mostly cloudy conditions prevailed on the night of April 30, 1980, and skies became completely overcast during the following morning. Nevertheless, a 7^{O}F temperature inversion was recorded in the vineyard at 11:21 p. m. This coincided with a transition period at Grand Rapids from a 5000-foot ceiling at 10 p. m. (8/10 cloud cover) to a 9000-foot ceiling at 1 a. m. (6/10 cloud cover). Vineyard inversions oscillated between 3°F and 5.5°F until 6:30 a. m., when it was less than 1°F. The ceiling at Grand Rapids lowered to 4500 feet at 7 a. m. The wind speeds were light throughout the course of the evening, varying between 3 and 6 knots.

Unusually brisk northwest winds characterized the night of May 6, 1980. The largest vineyard inversion occurred at 10:30 p. m. when the 1.0 m temperature was 50°F, and the 17.4 m temperature was 55°F. The second largest temperature inversion was not observed until 6:30 a. m. the following morning, when the minimum vineyard temperature of 34°F was recorded. The Grand Rapids wind speed at 7 a. m. was 15 knots, which accounts for a relatively low temperature inversion despite clear skies and a near-freezing temperature.

No inversions existed after 1:30 a. m. on the morning of May 8, 1980, when temperatures rose in the vineyard and at Grand Rapids during the early-morning hours. The largest temperature inversion of 5.5°F was once again recorded at 10:30 p. m. All of the sky cover observations at Grand Rapids for this morning were of overcast skies.

Perhaps the most significant vineyard temperature observation occurred during the morning of May 9, 1980. For the hours of 8:30 p. m. through 12:30 a. m., vineyard temperature inversions were never greater than 2°F. The

Grand Rapids 10 p. m. wind speed was 9 knots, accompanied by a 6000-foot ceiling. At 1 a. m. the wind speed diminished to 5 knots and the ceiling became unlimited. Vineyard temperature inversions subsequently increased between 2:30 a. m. and 4:30 a. m. with a temperature inversion of 6°F and a 1.0 m temperature of 27.5°F.

The last three evenings of the case study were characterized by clear skies and unlimited ceiling, with the exception of the latter part of the morning of May 15, 1980.

Very strong temperature inversions highlighted the evening of May 9, 1980, with an 8°F to 9.5°F temperature inversion sustained for 6 hours. The minimum vineyard temperature that morning approached critical levels at 2:30 a. m., when the 1.0 m temperature was 35.5°F and the 17.4 m temperature was 45°F.

The night of May 14, 1980 was quite unique because the 1 a. m. Grand Rapids observations were 2/10 cloud cover, unlimited ceiling, and calm winds, but at 4 a. m. rain showers were reported. A 9°F temperature inversion was recorded at 11:30 p. m., with a 1.0 m reading of 39.5°F and an 8°F temperature inversion at 2:30 a. m. occurred with a 1.0 m reading of 36.5°F. Warm advection was evident after this time, as the 5:30 a. m. 1.0 m temperature was 44°F.

The final night of the case study was May 15, 1980, and a 4°F to 7.5°F temperature inversion was sustained for 10 hours under clear skies and an unlimited ceiling. The minimum 1.0 m temperature was 39°F at 5 a. m., while the 17.4 m temperature at this time was 46°F.

An examination of the data presented reveals several occasions when the nocturnal temperature inversions exceed 10°F. During the nights of April 17 and 18, 1979, inversions of 12°F were recorded, and an 11°F inversion was noted during the following night. The largest temperature inversion observed (during the course of this study) was 14°F, which occurred on May 22, 1980 at 4:00 a. m. while the 1.0 m temperature was 46°F. A 12.5°F inversion had been observed at the previous hour. At 1:00 a. m., May 27, 1980, a 13.5°F temperature inversion was recorded, with 10.5°F temperature inversions one hour before and one hour after that observation.

Table 15 is a comparison of the minimum temperatures at Grand Rapids, Kalamazoo, and the 1.0 m height in the vineyard for the 15 nights in the case study that have been discussed. Indeed, under the dominating high-pressure system during the nights of April 16 through April 19, 1979, on two occasions the vineyard minimum temperatures at 1.0 m were 9°F lower than the Kalamazoo minimum temperature. Although the vineyard minimum temperature would be expected to be lower than the minimum temperatures observed in the city, part of the temperature differences

TABLE 15

COMPARISON OF THE MINIMUM TEMPERATURES AT GRAND RAPIDS, KALAMAZOO, AND THE VINEYARD* FOR NIGHTS WHEN SIGNIFICANT TEMPERATURE INVERSIONS WERE OCCURRING

Date	Grand Rapids	Kalamazoo	Vineyard
April 17, 1979	34	34	30
April 18	33	35	28
April 19	32	36	27
April 20	39	40	31
April 23	41	45	37
May 1	28	29	24
May 2	45	42	41
May 4	37	37	37
May 1, 1980	44	45	39
May 7	36	32	34
May 8	36	39	35
May 9	32	34	28
May 10	40	41	36
May 15	38	42	37
May 16	40	44	39

*1.0 m height

must be attributed to differences in height of measure (Kalamazoo observations are recorded at roughly 1.5 m).

B. Wind-Machine Trials. Wind-machine trials were conducted on the nights of May 3 and May 15, 1979, in the vineyard owned by Peter Dragecivich (maintained with the assistance of Max Miller), located on South Sixth Street, Texas Corners, Michigan. The objective of this experiment was to establish the magnitude of the temperature rise at various locations in the vineyard during the operation of the wind machine.

Data that were gathered during this experiment are presented in Table 16, which lists the ambient temperature just prior to and during the wind-machine operation. The numbers 1 through 15 correspond to the location of minimum-temperature thermometers throughout the vineyard, which were mounted on posts at a height of 1.5 m. Seven minimum thermometers, corresponding to numbers 1 through 7 in Table 11, were all located along row #49, which is oriented north-south. Station #1 was at the northern end, station #7 was at the southern end, and the wind machine is in the center of the row. Station #4 was located approximately 1 m north of the wind machine. The other minimum-temperature thermometers along row #49 were placed an equal distance apart (30 m). The eight remaining thermometers were placed along an east-west perpendicular, four on each side of the wind machine beginning 12 rows from it (in the center of the vineyard). Stations #8, 9, 10, and 15 were located in rows #61, 67, 73 and 79, respectively. Stations #11, 12, 13, and 14 were located in rows #37, 31, 25, and 19, respectively. There are approximately 100 rows in the vineyard, and its approximate dimensions are 650 m by 180 m.

The wind machine ran twice on the morning of May 4, the first time for 18 minutes between 3:50 a. m. and 4:08 a. m., and the second time for 15 minutes between

TABLE 16

AMBIENT TEMPERATURES OBSERVED BEFORE AND DURING WIND-MACHINE OPERATION AT 15 LOCATIONS (MINIMUM TEMPERATURE THERMOMETERS AT THE 1½ METER LEVEL) IN THE MILLER VINEYARD, SOUTH 6th STREET, NEAR TEXAS CORNERS, MI, THE MORNING OF MAY 4, 1979 (°F)

Station Number	Before Wind Machine Operation (5:05 a.m.)	During Wind Machine Operation (5:15 a.m.)
1	37.0	38.0
2	37.5	37.5
3	36.5	37.0
4	35.5	37.0
5	35.5	37.0
6	36.5	37.5
7	36.0	37.5
8	37.0	37.5
9	36.0	37.0
10	36.5	37.0
11	36.5	37.5
12	36.0	37.0
13	36.5	37.5
14	36.0	37.0
15	36.5	37.0

5:15 a. m. and 5:30 a. m. A thermograph was placed beside the instrumentation in the Kellogg vineyard, and it continuously monitored the ambient temperature throughout the course of the evening. The instantaneous 1.0 m temperature on the instrumentation tower agreed with the thermograph tracing for this time period.

Wind drift was determined prior to the first wind machine trial by a hot-wire anemometer between 1:50 a. m. and 2:45 a. m. A fairly light, steady breeze was observed, whose magnitude was usually from 1 to 2 m/s. The hot-wire anemometer malfunctioned at about this time, so that Table 16 only contains the ambient temperatures at 4:59 a. m. to 5:05 a. m., and the temperatures during the wind-machine operation, which began at 5:15 a. m. and ended at 5:30 a. m. Vine temperatures were periodically monitored at this time, and were consistently 1.5°F below the air temperature.

The results of the first wind machine trial (data is not shown) showed that temperatures actually decreased during its operation. Although the early-morning hours were characterized by weak inversions (the 3:45 and 4:15 a. m. temperature inversions were 2.5°F), substantial wind drift hampered the wind machine's effectiveness. However, the results of the second wind machine trial can at best be described as promising. The wind drift was much less during this time, and was visually observed to be calm or extremely light. Several stations, particularly those closest to the wind machine, recorded a temperature response of 1.0°F to 1.5°F (Table 16). The 1.0 m temperature (ambient temperature) at 5:45 a. m. was 37°F, which was a decrease of 1.0°F from the 5:15 a. m. observation, and the temperature inversion increased slightly to 2.0°F at 5:45 a. m.

Some additional observations of wind-machine gusts in a cherry orchard in Mattawan and in the Del Kellogg vineyard near Texas Corners were recorded on the morning of May 16, 1979. The temperature fluctuations at 7 a. m. in the Kellogg vineyard (½ km south of the Miller vineyard on 6th Street) were monitored by a hand-held digital thermometer. The series of temperatures that were the immediate temperature response to a wind-machine passage at several locations over a time period of 10 to 15 seconds were noted. The sequence indicated a rapid drop in temperature due to the influx of cold air at the surface, followed by a gradual rise. The time of arrival of the wind-machine gust from when the propeller blade was facing perpendicular to the observer, the time required to achieve maximum wind speed, and the end of the temperature cycle were also noted. The maximum wind speed of the gust decreased with distance from the wind machine, as evidenced by the quicker, more dramatic end to the wind-machine gust. Earlier that morning, temperature responses to the wind-machine passage were observed in Bob Kellogg's cherry orchard in Mattawan.

Both of the vineyards are very flat, whereas the cherry orchard contains numerous hollows. The first temperature cycle was recorded in a slight hollow, and, therefore, shows an apparently larger response to the wind machine, despite the fact that it is farther away from the wind machine than where the second observation was taken. That night, Mr. Kellogg observed (with his own minimum temperature thermometer at 1½ m) a low temperature of 34°F in his deepest hollow, and was able to bring the temperature up to 40°F by using the wind machine.

