TECHNICAL NOTE No. 157

TECHNIQUES OF FROST PREDICTION
AND
METHODS OF FROST AND COLD PROTECTION

by
A. Bagdonas, J.C. Georg and J.F. Gerber

Secretariat of the World Meteorological Organization - Geneva - Switzerland
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FOREWORD

The importance of frost as an environmental factor affecting crop growth is well known. It can cause partial or total destruction of crops, as well as retardation or termination of crop formation. Much damage to crops by frost and freezing temperature can be avoided by using either passive or active methods of protection; in employing either of these types of protection meteorologists can supply very useful advice. The Commission for Agricultural Meteorology of the World Meteorological Organization, at its fifth session (Geneva, 1971), therefore, considered it useful to review the techniques used for frost prediction as well as frost protection methods. Mr. James C. Georg (U.S.A.) was appointed as Rapporteur on Techniques for Frost Prediction and Mr. J. F. Gerber (U.S.A.) and Mr. A. Bagdonas (U.S.S.R.) as joint Rapporteurs on Frost Protection Methods. Their reports are reproduced in the present Technical Note.

It is with much pleasure that I take this opportunity of expressing the sincere thanks of WMO to these three rapporteurs for the time and effort they have devoted to the preparation of this valuable Technical Note.

D. A. Davies
Secretary-General
PART I

TECHNIQUES OF FROST PREDICTION

by J. C. Georg
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SUMMARY

Techniques of predicting minimum temperatures and/or frost occurrence used in various countries are discussed. The empirical, theoretical, semi-theoretical and ordinary subjective techniques currently employed are described and assessed.

In addition, a brief historical review describes the evolution of frost prediction formulae over the past 90 years.

RÉSUMÉ

Dans cette partie sont passées en revue les méthodes utilisées dans divers pays pour prévoir les températures minimales et/ou l'apparition du gel. On y décrit, en les évaluant, les méthodes empiriques, théoriques, semi-théoriques et subjectives classiques qui sont actuellement employées.

En outre, un bref historique rappelle l'évolution des formules pour la prévision du gel au cours des 90 dernières années.

РЕЗЮМЕ

В данной части излагаются методы предсказания минимальных температур и/или появления заморозков, которые используются в различных странах. Дается изложение и оценка эмпирических, теоретических, частично теоретических и обычных субъективных методик, используемых в настоящее время.

Помимо этого в кратком историческом обзоре дается описание эволюции формул предсказания заморозков за последние 90 лет.

RESUMEN

En este informe se examinan las técnicas utilizadas en varios países de predicciòn de temperaturas mínimas y/o de aparición de heladas. Igualmente, se describen y evalúan las técnicas empíricas, teóricas, semitéóricas y subjetivas ordinarias actualmente empleadas.

Además, en una breve reseña histórica se describe la evolución de las fórmulas de predicción de heladas durante los últimos 90 años.
LIST OF SYMBOLS

C  Specific heat of the air
C_s  Specific heat of the soil
e  Vapour pressure
H  Relative humidity
K_s  Thermal diffusivity of the soil
LST  Local standard time
R_n (O)  Net radiation from soil surface
T  Time
T  Ambient air temperature
T_d  Dew-point temperature
T_m  Minimum air temperature at shelter level
T_o  Temperature of the soil surface
T_s  Minimum temperature of soil surface
T_x  Maximum air temperature
T_w  Wet-bulb temperature
Δ T_o  Fall in temperature at the soil surface
U  Wind speed
U_Ψ  Friction velocity
w  Surface wind speed
Z  Distance from the Earth's surface into the atmosphere or soil
σ  Stefan-Boltzmann constant
ρ  Air density
ρ_s  Soil density
CHAPTER 1

INTRODUCTION

This note was prepared in response to an invitation from the World Meteorological Organization’s Commission for Agricultural Meteorology which, at its fifth session, October 1971, decided to appoint a rapporteur to obtain as much information as possible regarding frost prediction techniques.

Food supply for the increasing population of the Earth has become the concern of many governmental, educational, and private institutions throughout the world and damage to or destruction of crops by frost and/or freezing temperatures has become increasingly significant. Much of this crop loss could be prevented by passive or active cold protection practices. To be efficient and economical, however, these practices are dependent upon timely and accurate advice and warning. Techniques for frost and/or critical temperature prediction are presented in this Technical Note.

Most methods were designed for short-term (less than 24 hours) forecasts of the local minimum temperature whenever the synoptic situation posed some threat of frost and/or critical temperature. Light or calm winds, low humidity, dry soil, and clear skies favour nocturnal cooling of the Earth’s surface and the air immediately above it. Therefore application of any technique usually depends upon the synoptician’s assessment of the probability of occurrence of the weather patterns which favour these conditions. In many cases, however, the physical meteorologist with his simple, objective tools can be more accurate than the subjective synoptic meteorologist in borderline situations.