3. Minimum Temperature Forecasting for Selected Agricultural Weather Stations in Western Michigan

The 4 p. m. temperature, dew point, and cloud cover at the Kent County Airport, Grand Rapids, during the years 1967 through 1976 were used to evaluate the Soderberg technique. Only nights when the Grand Rapids minimum temperature was less than or equal to 45°F for the period April 15 through June 15 were used. The springs of 1977 and 1978 were chosen to test the method.

Figures 47 and 48 provide the forecast temperature for Grand Rapids during non-advective nights under fair skies (0 through 5/10 cloud cover at 4 p. m.), and under cloudy skies (6/10 through 10/10 cloud cover at 4 p. m.), respectively. For nights when the absolute magnitude of the 850 mb temperature advection was anticipated to be greater than 2°C, a correction equation was used to adjust the Grand Rapids forecast. This was obtained by linear regression, in which Y was the correction that must be applied to the Grand Rapids forecast ($^{\circ}$F), and X was the corresponding 24 hour 850 mb temperature change ($^{\circ}$C). The resulting equation, which was based on the years 1967 through 1976, was:

$$Y = .34X + 3.58 \qquad r^2 = .76 \qquad (4.1)$$

In testing the method, the 850 mb temperature change was already known. However, for operational purposes, this parameter must be predicted by the forecaster.

Table 17 contains the results of taking the average difference between the minimum temperatures at the indicated agricultural station and Grand Rapids. This table is used in conjunction with the Grand Rapids forecast to obtain a forecast for the selected agricultural weather station.

The frequency distribution of weather conditions at Grand Rapids with respect to minimum temperature is reported in Table 18, where n represents the total number of observations. The term "weather condition" here refers primarily to cloud cover during the course of the evening. Clear skies (possibly with high cirrus) would indicate radiational cooling, and cloudy evenings would be classified according to whether cold or warm advection was occurring. Other criteria which played a role in this categorization were wind speed, wind direction, and the 24 hour 850 mb temperature change.

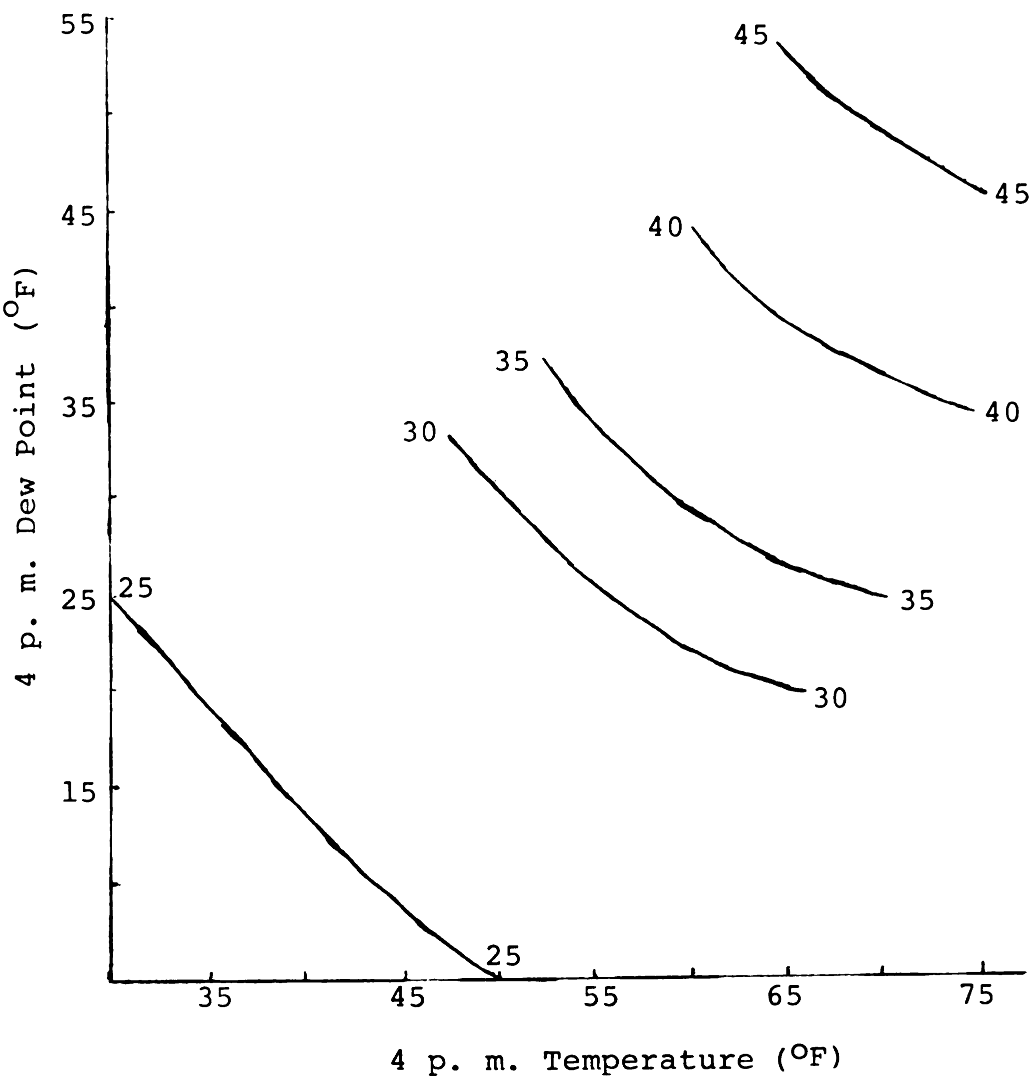


Figure 47. Minimum temperature (°F) for non-advection nights when cloud cover at 4 p. m. ranges from 0 through 5/10. Data from April 15 through June 15, 1967 through 1976.

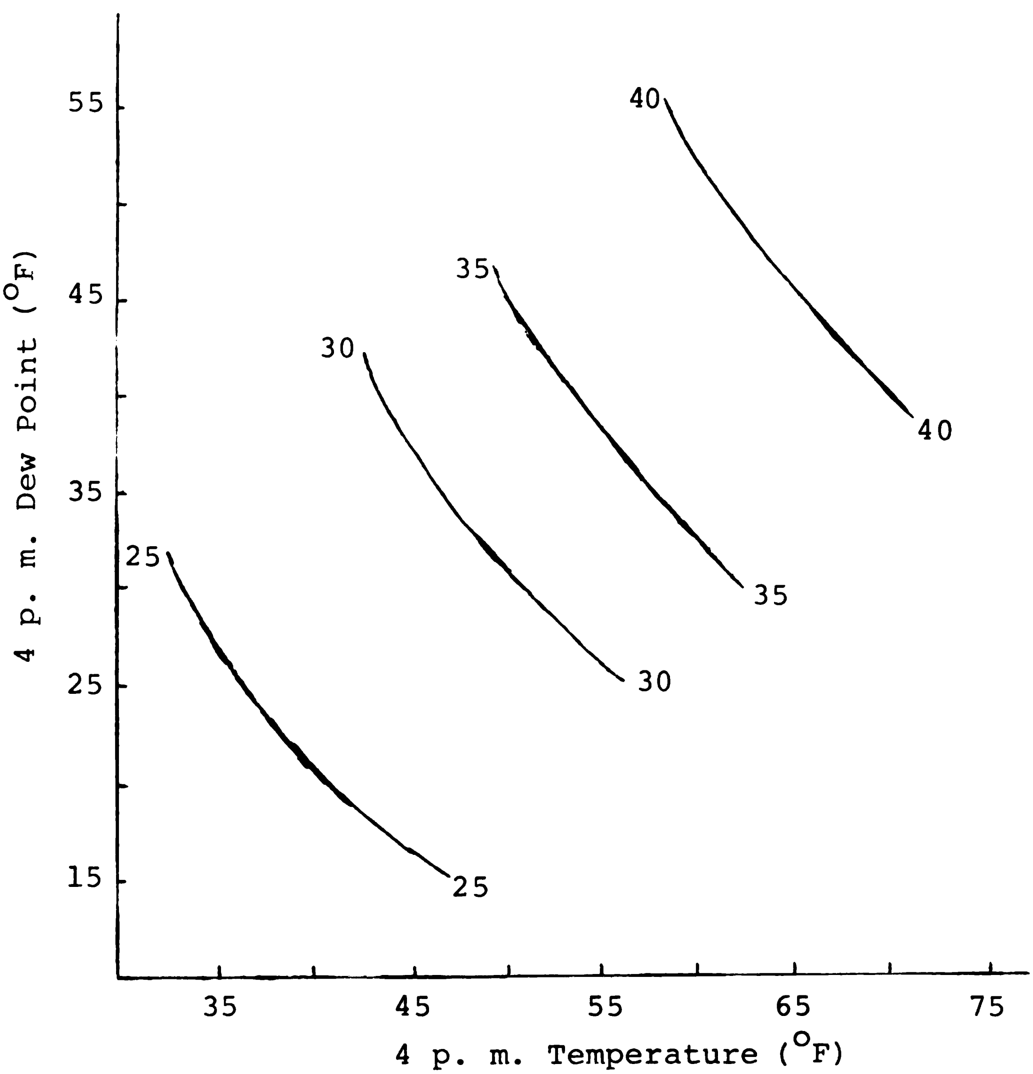


Figure 48. Minimum temperatures (°F) for non-advection nights when cloud cover at 4 p. m. ranges from 6/10 to 10/10. Data from April 15 through June 15, 1967 through 1976.

TABLE 17

AVERAGE DIFFERENCE IN MINIMUM TEMPERATURES BETWEEN THE INDICATED STATION AND GRAND RAPIDS (APRIL 15-JUNE 15, 1967-1976)

Station	Radiational Cooling	Cold Advection	Warm Advection
1. Belding	-1	1	2
2. Edmore	0	-1	-1
3. Empire	-1	-2	-2
4. Fremont	0	1	1
5. Glendora	0	2	2
6. Graham	1	2	2
7. Grand Junction	-2	1	0
8. Grant	-2	1	1
9. Holland	-1	2	2
10. Hudsonville	0	3	3
11. Kent City	-1	0	2
12. Kewadin	0	-2	0
13. Lake City	-3	-3	-2
14. Lake Leelanau	0	-3	-1
15. Lansing	0	0	0
16. Ludington	1	0	0
17. Mapleton	-1	-3	-1
18. Mears	2	0	1
19. Muskegon	2	1	0
20. Nunica	-2	1	1
21. Paw Paw	2	3	4
22. Peach Ridge	1	2	3
23. Sodus	6	4	5
24. Traverse City	-2	-3	-2
25. Watervliet	0	2	3

TABLE 18

FREQUENCY DISTRIBUTION OF WEATHER CONDITIONS AT GRAND RAPIDS, MICHIGAN ACCORDING TO MINIMUM TEMPERATURE (APRIL 15 THROUGH JUNE 15, 1967-1976)

n	Min. Temp.	Radiational	Cold Advection	Warm Advective	Advective-Radiative
143	36°F	62% (88)	22% (31)	15% (22)	1% (2)
185	38°F	59% (110)	23% (42)	16% (30)	2% (3)
224	40°F	59% (132)	22% (50)	17% (39)	1% (3)
316	45°F	49% (156)	27% (84)	21% (67)	3% (9)

The results of the minimum temperature forecasting scheme are presented in Table 19, which lists the average absolute error of the predictions, with the standard deviation in parentheses. The most noteworthy result is that the average absolute error of the prediction for Grand Rapids, under radiative conditions only, is 2.48°F. There are 31 radiative cases, and 18 advective cases. For all observations, the average absolute difference between the minimum temperature predictions using the Soderberg technique and the observed minimum temperatures was 4.10°F. Some of the larger errors resulted because agricultural weather stations have been moved during the period that this study covered, or have been located on soils of low thermal conductivity. For example, Empire has been moved

TABLE 19

AVERAGE ABSOLUTE DIFFERENCE BETWEEN THE MINIMUM TEMPERATURE PREDICTIONS USING THE SODERBERG TECHNIQUE AND THE OBSERVED MINIMUM TEMPERATURE

Station	All Observations		Radiative Only		Advective Only	
1. Grand Rapids	3.10	(2.31)	2.48	(1.71)	4.16	(2.83)
2. Belding	3.00	(2.63)	3.08	(2.64)	2.88	(2.70)
3. Edmore	3.66	(2.79)	3.79	(2.58)	3.00	(2.96)
4. Empire	5.31	(3.21)	5.55	(3.37)	4.89	(2.95)
5. Fremont	2.88	(2.17)	2.86	(1.46)	2.93	(3.17)
6. Glendora	3.65	(2.29)	3.64	(2.23)	3.67	(2.50)
7. Graham	2.83	(2.38)	2.65	(2.32)	3.18	(2.53)
8. Grand Junction	4.92	(2.82)	4.97	(2.71)	4.82	(3.09)
9. Grant	4.02	(2.59)	4.10	(2.45)	3.89	(2.87)
10. Holland	5.45	(3.65)	4.84	(2.66)	6.50	(4.82)
11. Hudsonville	3.88	(2.70)	3.42	(2.51)	4.67	(2.89)
12. Kent City	3.00	(2.57)	2.94	(2.70)	3.09	(2.47)
13. Kewadin	3.61	(3.21)	3.39	(3.35)	4.00	(3.01)
14. Lake City	4.57	(3.77)	4.87	(3.86)	4.06	(3.65)
15. Lake Leelanau	5.30	(3.80)	5.39	(4.02)	5.13	(3.42)
16. Lansing	3.51	(2.99)	3.29	(2.37)	3.89	(3.88)
17. Ludington	4.35	(3.31)	4.81	(3.27)	3.56	(3.31)
18. Mapleton	4.88	(3.16)	4.65	(2.90)	5.29	(3.64)
19. Mears	3.59	(3.19)	3.44	(3.15)	3.81	(3.35)
20. Muskegon	3.33	(2.63)	2.90	(2.51)	4.06	(2.73)
21. Nunica	4.37	(2.74)	3.97	(2.26)	5.06	(3.39)
22. Paw Paw	4.77	(3.23)	4.77	(2.42)	4.78	(4.35)
23. Peach Ridge	3.29	(2.44)	3.35	(2.24)	3.17	(2.81)
24. Sodus	5.55	(3.40)	6.39	(3.40)	4.11	(2.97)
25. Traverse City	5.14	(3.77)	5.32	(3.89)	4.83	(3.65)
26. Wavervliet	4.53	(2.99)	4.26	(2.99)	5.00	(3.01)

NOTE: Numbers in parentheses are standard deviations.

several times, and is now located in a relatively colder location approximately 1½ miles from Lake Michigan. The Holland and Grand Junction agricultural weather stations are both located on cold soils. Especially on radiative nights, Lake Leelanau will be relatively cold (as compared with Kewadin) due to northerly or northeasterly wind drift off the land. Lake Leelanau is located 2 miles due east of Lake Michigan.

Table 20 compares the prediction from the Soderberg method and the 4 p. m. dew point method forecasting the minimum temperature at Grand Rapids. The results are categorized according to whether 850 mb cooling, 850 mb warming, or no temperature change at 850 mb had occurred. Of these cases, 31 were considered to be radiative, and the average absolute error was found to be 6.45°F.

The frequency distribution of the absolute error of the Soderberg prediction method for Grand Rapids during 1977 and 1978 is presented in Table 21. This table shows that the minimum temperature prediction for Grand Rapids using the Soderberg technique is usually not more than 4°F. However, for more than half of the cases when no 850 mb temperature change was observed (i. e., radiative-freeze conditions), the Soderberg prediction was not in error by more than 2°F.

Table 22 reports the results of comparing the average absolute error of the MOS minimum temperature forecast (Jensensius et al., 1978) to the average

TABLE 20

COMPARISON BETWEEN MINIMUM TEMPERATURE FORECASTS USING THE "SODERBERG" PREDICTION METHOD AND THE "4 P. M. DEW POINT" METHOD FOR GRAND RAPIDS (1977 AND 1978)

Type of Temperature Change	Number of cases	Soderberg*	Dew Point**
850 mb cooling	12	3.08	8.58
850 mb warming	16	2.88	5.13
No 850 mb change (total)	21	2.53	7.14
Cloud cover 0 through 5/10	9	2.78	5.44
Cloud cover 6/10 through 10/10	12	2.25	8.42

*Average absolute difference between "Soderberg" prediction and observed minimum temperature

**Average absolute difference between "4 p. m. dew point" method and observed minimum temperature

absolute error of the Soderberg minimum temperature forecast for selected agricultural weather stations in western Michigan, April 15 through June 15, 1978. (The MOS forecasts were not archived during 1977 on a station-by-station basis.) The Soderberg prediction method results in a comparable average absolute error for all observations in the study, being only 0.2^{o}F greater than the average absolute error of the MOS minimum temperature forecasts. (It should be noted that MOS forecasts are made 36 hours in advance, and the Soderberg predictions are made 12 hours in advance.) As one may anticipate, it appears to perform better than the MOS forecast in the vicinity of Grand Rapids, i. e., at Hudsonville, Graham, Grand Junction, and Paw Paw. The MOS forecast was better than the Soderberg forecast for slightly more than half of the stations, including Kent City, Lake City, Ludington, Mapleton, Nunica, Peach Ridge, and Sodus. No overall pattern of predicting above or below the observed minimum temperature was discernible in either method.

In an attempt to explain the performance of the

TABLE 21

FREQUENCY DISTRIBUTION OF THE ABSOLUTE ERROR OF THE SODERBERG PREDICTION METHOD DURING 1977 AND 1978 FOR GRAND RAPIDS (PERCENTAGES OF TOTAL FOR EACH TYPE OF TEMPERATURE CHANGE ARE GIVEN IN PARENTHESES)

Type of Temperature Change	Range of Error in ^{o}F			
	0-2	3-4	5-6	7 & over
850 mb cooling	3 (25%)	6 (50%)	1 (8%)	2 (17%)
850 mb warming	7 (50%)	5 (36%)	0	2 (14%)
No 850 mb change (total)	12 (57%)	5 (24%)	4 (19%)	0
Cloud cover 0 through 5/10	4 (44%)	3 (33%)	2 (23%)	0
Cloud cover 6/10 through 10/10	8 (67%)	2 (16.5%)	2 (16.5%)	0

TABLE 22

COMPARISON BETWEEN THE AVERAGE ABSOLUTE ERROR* USING THE MOS FORECAST AND THE SODERBERG FORECAST FOR SELECTED AGRICULTURAL WEATHER STATIONS IN WESTERN MICHIGAN (APRIL THROUGH JUNE, 1978)

Station	AAE* from MOS Forecast	AAE* from Soderberg Forecast	Number of Observations
1. Belding	1.95	3.00	20
2. Edmore	3.67	3.79	24
3. Empire	4.24	4.64	25
4. Fremont	3.10	2.55	20
5. Glendora	3.95	3.85	20
6. Graham	3.44	2.96	25
7. Grand Junction	5.29	4.79	24
8. Grant	4.48	4.08	25
9. Holland	5.08	5.00	25
10. Hudsonville	4.92	4.32	25
11. Kent City	2.56	3.36	25
12. Kewadin	2.96	2.76	25
13. Lake City	3.28	4.28	25
14. Lake Leelanau	4.14	4.32	22
15. Ludington	3.52	4.36	25
16. Mapleton	3.68	4.12	24
17. Mears	3.04	3.64	25
18. Nunica	3.44	4.44	25
19. Paw Paw	4.12	3.88	25
20. Peach Ridge	2.88	3.52	25
21. Sodus	4.60	5.64	25
22. Watervliet	4.88	4.24	25

NOTES: No. of observations (all stations): 529
AAE* -- MOS (all stations): 3.80
AAE* -- Soderberg (all stations): 4.00

*AAE = Average Absolute Error, the difference between predicted and observed minimum temperature, ^{o}F

Soderberg technique in predicting minimum temperatures, Table 23 shows the results of correlating selected agricultural weather stations with Grand Rapids, Michigan. The correlations were found to be within the range of those reported in Table 10, which lists the equations for predicting minimum temperatures for the agricultural weather network from the climatological network. The six worst and the five best stations (highest and lowest average absolute difference between the Soderberg prediction and the observed minimum temperature) were chosen to see whether correlations with Grand Rapids paralleled these results. With the exception of Holland, which was well-correlated with Grand Rapids but not predicted well by the Soderberg method, all stations with average absolute errors of at least $5^{o}F$ were poorly correlated with Grand Rapids, and the stations for which lower absolute errors were found were well-correlated with Grand Rapids. This indicates that the success of the Soderberg method is dependent on how well the agricultural weather station is correlated with Grand Rapids.