To put the present-day frost-prediction techniques in proper perspective, to assess the progress made over the past ten to twenty years, and to observe the extent to which the practical, everyday forecaster has used and is using the more rigorous techniques developed by workers in the academic community, it seems appropriate to review briefly the history of frost-prediction. Most techniques have been concerned with minimum temperature forecasting and not frost forecasting per se, as plants may be killed or injured without the occurrence of frost. The frost or no-frost prediction is simply dependent on the forecaster’s evaluation of the night-time wind, the temperature of the vegetative surface and the dew-point temperature during the critical period. These evaluations have always been, and still are, largely subjective.
CHAPTER 2

HISTORY

2.1 Empirical formulae

Empirical formulae for forecasting the minimum temperature are believed to have been made as early as 1885, according to Jorgensen (1960). Sutton (1953) cites Kammerman's rule as among the early ones for forecasting minimum air temperature, which in this case is obtained by subtracting a constant value from a previously observed wet-bulb temperature. Ångström (1920) found that fairly accurate results could be obtained for clear nights if Kammerman's rule were applied at sunset, but that better results were obtained if both wet-bulb and dry-bulb temperatures were combined with other factors.

Early in this century, cold damage to fruit and crops in the far western regions of the United States prompted studies of local temperature forecasting formulae, which were derived from data by statistical means. Some of the earliest empirical formulae simply related the minimum air temperature ($T_M$) to air temperature ($T$). Beals (1912) suggested a relationship using the "median-hour" which he defined as the mean time of occurrence of the point midway between the maximum and minimum temperatures, i.e., the mean hour at which one-half of the temperature fall from maximum to minimum occurred. The temperature at this time was subtracted from the maximum temperature yielding a difference which indicated the approximate amount that air temperature would fall after the median hour.

Nichols (1920) proposed a "maximum-minimum" relationship which gave $T_M$ as a direct function of the maximum temperature ($T_X$) from which it may be determined.

A "daily temperature range" method was formulated by Smith (1914) in which the mean, greatest and least daily temperature ranges were computed for semi-monthly periods and these used to forecast $T_M$ from the maximum.

Coincident with the development of earlier functions, $T_M = F(T)$, investigators were examining relationships between $T_M$ and the dew-point temperature ($T_d$), or the wet-bulb temperature ($T_W$). Humphreys (1914) proposed an "evening dew-point" relationship which essentially predicted that $T_M$ should equal the evening $T_d$. Keyser (1922a) proposed the "wet-bulb-minimum-temperature method". From past data the average difference between 1700 LST readings of $T_W$ and $T_M$ was subtracted from the current 1700 LST $T_W$ to arrive at a forecast minimum. Smith (1920) correlated the difference between evening values of $T$ and $T_d$ with the difference between the evening $T_d$ and the ensuing $T_M$. In 1926 Nichols originated another method involving the depression of $T_d$ below $T_X$; the depression is correlated with the fall in temperature from maximum to minimum.

Much of the published work on predicting minimum temperature has been based upon empirical hygrometric relationships involving relative humidity ($H$) such as:

$$T_M = F(T_d) + F(H).$$

According to Ellison (1928) the hygrometric relationship was first proposed by Donnel in 1910 while working on Boise, Idaho frost records. His equation was:

$$T_M = T_d - \frac{H - a}{b}.$$
where $a$ and $b$ are constants. It does not appear that any extended practical use was ever made of this equation in its original form.

Smith (1917) studied the hygrometric relationship for Ohio, but unlike Donnel, who assumed the best-fit line was straight, he used the least squares method and obtained:

$$Y = a - bH$$

where $Y$ is the difference between $T_M$ and the evening $T_d$; Marvin (1917) showed that these two equations were mathematically identical.

The first application of a curvilinear hygrometric formula to forecast actual minimum temperature was made by Young (1920). His equation was:

$$T_M = T_d - \frac{H - n}{4} + V_d + V_H$$

where $n = 20, 30$ and $40$ for clear, partly cloudy and cloudy skies, respectively, and $V_d$ and $V_H$ are parameters depending on evening values of $T_d$ and $H$, respectively.

Smith (1920), using the Marvin (1920) "star" point method to fit parabolic curves to the hygrometric data, obtained:

$$T_M - T_d = a + bH + cH^2.$$  
Nichols (1920) and Keyser (1922b) suggested that the line of best fit might be drawn by inspection rather than by fitting curves. Nichols' equation had the form:

$$T_M = T_d + V_H.$$  

Of all the empirical formulae given, Ellison (1928) concluded that the hygrometric types were superior, and Young's formula was best when sufficient data existed for determining its constants; otherwise the formulae of Smith or Nichols were best.