TABLE 23

CORRELATION COEFFICIENT OF THE MINIMUM TEMPERATURES AT SELECTED AGRICULTURAL WEATHER STATIONS IN MICHIGAN AS COMPARED WITH GRAND RAPIDS, MICHIGAN

Y	X	r*	r^2	n**
1. Belding	Grand Rapids	.91	.83	198
2. Empire	Grand Rapids	.78	.61	195
3. Fremont	Grand Rapids	.88	.78	216
4. Graham	Grand Rapids	.92	.85	227
5. Holland	Grand Rapids	.90	.81	203
6. Hudsonville	Grand Rapids	.90	.81	227
7. Kent City	Grand Rapids	.89	.80	236
8. Lake Leelanau	Grand Rapids	.79	.62	214
9. Peach Ridge	Grand Rapids	.90	.82	227
10. Sodus	Grand Rapids	.75	.56	184
11. Traverse City	Grand Rapids	.79	.62	214

*correlation coefficient

**number of observations

SUMMARY AND CONCLUSIONS

1. Certain aspects of the occurrence of freezes in Michigan have been addressed. These include the climatology of freezes, vineyard temperature profiles as a parameter to evaluate the wind machine as a freeze-protection device, field trials with a wind machine in a vineyard, and a method to predict the minimum temperature for selected agricultural network stations in western Michigan.

Temperature records from selected agricultural weather stations in Michigan have been compared to the climatic stations maintained by the USDC/NOAA/NWS Cooperative Observers Network to determine whether the average freeze dates differ. The last date of occurrence in the spring and the first date of occurrence in the fall were determined for five different temperatures for 17 agricultural weather stations, from the first year that it had been in existence (circa 1962) through 1979. These data were punched onto cards and analyzed by a FORTRAN computer program to determine the freeze statistics. The absence of agricultural weather records before 1962 necessitated using the statistical technique of linear regression to construct a 30-year freeze climatology for this network. By incorporating agricultural weather stations and the USDC/NOAA/NWS Cooperative Observers Network, a more-refined analysis of the freeze dates was obtained.

2. Graphs of temperature profiles from two vineyards were drawn, as well as graphical and tabular summaries for the three years of observations. The average temperature inversions were obtained between the 1 and 15 meter levels (approximately) for temperatures at the 1-meter level that may be critical to grapes. These inversions were of a sufficient magnitude to provide an ample heat source for a wind machine to be potentially effective in the vineyard. This conclusion is based solely upon the Reese and Gerber (1969) graph of area of protection (acres) vs. degree of protection (^{o}F), according to inversion strength. For a 6^{o}F inversion (e. g., when a 1-meter temperature of 30^{o}F is occurring), a 2^{o}F protection over an area of 3½ acres, or a 1^{o}F protection over an area 6 acres may be expected. For a 10^{o}F inversion, a 2^{o}F protection over 6 acres, or a 1^{o}F protection over an area of nearly 10 acres may be anticipated.

The temperature response to the passage of a wind machine was monitored on May 4, 1979, by 14 minimum temperature thermometers in a Texas Corners vineyard, during which increases of 0^{o}F to 1.5^{o}F were noted. Temperature profiles recorded in a nearby vineyard indicated a small temperature inversion of 2.0°F. Although a strong conclusion should not be gleaned from this isolated observation, this is nevertheless a positive result as the ambient temperature fell 1.0°F during the wind-machine trial.

3. A minimum temperature forecasting scheme developed by Marshall Soderberg of the National Weather Service (NWS) for agricultural weather stations in western Michigan was evaluated. The 4 p. m. temperature, dew point, cloud cover, and anticipated 850 mb temperature trend are used to predict the Grand Rapids minimum temperature. This prediction serves as a basis to establish a forecast for 25 agricultural weather stations in southwestern Michigan, provided that an average difference between Grand Rapids and the station in question, for different synoptic conditions, has been determined.

The average absolute error of 31 predictions under radiative conditions ranged from 2.48°F for Grand Rapids to 6.39°F for Sodus. These results are very comparable to those obtained during 1978 from a computerized agricultural weather forecast guidance developed by the NWS for Michigan and Indiana (see Table 22). As the NWS guidance was quite complex in its statistical development and operation, it is concluded that the Soderberg technique is useful as a simple method to forecast nocturnal minimum temperatures at agricultural weather sites in Michigan.

RECOMMENDATIONS

1. The existence of a heat source within the nocturnal temperature profile (i. e., strong inversion) is imperative to the successful operation of a wind machine. Looking ahead to the time when on-farm computers will prevail, a program to forecast such information would be an invaluable potential tool in aiding the grower to decide when to turn on his wind machine.

The objective of a boundary-layer model developed by Georg (1971) is to predict the nocturnal air temperature profile from 1.5 to 24 meters. The input parameters are: the measured net radiation; the ambient temperature at the reference level (T_R), and 1.5 m; the wind speeds at 9.0 and 18.0 m; the maximum and minimum soil temperatures for the day at 0, 5, 10, 20, and 50 cm; the percentage of water in the soil on a volume basis; and dew-point temperature. The program will compute a temperature profile up to 24 m with T_R as a base, and subsequently generate a new value for T_R one time-step into the future (see Appendix D).

There is no explicit function within the program to calculate the flux of latent heat due to condensation and sublimation. There is a command within the model that tests for $T_R \leq T_d$, which will reduce all temperature changes with respect to time by one-half when this condition is encountered.

This model differs from the Brunt equation by utilizing assumed air, soil, and wind profiles to calculate eddy conductivity, soil heat flux, and convective heat flux within the boundary layer.

No other models of this nature have appeared in the literature, and it would be invaluable to merely validate the model as is, let alone improve various aspects of it.

2. Future frost researchers who are cognizant of Businger's dimensionless coefficient may apply this concept to the prediction of minimum temperatures. Observations of downward longwave sky radiation coupled with air temperature at the five-foot level may be used to compute γ over the course of several frost evenings, weather permitting. By measuring γ in the early evening, one may extrapolate to find γ for the early morning, based upon past observations. As downward radiation will remain nearly constant, the minimum temperature may be approximated.

Characterizing the effective sky temperature may enable one to know the magnitude of the difference between leaf (or bud) and ambient temperature. Thus, a fruit grower would know whether or not it would be economical to run his wind machine (or other freeze-protection device) when the ambient temperature is above freezing.

3. Additional statistical procedures may be incorporated into the Soderberg method. Following the methodology developed for the Mendoza region of Argentina (cf. Bagdonas, 1978), a correction factor may be applied to the average difference between Grand Rapids and the agricultural station in question: $\sigma_Y\sqrt{1-r^2}$, where σ_Y is the standard deviation of the minimum temperatures at Grand Rapids, and r is the correlation coefficient between Grand Rapids and the agricultural station.

4. If resources were available, dew-point hygrometers (or some other suitable means) might be provided at selected agricultural stations. To facilitate the choice of locations, correlations between relatively close agricultural stations might be established. Thus, one or more agricultural station(s) might serve as "key" stations, augmenting Grand Rapids in the role of reference forecasting station.

APPENDICES

APPENDIX A

ACREAGE, YIELD (TONS), USES (TONS), AND RAW PRODUCT VALUES FOR MICHIGAN GRAPES, 1965-1976

Year	Acreage	Yield (Tons)	Uses			Raw Product Value (Dollars)
			Juice	Wine	Fresh	
1976	15,800	14,500	10,700	*	1,400	*
1975	15,800	56,000	47,000	5,000	3,000	$6,710,000
1974	15,800	47,500	40,000	5,500	2,000	8,740,000
1973	15,800	23,500	17,800	4,100	1,600	4,630,000
1972	15,800	53,000	45,500	4,700	2,800	8,798,000
1971	15,900	69,000	59,600	6,000	3,400	8,280,000
1970	15,900	62,000	*	*	3,600	8,804,000
1969	16,000	38,000	28,200	7,300	2,200	5,510,000
1968	16,100	23,000	16,200	4,600	1,900	2,852,000
1967	16,000	39,000	27,900	7,700	3,100	4,446,000
1966	16,600	49,000	36,400	8,800	3,400	5,145,000
1965	16,600	71,500	54,600	13,200	3,400	7,575,000

*Not available

APPENDIX B

ESTIMATION OF WIND-MACHINE DESIGN FOR THRUST PER HORSEPOWER

The thrust of a wind machine will depend upon the power (P), the diameter of the propeller (d_{wm}), the power coefficient (C_P), and the thrust coefficient (C_F). Leonard (1953) defined the relation between power, revolutions per minute (N), and diameter of wind-machine propeller:

$$C_P = P/\rho N^3 d_{wm}^{\ 5} \qquad (B.1)$$

where $\rho = 1.29 \times 10^{-3}$ grams per cm^3. The thrust coefficient is the relation between pounds thrust (F), revolutions, and diameter:

$$C_F = F/\rho N^2 d_{wm}^{\ 4} \qquad (B.2)$$

Solving these equations for thrust in terms of power and diameter:

$$F = C_F \sqrt[3]{\rho P^2 d_{wm}^{\ 2} / C_p^{\ 2}} \qquad (B.3)$$

APPENDIX C

FREEZE STATISTICS FOR THE AGRICULTURAL WEATHER STATIONS

The freeze statistics for the agricultural weather stations are presented in Tables C1 through C17. The following abbreviations have been used:

M	= number of years of freeze dates that have been read by the computer program
N	= number of years of freeze dates for which a complete data set was found
VAR	= variance of the freeze dates
XBAR	= mean of the freeze dates
SD	= standard deviation of the freeze dates
SD/XBAR	= coefficient of variation which is the standard deviation of the freeze dates divided by the mean of the freeze dates
THRES	= threshold (followed by temperature, ^{o}F)

Under the column titled "Percent Chance of Season Longer Than Indicated Length (days)," MAX refers to the longest growing season in the data set of the indicated temperature threshold, preceded by the last two digits of the year during which it occurred.

TABLE C1

FREEZE STATISTICS FOR BELDING, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
N	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	98.02[illegible]	142.326	127.200	104.121	89.045	86.602	160.366	144.966	105.263	161.214
XBAR	325.8[illegible]	317.133	302.8[illegible]	287.500	277.7[illegible]	86.533	97.600	113.000	124.800	133.600
SD	9.901	11.930	11.278	10.204	9.436	9.306	12.664	12.040	10.260	12.697
SD/XB	.030	.038	.037	.035	.034	.108	.130	.107	.082	.095

	GROWING SEASON STATISTICS 36	32	28	24	20
N	30	30	30	30	30
N	30	30	30	30	30
VAR	185.55	242.56	216.81	202.12	232.12
XBAR	124.367	144.700	174.433	201.533	226.133
SD	13.622	15.574	14.724	14.217	15.235
SD/XB	.109	.108	.084	.071	.069

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	612	607	603	526	522	515	509	506	426
THRES 32	612	602	528	521	513	505	428	424	420
THRES 28	523	517	513	506	429	421	414	410	409
THRES 24	510	430	427	420	414	407	331	328	326
THRES 20	424	419	416	410	404	328	323	319	309

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	9[illegible]6	909	913	919	925	1001	1006	1010	1014
THRES 32	919	915	919	927	1026	1014	1022	1026	1101
THRES 28	920	1001	1006	1013	1021	1029	1105	1110	1115
THRES 24	1011	1016	1020	1026	1102	1109	1115	1119	1123
THRES 20	1019	1021	1025	1102	1111	1119	1127	1201	1203

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	77/147	147	142	134	125	116	108	103	62/ 95
THRES 32	66/175	170	165	155	145	134	125	119	66/119
THRES 28	6[illegible]/194	1[illegible]9	193	184	174	165	156	150	67/139
THRES 24	55/231	225	220	211	202	192	183	174	74/164
THRES 20	7[illegible]/248	245	240	230	220	210	201	195	72/192

TABLE C2

FREEZE STATISTICS FOR EDMORE, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS					FIRST FALL FREEZE STATISTICS				
	36	32	28	24	20	36	32	28	24	20
M	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	[illegible]	176.579	92.047	88.309	72.754	117.845	140.930	191.620	189.706	191.289
XBAR	[illegible]	318.200	307.567	289.633	277.933	83.500	92.033	106.367	122.133	131.233
SD	12.472	13.288	9.594	9.397	[illegible]	10.856	11.871	13.843	13.773	13.831
SD/XB	.038	.042	.032	.032	.031	.130	.129	.130	.113	.105

	GROWING SEASON STATISTICS				
	36	32	28	24	20
M	30	30	30	30	30
N	30	30	30	30	30
VAR	283.93	286.96	278.79	320.13	298.95
XBAR	119.533	138.067	167.033	196.733	217.533
SD	16.852	16.940	16.697	17.892	17.290
SD/XB	.141	.123	.100	.091	.079

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	621	614	609	602	524	516	508	504	422
THRES 32	612	605	531	523	514	505	427	422	414
THRES 28	522	515	512	506	430	423	417	414	412
THRES 24	510	501	428	422	416	409	404	331	330
THRES 20	415	418	415	410	414	329	324	321	309

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	902	904	908	914	922	929	1005	1009	1014
THRES 32	906	911	915	922	930	1008	1015	1020	1029
THRES 28	923	922	927	1005	1014	1024	1101	1106	1115
THRES 24	1003	1007	1012	1021	1030	1108	1117	1122	1201
THRES 20	1018	1016	1022	1030	1108	1118	1126	1201	1201

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	76/159	147	141	131	120	108	98	92	63/ 82
THRES 32	75/175	166	160	149	139	127	116	110	64/105
THRES 28	[illegible]/216	194	188	178	167	156	146	140	74/138
THRES 24	63/235	226	220	205	197	185	174	167	74/148
THRES 20	63/254	246	240	229	218	206	195	189	76/18[illegible]

TABLE C3

FREEZE STATISTICS FOR FREMONT, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
M	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	167.492	167.697	126.537	95.840	66.171	191.082	169.344	270.455	219.099	176.303
XBAR	326.367	317.600	300.900	289.767	280.633	83.433	98.633	113.400	123.267	136.200
SD	13.692	12.950	11.248	9.790	8.135	13.823	13.013	16.446	14.802	13.278
SD/XB	.042	.041	.037	.034	.029	.166	.132	.145	.120	.097

	GROWING SEASON STATISTICS 36	32	28	24	20
M	30	30	30	30	30
N	30	30	30	30	30
VAR	499.11	379.65	455.17	281.03	176.99
XBAR	119.300	145.267	176.733	197.733	219.800
SD	22.341	19.485	22.252	16.764	13.304
SD/XB	.187	.134	.126	.085	.061

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	622	616	611	603	524	515	507	502	428
THRES 32	617	604	530	522	514	505	427	422	422
THRES 28	523	515	511	504	427	419	412	408	331
THRES 24	510	502	428	422	416	409	403	331	330
THRES 20	424	420	417	412	407	401	327	324	319

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	809	830	904	912	921	1001	1009	1014	1021
THRES 32	916	915	920	928	1007	1015	1023	1028	1104
THRES 28	921	924	930	1010	1021	1101	1111	1117	1129
THRES 24	1003	1007	1012	1021	1031	1110	1119	1125	1129
THRES 20	1019	1022	1027	1104	1113	1122	1130	1205	1216

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	53/161	156	148	134	119	104	91	63	64/ 53
THRES 32	59/179	177	170	158	145	132	120	113	64/ 87
THRES 28	61/231	213	205	192	177	162	148	140	76/138
THRES 24	61/231	225	219	209	193	186	176	170	53/167
THRES 20	54/241	242	237	229	220	211	203	198	72/192

TABLE C4

FREEZE STATISTICS FOR GLENDORA, MICHIGAN (1950 THROUGH 1979)

LAST SPRING FREEZE STATISTICS

	36	32	28	24	20
N	30	30	30	30	30
N	30	30	30	30	30
VAR	203.252	225.621	209.629	244.207	146.585
KVAR	325.467	314.200	297.400	265.000	269.633
SD	14.252	15.027	14.479	15.627	12.107
SD/XB	.044	.048	.049	.055	.045

FIRST FALL FREEZE STATISTICS

	36	32	28	24	20
N	30	30	30	30	30
N	30	30	30	30	30
VAR	171.559	216.024	189.564	240.671	203.724
KVAR	66.600	96.900	115.767	131.867	144.600
SD	13.098	14.698	13.768	15.514	14.273
SD/XB	.151	.149	.119	.118	.099

GROWING SEASON STATISTICS

	36	32	28	24	20
N	30	30	30	30	30
N	30	30	30	30	30
VAR	412.24	391.86	453.83	555.54	417.83
KVAR	125.367	148.933	162.600	211.110	238.600
SD	20.[illegible]4	19.795	21.303	23.570	20.441
SD/XB	.162	.133	.117	.112	.086

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	622	614	609	531	521	512	503	428	423
THRES 32	612	604	529	520	510	430	421	415	408
THRES 28	517	517	512	503	423	414	405	331	323
THRES 24	510	507	501	422	411	331	322	316	309
THRES 20	413	416	411	404	327	318	311	307	221

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	[illegible]	903	908	916	925	1003	1011	1016	1019
THRES 32	[illegible]	913	918	927	1007	1017	1026	1031	1105
THRES 28	[illegible]	1001	1006	1014	1024	1102	1110	1115	1116
THRES 24	1003	1014	1020	1029	1109	1119	1129	1204	1206
THRES 20	1019	1029	1103	1111	1121	1201	1209	1214	1213

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	51/168	159	151	139	125	112	99	92	63/ 83
THRES 32	55/203	181	174	162	149	136	124	116	64/105
THRES 28	55/221	218	210	197	183	163	155	149	76/138
THRES 24	58/247	250	241	227	211	155	161	172	74/149
THRES 20	59/279	272	265	252	239	225	212	205	72/192

TABLE C5

FREEZE STATISTICS FOR GRAHAM, MICHIGAN (1950 THROUGH 1979)

LAST SPRING FREEZE STATISTICS / FIRST FALL FREEZE STATISTICS

	Last Spring 36	32	28	24	20	First Fall 36	32	28	24	20
M	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	149.545	186.952	133.426	143.890	553.269	103.292	149.085	144.133	160.028	241.793
XBAR	321.200	310.100	298.233	295.200	269.200	86.867	99.867	117.933	129.000	144.600
SD	12.229	13.669	11.551	11.995	23.522	10.163	12.210	12.006	12.682	15.550
SD/XB	.035	.044	.039	.042	.087	.114	.122	.102	.098	.108

GROWING SEASON STATISTICS

	36	32	28	24	20
M	30	30	30	30	30
N	30	30	30	30	30
VAR	313.89	322.21	314.41	363.07	950.93
XBAR	131.900	154.000	183.933	209.033	239.033
SD	17.717	17.950	17.732	19.054	30.837
SD/XB	.134	.117	.096	.092	.129

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	612	606	602	525	517	509	502	427	422
THRES 32	612	529	524	515	506	427	419	414	415
THRES 28	513	513	509	502	424	416	409	405	330
THRES 24	510	501	427	415	411	403	327	322	322
THRES 20	413	504	425	411	326	310	224	216	1207

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	916	910	914	920	927	1004	1010	1014	1022
THRES 32	919	918	922	930	1008	1016	1024	1028	1101
THRES 28	1003	1006	1011	1018	1026	1103	1110	1115	1116
THRES 24	1017	1016	1021	1028	1106	1115	1122	1127	1130
THRES 20	1019	1026	1101	1111	1121	1201	1211	1217	1215

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	59/177	161	155	144	132	120	109	103	66/105
THRES 32	75/191	184	177	166	154	142	131	124	66/118
THRES 28	55/230	213	207	196	184	172	161	155	66/148
THRES 24	63/252	239	232	221	208	195	184	177	74/164
THRES 20	79/356	270	279	260	239	218	200	188	72/192

TABLE C6

FREEZE STATISTICS FOR GRAND JUNCTION, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
M	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	231.413	254.533	174.621	149.683	140.510	325.592	214.644	274.309	191.237	316.047
XBAR	332.633	325.467	304.030	295.200	283.200	75.167	89.667	105.367	120.733	135.567
SD	15.212	15.954	13.365	12.234	11.854	18.044	14.651	16.562	13.829	17.776
SD/XB	.046	.049	.043	.041	.042	.240	.163	.157	.115	.131

	GROWING SEASON STATISTICS 36	32	28	24	20
M	30	30	30	30	30
N	30	30	30	30	30
VAR	750.53	517.48	511.77	497.01	434.94
XBAR	106.767	128.033	161.600	189.767	216.600
SD	27.396	22.748	22.622	22.294	20.855
SD/XB	.257	.174	.140	.117	.096

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	636	623	617	608	529	518	509	504	504
THRES 32	636	617	611	602	522	511	501	426	424
THRES 28	612	526	521	513	504	425	417	412	412
THRES 24	510	511	507	429	421	413	406	401	330
THRES 20	510	429	424	417	409	401	325	321	319

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	895	814	821	901	913	925	1006	1013	1014
THRES 32	930	904	909	916	928	1008	1016	1022	1101
THRES 28	906	916	922	1002	1013	1025	1104	1110	1119-
THRES 24	924	1006	1011	1019	1029	1107	1115	1120	1123
THRES 20	1003	1014	1021	1101	1113	1125	1205	1212	1212

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	53/155	152	142	125	107	88	72	62	72/ 30
THRES 32	61/169	165	157	143	128	113	99	91	72/ 78
THRES 28	61/200	199	191	177	162	146	133	124	72/102
THRES 24	55/230	226	218	205	190	175	161	153	76/138
THRES 20	61/248	251	243	231	217	203	190	182	66/172

TABLE C7

FREEZE STATISTICS FOR HOLLAND, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
N	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	248.489	364.372	264.373	233.407	202.786	213.655	208.343	168.616	334.654	223.145
XBAR	330.167	319.200	302.633	287.800	275.200	84.000	94.933	116.067	129.367	142.400
SD	15.764	19.089	16.260	15.278	14.240	14.617	14.434	13.734	18.294	14.938
SD/XB	.045	.060	.054	.053	.052	.174	.152	.118	.141	.105

	GROWING SEASON STATISTICS 36	32	28	24	20
N	30	30	30	30	30
N	30	30	30	30	30
VAR	546.46	665.83	576.37	724.99	467.08
XBAR	113.067	139.967	177.667	205.600	231.433
SD	23.377	25.804	24.008	26.926	21.612
SD/XB	.193	.184	.135	.131	.093

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	625	621	615	606	526	516	506	430	417
THRES 32	622	616	609	528	515	502	421	414	415
THRES 28	612	525	519	510	429	418	408	402	330
THRES 24	510	509	503	424	414	403	325	320	309
THRES 20	510	425	419	411	401	323	314	309	309

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	809	829	903	912	922	1002	1011	1016	1018
THRES 32	906	909	914	923	1003	1013	1021	1027	1102
THRES 28	924	1001	1006	1015	1024	1102	1111	1116	1122
THRES 24	928	1007	1014	1025	1106	1119	1130	1206	1205
THRES 20	1018	1026	1031	1109	1119	1129	1209	1214	1212

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	52/169	157	148	134	118	102	89	80	64/ 53
THRES 32	51/190	182	173	157	140	123	107	98	64/102
THRES 28	58/209	217	208	194	178	161	147	138	72/119
THRES 24	59/247	250	240	224	206	180	171	162	66/140
THRES 20	57/269	267	259	246	231	217	204	196	66/172

TABLE C8

FREEZE STATISTICS FOR HUDSONVILLE, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
M	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	229.075	299.752	156.695	143.030	134.944	244.464	242.033	332.414	252.326	308.064
XBAR	324.600	315.200	297.167	285.933	273.233	83.533	97.033	116.000	126.533	141.067
SD	15.135	17.313	12.518	11.960	11.617	15.635	15.557	18.232	15.885	17.552
SD/XB	.047	.055	.042	.042	.043	.167	.160	.157	.124	.124

	GROWING SEASON STATISTICS 36	32	28	24	20
M	30	30	30	30	30
N	30	30	30	30	30
VAR	646.63	631.51	597.10	451.73	498.55
XBAR	123.167	146.067	183.067	206.833	232.067
SD	25.429	25.130	24.436	21.254	22.328
SD/XB	.206	.172	.133	.103	.095

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	622	614	609	531	521	510	501	426	422
THRES 32	622	609	602	523	511	430	419	413	415
THRES 28	524	514	505	502	423	415	407	403	330
THRES 24	510	502	427	420	412	404	328	323	326
THRES 20	413	418	414	407	330	322	315	311	221

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	829	827	901	911	922	1002	1012	1017	1022
THRES 32	906	909	915	925	1005	1016	1025	1031	1101
THRES 28	913	924	1001	1012	1024	1105	1116	1123	1118
THRES 24	929	1010	1016	1026	1106	1116	1126	1202	1205
THRES 20	929	1020	1027	1106	1118	1130	1211	1217	1215

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	59/166	165	156	140	123	106	91	81	63/ 56
THRES 32	63/187	187	179	163	146	129	114	105	63/ 82
THRES 28	55/230	223	214	200	183	167	152	143	66/134
THRES 24	54/244	242	234	221	207	192	180	172	74/166
THRES 20	58/277	269	261	247	232	217	203	195	65/178

TABLE C9

FREEZE STATISTICS FOR KEWADIN, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
N	30	30	30	30	30	30	30	30	30	30
Y	30	30	30	30	30	30	30	30	30	30
VAR	112.064	80.533	113.637	133.137	89.803	193.137	123.344	125.430	153.154	120.930
XBAR	329.733	319.467	306.533	288.967	278.700	93.033	107.633	117.467	134.533	141.633
SD	10.586	8.974	10.660	11.538	9.476	13.897	11.106	11.200	12.376	10.997
SD/XL	.032	.029	.035	.040	.034	.149	.103	.095	.092	.078

	GROWING SEASON STATISTICS 36	32	28	24	20
N	30	30	30	30	30
Y	30	30	30	30	30
VAR	341.36	207.70	196.14	248.03	141.11
XBAR	127.533	152.400	175.167	209.800	227.167
SD	18.476	14.412	14.076	15.749	11.879
SD/XB	.145	.095	.080	.075	.052

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	618	612	608	602	526	519	512	508	501
THRES 32	606	530	527	522	515	509	504	501	425
THRES 28	525	520	516	510	513	425	419	415	409
THRES 24	510	504	430	423	415	407	331	327	326
THRES 20	503	420	417	411	405	329	324	320	309

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	909	908	913	922	1001	1010	1019	1024	1101
THRES 32	927	927	1001	1008	1016	1023	1030	1103	1106
THRES 28	1005	1007	1011	1018	1025	1102	1109	1113	1110
THRES 24	1021	1022	1027	1103	1112	1120	1127	1202	1202
THRES 20	1028	1101	1105	1111	1119	1126	1203	1207	1229

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	73/159	158	151	140	128	116	104	97	56/ 97
THRES 32	70/180	176	171	162	152	143	134	129	61/120
THRES 28	73/204	198	193	185	175	166	157	152	56/139
THRES 24	54/241	236	230	220	210	199	190	184	50/170
THRES 20	69/247	247	242	235	227	219	212	208	57/204

TABLE C10

FREEZE STATISTICS FOR LAKE LEELANAU, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
M	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	110.006	102.616	123.200	169.040	123.126	230.754	145.551	167.131	119.137	115.661
XBAR	336.167	324.267	313.200	292.167	278.333	88.933	102.967	117.800	134.033	144.167
SD	10.488	10.130	11.100	13.002	11.096	15.191	12.064	12.928	10.915	10.755
SD/XB	.031	.031	.035	.045	.040	.171	.117	.110	.081	.075

	GROWING SEASON STATISTICS 36	32	28	24	20
M	30	30	30	30	30
N	30	30	30	30	30
VAR	295.24	307.24	194.35	316.44	229.24
XBAR	117.000	142.933	166.633	206.100	230.067
SD	17.183	17.528	13.941	17.789	15.141
SD/XB	.147	.123	.083	.086	.066

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	624	618	615	608	601	525	519	515	509
THRES 32	626	606	602	527	520	513	507	504	426
THRES 28	527	527	523	517	509	502	425	421	412
THRES 24	513	510	505	427	418	409	402	320	326
THRES 20	509	423	419	412	404	328	321	317	309

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	812	902	907	917	927	1007	1016	1022	1101
THRES 32	921	921	926	1003	1011	1019	1026	1031	1106
THRES 28	1005	1005	1009	1017	1026	1104	1111	1116	1124
THRES 24	1021	1024	1028	1104	1111	1118	1125	1129	1201
THRES 20	1102	1103	1107	1114	1121	1128	1205	1209	1209

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	69/154	145	139	129	117	105	95	89	64/ 68
THRES 32	64/173	172	165	155	143	131	120	114	73/113
THRES 28	75/200	192	187	178	169	159	151	146	56/139
THRES 24	68/235	235	229	218	206	194	183	177	50/170
THRES 20	64/269	255	249	240	230	220	211	205	57/198

TABLE C11

FREEZE STATISTICS FOR LUDINGTON, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
N	30	30	30	30	30	30	30	30	30	30
Y	30	30	30	30	30	30	30	30	30	30
VAR	206.392	154.828	183.620	103.826	117.897	229.409	224.116	233.528	211.444	179.361
XBAR	329.567	318.000	300.967	286.367	274.200	85.933	101.767	115.300	134.667	147.133
SD	14.366	12.443	13.551	10.190	10.858	15.113	14.971	15.282	14.541	13.393
SD/XB	.044	.039	.045	.036	.040	.176	.147	.133	.108	.091

GROWING SEASON STATISTICS

	36	32	28	24	20
N	30	30	30	30	30
Y	30	30	30	30	30
VAR	552.54	491.10	459.01	399.31	294.07
XBAR	120.600	148.000	176.567	211.933	237.167
SD	23.515	22.161	21.425	19.983	17.149
SD/XB	.195	.150	.120	.094	.072

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	622	618	613	604	526	516	507	502	417
THRES 32	612	603	530	522	514	506	428	424	417
THRES 28	523	519	514	506	427	418	410	405	326
THRES 24	510	429	425	419	412	405	330	327	326
THRES 20	413	418	414	408	331	324	317	313	309

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	827	830	905	914	924	1004	1013	1019	1021
THRES 32	914	915	921	930	1010	1020	1029	1103	1107
THRES 28	916	928	1004	1013	1023	1103	1112	1117	1110
THRES 24	1011	1018	1023	1101	1111	1121	1130	1205	1208
THRES 20	1019	1102	1107	1115	1124	1203	1211	1216	1221

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	52/169	159	151	136	121	105	90	82	63/ 82
THRES 32	53/198	194	176	163	148	133	120	112	63/113
THRES 28	51/220	214	206	193	179	164	151	143	76/142
THRES 24	61/243	245	238	225	212	198	186	179	66/167
THRES 20	61/266	265	259	245	237	226	215	209	72/192

TABLE C12

FREEZE STATISTICS FOR MAPLETON, MICHIGAN (1950 THROUGH 1979)

LAST SPRING FREEZE STATISTICS / FIRST FALL FREEZE STATISTICS

	Last spring 36	Last spring 32	Last spring 28	Last spring 24	Last spring 20	First fall 36	First fall 32	First fall 28	First fall 24	First fall 20
M	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	111.385	73.495	128.378	136.340	114.565	160.051	161.059	164.921	138.120	142.328
XBAR	335.167	322.767	312.033	294.067	279.033	88.867	104.900	115.900	136.467	143.500
SD	10.554	8.573	11.330	11.676	10.704	12.651	12.691	12.842	11.752	11.930
SD/XB	.031	.027	.036	.040	.039	.142	.121	.111	.086	.083

GROWING SEASON STATISTICS

	36	32	28	24	20
M	30	30	30	30	30
N	30	30	30	30	30
VAR	231.93	279.83	280.71	253.21	235.46
XBAR	117.333	146.367	166.100	206.633	228.700
SD	15.229	16.728	16.755	15.912	15.345
SD/XB	.129	.114	.100	.077	.067

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	625	618	614	607	531	524	518	514	514
THRES 32	616	602	530	525	519	513	506	505	507
THRES 28	526	527	523	516	508	430	424	419	411
THRES 24	510	509	505	428	421	412	405	401	326
THRES 20	509	423	419	412	405	329	322	318	309

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	902	906	911	918	927	1005	1013	1018	1101
THRES 32	921	922	927	1004	1013	1021	1029	1103	1108
THRES 28	1003	1003	1007	1015	1024	1102	1109	1114	1124
THRES 24	1021	1025	1029	1106	1113	1121	1129	1203	1206
THRES 20	1029	1101	1105	1112	1121	1129	1206	1210	1222

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	68/151	143	137	128	118	108	98	93	79/ 88
THRES 32	70/184	174	168	158	146	135	125	119	58/120
THRES 28	75/211	196	190	179	168	157	147	141	56/139
THRES 24	60/234	233	227	217	207	196	166	180	50/170
THRES 20	69/262	254	246	235	229	218	209	203	57/198

TABLE C13

FREEZE STATISTICS FOR MEARS, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
N	30	30	30	30	30	30	30	30	30	30
J	30	30	30	30	30	30	30	30	30	30
VAR	140.838	157.426	102.852	143.459	120.833	296.920	256.420	223.223	185.592	128.299
XBAR	329.700	321.233	306.900	290.300	277.833	85.333	99.167	112.533	132.833	142.333
SD	11.865	12.547	10.142	11.977	10.992	17.231	16.013	14.941	13.623	11.327
SD/XB	.036	.039	.033	.041	.040	.202	.161	.133	.103	.080

	GROWING SEASON STATISTICS 36	32	28	24	20
N	30	30	30	30	30
J	30	30	30	30	30
VAR	547.22	468.97	428.43	281.22	241.58
XBAR	119.867	142.167	169.867	206.767	228.733
SD	23.393	21.656	20.698	16.770	15.543
SD/XB	.195	.152	.122	.081	.068

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	617	614	610	603	526	518	510	506	426
THRES 32	612	607	602	526	517	509	501	427	420
THRES 28	527	520	516	510	503	426	420	416	413
THRES 24	510	506	502	424	416	409	401	328	324
THRES 20	424	422	418	411	404	327	321	317	307

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	809	826	901	912	923	1005	1015	1022	1101
THRES 32	906	911	917	926	1007	1018	1028	1103	1106
THRES 28	924	926	1001	1010	1021	1031	1109	1114	1124
THRES 24	1005	1018	1023	1101	1110	1119	1127	1202	1202
THRES 20	1021	1101	1105	1112	1119	1127	1204	1208	1208

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	78/174	158	150	136	120	104	90	81	64/ 53
THRES 32	75/166	178	170	157	142	128	114	107	64/108
THRES 28	75/216	204	196	184	170	156	143	136	61/126
THRES 24	68/253	234	228	218	207	195	185	179	66/175
THRES 20	68/267	254	249	239	229	218	209	203	52/192

TABLE C14

FREEZE STATISTICS FOR PAW PAW, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
N	30	30	30	30	30	30	30	30	30	30
[illegible]	30	30	30	30	30	30	30	30	30	30
VAR	158.116	183.926	162.461	146.133	128.944	76.692	168.079	129.390	158.092	203.752
MEAN	325.233	311.967	300.233	290.067	277.567	84.067	98.300	112.300	123.667	136.200
SD	12.574	13.558	12.746	12.089	11.355	8.769	12.965	11.375	12.575	14.274
SD/XB	.039	.043	.042	.042	.041	.104	.132	.101	.102	.105

	GROWING SEASON STATISTICS 36	32	28	24	20
N	30	30	30	30	30
[illegible]	30	30	30	30	30
VAR	227.79	282.46	237.53	352.42	339.91
MEAN	123.067	150.567	176.300	197.833	222.867
SD	15.093	16.807	15.412	18.773	18.437
SD/XB	.123	.112	.087	.095	.083

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	622	611	606	530	521	513	505	501	427
THRES 32	612	530	525	517	508	429	421	416	415
THRES 28	530	517	513	505	426	418	410	405	409
THRES 24	510	506	502	424	416	408	401	327	326
THRES 20	510	422	418	411	404	327	320	316	308

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	904	908	911	916	922	928	1003	1006	1007
THRES 32	913	915	920	928	1006	1015	1023	1029	1101
THRES 28	929	1002	1006	1013	1020	1028	1104	1108	1109
THRES 24	1010	1011	1016	1023	1101	1109	1117	1121	1129
THRES 20	1019	1021	1026	1104	1113	1123	1201	1207	1208

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	65/150	148	142	133	123	113	104	98	63/ 82
THRES 32	75/162	176	172	162	151	139	129	123	66/116
THRES 28	73/204	202	196	187	176	166	157	151	66/128
THRES 24	79/232	229	222	210	198	185	174	167	74/165
THRES 20	78/250	253	246	235	223	219	199	193	66/172

TABLE C15

FREEZE STATISTICS FOR PEACH RIDGE, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
M	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	141.49[illegible]	174.368	142.723	78.593	190.82[illegible]	126.051	179.293	161.086	223.200	259.638
XBAR	324.400	310.333	297.367	264.600	274.267	87.467	101.500	119.500	126.80[illegible]	142.56[illegible]
SD	11.895	13.205	11.947	8.865	13.814	11.227	13.390	12.692	14.940	16.113
SD/XB	.037	.043	.040	.031	.050	.128	.132	.107	.118	.113

	GROWING SEASON STATISTICS 36	32	28	24	20
M	30	30	30	30	30
N	30	30	30	30	30
VAR	275.94	317.01	333.14	325.91	528.46
XBAR	127.300	155.400	185.367	206.433	232.467
SD	16.611	17.805	18.252	18.053	22.948
SD/XB	.130	.115	.098	.087	.099

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	614	609	605	528	520	512	505	501	426
THRES 32	539	524	523	515	516	427	419	415	415
THRES 28	523	513	509	501	423	415	408	404	330
THRES 24	510	425	422	417	411	405	330	327	329
THRES 20	510	423	418	410	331	322	314	309	221

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	830	907	911	918	925	1003	1010	1014	1017
THRES 32	921	917	922	930	1010	1019	1027	1101	1114
THRES 28	927	1006	1010	1018	1027	1104	1112	1116	1116
THRES 24	1025	1010	1016	1025	1104	1114	1123	1125	1130
THRES 20	1019	1024	1030	1109	1120	1130	1210	1216	1215

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	59/168	155	149	139	127	116	106	100	76/ 97
THRES 32	70/131	185	178	167	155	143	133	126	66/119
THRES 28	55/230	215	209	198	185	173	162	155	74/146
THRES 24	68/237	236	230	219	206	194	183	177	66/172
THRES 20	54/277	270	262	246	232	217	203	195	72/192

TABLE C16

FREEZE STATISTICS FOR SODUS, MICHIGAN (1950 THROUGH 1979)

	LAST SPRING FREEZE STATISTICS 36	32	28	24	20	FIRST FALL FREEZE STATISTICS 36	32	28	24	20
N	29	29	29	29	29	29	29	29	29	29
N	29	29	29	29	29	29	29	29	29	29
VAR	166.291	211.909	276.714	251.458	183.281	96.677	190.525	266.365	217.034	160.616
XBAR	322.828	305.138	291.030	276.621	262.931	90.034	106.897	121.690	138.034	149.483
SD	12.895	14.557	16.635	15.857	13.538	9.832	13.803	16.321	14.732	12.673
SD/XB	.040	.048	.057	.057	.051	.109	.129	.134	.107	.085

	GROWING SEASON STATISTICS 36	32	28	24	20
N	29	29	29	29	29
N	29	29	29	29	29
VAR	253.90	310.00	708.14	624.38	369.38
XBAR	131.448	166.069	194.931	225.655	250.793
SD	15.934	17.607	26.074	24.989	19.219
SD/XB	.121	.106	.144	.111	.077

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	612	609	604	528	519	510	502	428	423
THRES 32	524	525	520	511	501	421	412	407	409
THRES 28	510	514	509	428	417	406	327	321	309
THRES 24	510	429	423	413	403	323	313	308	221
THRES 20	417	411	406	329	320	311	303	226	215

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	916	912	915	921	928	1005	1011	1014	1019
THRES 32	920	922	927	1006	1015	1024	1102	1107	1110
THRES 28	1023	1003	1009	1019	1030	1110	1120	1126	1209
THRES 24	1019	1022	1027	1105	1115	1125	1204	1209	1213
THRES 20	1027	1106	1110	1118	1126	1205	1213	1217	1222

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 36	51/168	158	152	142	131	121	111	105	64/105
THRES 32	58/201	195	189	178	166	154	143	137	66/129
THRES 28	53/250	241	231	214	195	176	159	149	66/148
THRES 24	58/279	267	258	243	226	209	194	185	66/168
THRES 20	73/286	282	275	264	251	233	226	219	66/217

TABLE C17

FREEZE STATISTICS FOR WATERVLIET, MICHIGAN (1950 THROUGH 1979)

LAST SPRING FREEZE STATISTICS / FIRST FALL FREEZE STATISTICS

	Spring 36	Spring 32	Spring 28	Spring 24	Spring 20	Fall 36	Fall 32	Fall 28	Fall 24	Fall 20
M	30	30	30	30	30	30	30	30	30	30
N	30	30	30	30	30	30	30	30	30	30
VAR	212.933	258.579	185.775	186.041	146.317	175.637	196.326	213.972	189.937	223.168
XBAR	327.967	315.200	301.867	285.600	275.600	82.133	97.133	109.400	123.167	137.933
SD	14.592	16.080	13.630	13.640	12.096	13.253	14.012	14.628	13.782	14.939
SD/XB	.044	.051	.045	.048	.044	.161	.144	.134	.112	.108

GROWING SEASON STATISTICS

	36	32	28	24	20
M	30	30	30	30	30
N	30	30	30	30	30
VAR	456.46	417.52	301.36	412.99	411.43
XBAR	118.400	146.167	171.767	201.600	226.567
SD	21.365	20.433	17.360	20.322	20.284
SD/XB	.180	.140	.101	.101	.090

PROBABILITIES OF LAST SPRING DATES

	LAST	.05	.10	.25	.50	.75	.90	.95	FIRST
THRES 36	625	617	612	603	524	514	505	430	423
THRES 32	610	607	601	522	511	430	421	415	408
THRES 28	527	520	515	507	428	419	410	405	408
THRES 24	510	504	429	421	412	402	325	320	309
THRES 20	510	421	417	410	402	324	317	313	309

PROBABILITIES OF FIRST FALL DATES

	FIRST	.05	.10	.25	.50	.75	.90	.95	LAST
THRES 36	809	829	903	911	920	929	1007	1012	1014
THRES 32	912	912	917	926	1005	1115	1023	1028	1101
THRES 28	921	923	929	1008	1017	1027	1105	1110	1108
THRES 24	924	1008	1014	1022	1031	1109	1118	1123	1126
THRES 20	1019	1021	1027	1105	1115	1125	1204	1210	1210

PERCENT CHANCE OF SEASON LONGER THAN INDICATED LENGTH (DAYS)

	MAX	.05	.10	.25	.50	.75	.90	.95	MIN
THRES 35	51/168	154	146	133	118	104	91	83	64/ 67
THRES 32	55/203	180	172	160	146	132	120	113	66/105
THRES 28	55/209	200	194	183	172	160	150	143	76/132
THRES 24	56/247	235	228	216	202	198	176	168	76/163
THRES 20	53/264	260	253	240	227	213	201	193	66/172

APPENDIX D

TEMPERATURE-PROFILE PREDICTION MODEL

There are five distinct steps in the model:

1. soil heat flux
2. convective heat flux
3. friction velocity
4. air-temperature profile
5. temperature change with time

Input Parameters

Input parameters at t_o were:

$R_n(0)$	an hourly mean value preceding t_o (cal cm^{-2} min^{-1})
T_R	ambient air temperature at the reference level, 150 cm (^oK)
$\bar{U}_1$, $\bar{U}_2$	wind speeds at 900 and 1800 cm, respectively
T_{xi}	maximum soil temperature for the day at i = 0, 5, 10, 20, and 50 cm (^oK)
T_{ni}	minimum soil temperature at same levels (^oK)
PW	percent water in the soil on a volume basis
T_d	dew-point temperature (^oK)

Soil Heat Flux

The heat flux through the upper boundary of a slab of soil at the earth-air interface during periods of net outgoing radiation is

$$S(0) = \int_0^z (\rho_S C_S \Delta T/\Delta t)\, dZ \qquad \text{(D.1)}$$

Soil layers which exhibit diurnal temperature variation are responsible for the total flux of heat across the earth's surface. Equation D.1 is then evaluated as an algebraic sum:

$$S(0) = (\rho_S C_S \Delta T/\Delta t)_1 + (\rho_S C_S \Delta T/\Delta t)_2 + \ldots + (\rho_S C_S \Delta T/\Delta t)_I \qquad \text{(D.2)}$$

where the subscripts refer to depths 1 cm, 2 cm, etc., to the depth where $\Delta T/\Delta t = 0$.

The soil heat capacity per unit volume (volumetric heat capacity) is computed by the formula

$$C_V = \rho_B (C_S + PW/100) \qquad \text{(D.3)}$$

A moist, homogeneous soil is assumed, where ρ_B is the bulk density of the soil, 1.6 g cm^{-3}, and C_S is the specific heat of the soil, 0.18 cal g^{-1} C^{-1}.

Van Wijk (1965) bypassed the need for precise knowledge of the thermal diffusivity of the soil when deriving his equation of the soil temperature profile with respect to time. His equation is:

$$T(Z,t) = T_A + AT_0\, e^{-(Z/D)} \sin(wt+C_o-Z/D) \qquad (D.4)$$

where

T_A is the average soil temperature and is often the same at any level within the depth of diurnal temperature change (^oK)

AT_0 is the amplitude of the soil surface temperature ($^oK/100$ m)

D is the damping depth: the depth at which the amplitude of the temperature wave has increased to 1/e of its value at the surface (cm)

C_0 is a constant which depends upon the choice of the zero point on the time scale

w is $2\pi/P$, where P is the period (sec^{-1})

This equation is actually a solution to the classical Fourier heat conduction equation:

$$\partial T/\partial t = K_s \partial^2 T/\partial^2 Z$$

which fits the boundary condition

$$T = T_o \sin wt.$$

This assumption is based upon the observation that, on cloudless days, the diurnal fluctuation of soil temperature may be approximated by a sine function of the time.

The soil heat flux each hour was computed by use of D.2, D.3, and D.4. Finally, the derivatives of D.4 for each soil level at t_o and at hourly increments after t_o were used in a form of D.2 designed to account for the uneven spacing of maximum soil temperature measurements:

$$S(0) = 5C_v\left[\overline{(\Delta T/\Delta t)}_1 + \overline{(\Delta T/\Delta t)}_2 + 2(\Delta T/\Delta t)_3 + 6\overline{(\Delta T/\Delta t)}_4\right] \qquad (D.5)$$

The subscripts refer to descending soil slab numbers, and bars denote averages of the change in temperature with respect to time at the bounding surfaces of each slab. For example,

$$(\Delta T/\Delta t)_1 = \left[(\Delta T/\Delta t)_{0\ cm} + (\Delta T/\Delta t)_{5\ cm}\right]/2$$

Convective Heat Flux

The convective heat flux was solved by

$$F_H(0) = R_n(0) - S(0) \qquad \text{(D.6)}$$

where the horizontal and vertical divergence of heat flux were assumed to be zero, and the net radiation considered to be constant throughout the forecast period.

Friction Velocity

An approximation to the friction velocity was found from the difference form of Prandtl's logarithmic law, which models the wind velocity in an adiabatic atmosphere:

$$\begin{aligned} U_2 - U_1 &= \left[(U_*/K)(\ln Z_2/Z_o)\right] - \left[(U_*/K)(\ln Z_1/Z_o)\right] \\ &= (U_*/K)\ \ln\ (Z_2 Z_1) \qquad \text{(D.7)} \end{aligned}$$

Alternatively,

$$U_* = (U_2 - U_1)k/\ln(Z_2/Z_1) = (U_2 - U_1)k/\ln 2 \qquad \text{(D.8)}$$

where k is von Karman's constant, 0.40.

In the non-adiabatic case, it was necessary to compute a thermal stability index known as the Monin-Obukhov scale length:

$$L = U_*^3 c \quad T/(kgF_H) \qquad \text{(D.9)}$$

The scale length is constant with height, making it convenient to express wind and temperature gradients as a function of the dimensionless height ratio Z/L. The non-neutral wind profile is

$$dU/dZ = (U_*/kZ)(1+\alpha Z/L) \tag{D.10}$$

where the term $(1+\alpha Z/L)$ represents the first term in the power series expansion of f(Z/L). Integrating D.10:

$$U = (U_*/K)\left[\ln(Z/z_o)+\alpha(Z-z_o)/L\right] \tag{D.11}$$

but z_o is very small, so that the non-adiabatic profile is

$$U = (U_*/K)\left[\ln(Z/z_o)+\alpha Z/L\right] \tag{D.12}$$

Air-Temperature Profile

The Lumley-Panofsky scaling temperature

$$T_* = F_H/KU_*c\rho \tag{D.13}$$

appeared in the temperature profile equation,

$$\Theta-\Theta_{z_o} = T_*\left[\ln(Z/z_o)+\alpha Z/L\right] \tag{D.14}$$

By neglecting vertical motions in a stable atmosphere, the profile equation was solved in a manner similar to that for obtaining D.7:

$$T_{z_2}-T_{z_1} = T_*\left[\ln(Z_2/Z_1)+\alpha\left(\frac{Z_2-Z_1}{L}\right)\right] \tag{D.15}$$

T_{z_1} was designated as the reference temperature T_R at 150 cm. Typically L is much greater than Z_1, so that Z_1/L was neglected and the final profile equation was

$$T_z = T_R + T_* \left[\ln Z/Z_R + \alpha Z/L\right] \tag{D.16}$$

Temperature Change with Time

From the air-temperature profile, dT/dZ at the reference level was computed and then used with $F_H(0)$ to find the exchange coefficient:

$$K_H = -F_H(0)/\rho c_p(dT/dZ) \tag{D.17}$$

This enabled the computation of the eddy conductivity (λ):

$$\lambda = K_H \rho c_p \tag{D.18}$$

By considering heat flux across any plane, Brunt (1941) derived an equation for the air-temperature profile valid for the case of constant flux across Z=0, with the boundary condition $T_{(z=0)}=0$. This equation was then solved to compute the predicted change in temperature at 150 cm during the next hour, which then establishes the value of the reference temperature for the next iteration of the program:

$$T(Z,t) = 2F_H/\lambda \left[(K_H t/\pi)^{1/2} \exp(-Z^2/4K_H t) - (Z/2)\,\mathrm{erfc}(Z/\sqrt{4K_H t})\right] \tag{D.19}$$

where erfc is the complimentary error function.

The main assumptions in the model were:

1. constant net radiation

2. a homogeneous soil with respect to conductivity and water

3. equality of the exchange coefficients for

momentum and heat

4. a neutral wind profile

5. zero advection of heat

This model was tested by the Agricultural Weather Service in Florida and presented by J. C. Georg in partial fulfillment of a master's degree from the University of Florida. His results in predicting the nocturnal minimum temperature are very promising: the mean error was -0.16^{o}C, with a standard deviation of 2.4^{o}C. Seventy percent of the errors were within one standard deviation of the mean, and 100% were within two standard deviations.

Georg cited the need to improve computation of the friction velocity, both initially and in subsequent time periods. To accomplish this, he suggested obtaining longer time averages of the input wind velocities, and using a log-linear wind profile on nights when the expected wind speed is less than 2.0 m sec^{-1}. He also concluded that omitting a net radiation divergence term distorted some of the temperature profiles. Finally, a means for computing the change in net radiation during the course of the evening would improve the model.

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