Since 1930 most of the studies concerned with forecasting local $T_M$ by empirical formulae have essentially followed the hygrometric approach. Kessler and Kaempfert (1940) surveyed and discussed the empirical relationships developed before 1940. More recently, Kangieser (1959) remarked on the usefulness of some of the better-known empirical formulae for clear nights in an arid region.

Sutton (1953) states that hygrometric equations are often reasonably successful when used by experienced meteorologists with a knowledge of local conditions. Jorgensen reported that the United States hygrometric formulae had been developed and used by the Frost Warning Service of the Weather Bureau for some 40 years with excellent success. In his bibliography he gave a good account of the unpublished papers by California workers: in Florida, Dean (1965), Yates (1965) and Davis (1967) have addressed themselves to the problem; in Massachusetts, Franklin and Stevens (1946); in Wisconsin, Cox (1912), Kenney (1946), and Georg (1960); and in Michigan, Soderberg (1969). Many other contributions probably have not found their way into the literature.

2.2 Semi-empirical and theoretical techniques

By applying the laws of heat transfer it can be shown that the temperature of the Earth's surface at night should be highly correlated with that of the air in the surface layer. Therefore a good forecast of the minimum temperature of the soil should provide a good forecast of the minimum air temperature. This logic resulted in the development of several semi-empirical and theoretical techniques early in this century, and these have become increasingly popular in recent years.
According to Gröen (1947) the first theoretical attack on the problem of predicting surface temperature was made by Richardson (1922) whose work, although complete from a theoretical point of view, was not developed into a practical form. Reuter (1951) credits Brunt (1941) with the first theoretical solution for nocturnal cooling of the Earth’s surface, which serves for approximating the air temperature on clear, calm nights. Brunt’s formula was:

$$\Delta T_0 = \frac{2}{\pi} \frac{\sigma T_n^4 (1 - a - b V_e)}{\rho_s C_s K_s} \sqrt{t}$$

where $\Delta T_0$ is the fall in temperature at the ground surface; $T_0$ is the sunset temperature of the ground, and $t$ is time from sunset to sunrise. Phillips (1940) gave a solution which was essentially an extension of the Brunt formula for the case where the convective heat flux is not equal to zero. Later Jaeger (1945) formulated the effect of wind on nocturnal cooling, first by simply assuming that the eddy conductivity and diffusivity were constant with height and then by more realistically assuming they were not. For the latter he assumed that the heat transfer coefficient varied as a constant power of height above the ground. Sutton commented on (1953) Jaeger’s solution: “the difficulty of finding reliable values of the parameters expressing the eddy conduction of heat in an unsteady airstream of varying degree of turbulence probably makes this expression of little practical value in the problems of forecasting night temperatures.”

Gröen (1947) basically extended the work of Brunt by treating the general case where the net radiation at the surface, $R_n (0)$, was not assumed to be constant but rather, an explicit function of time. Sutton (1953) demonstrated that the results given by the Brunt and Gröen cooling formulae are quite similar for time periods of the order of a night, but that they diverge for longer periods, such as the polar night.

Whereas the Brunt formula, and most of its theoretical extensions, assume that all of the heat radiated from the ground is supplied by the upper layers of soil, Frost (1948) assumed that all this heat was supplied by the air above the surface. Frost’s formula was:

$$\Delta T_0 = \frac{R_n (0)}{am} \frac{[(m + 1)^2 \text{at}]^{m/(m + 1)}}{c \Gamma (1/(m + 1))}$$

where $a$ and $m$ are turbulence parameters defined as 40 and 1/3, respectively and $\Gamma$ is the adiabatic lapse rate. Knighting (1950) examined these two fundamentally different approaches and derived a more comprehensive formula which took into account the heat transport from both soil and air. Reuter (1951) devised a semi-empirical method of finding the nocturnal cooling of the ground which included all of the relevant parameters but excluded advection and latent heat processes. His formula was:

$$\Delta T_0 = \frac{2}{\pi} \frac{R_n (0) \lambda dT}{\sqrt[4]{\rho_s C_s K_s} + C \sqrt{A_p}} - \sqrt{t}$$

where $\lambda$ is the coefficient of the heat conductivity of the soil, $dT/dz$ is the change of temperature with depth in soil, $\Gamma_s$ is the lapse rate of air temperature at sunset and $A$ is the coefficient of eddy conductivity in air.
CHAPTER 3

PRODUCTION TECHNIQUES USED BY VARIOUS COUNTRIES

With this brief review of the history* the present-day techniques of minimum temperature and/or frost prediction are presented. Contributions from Member countries of WMO were solicited and the response was gratifying. It would therefore seem logical to report on the subject according to nation and this procedure is followed below.

3.1 Argentina

There are at least two areas in Argentina where there is considerable interest in minimum temperature and frost prediction techniques. One is the Alto Valle del Rio Negro and Neuquen area (approximately 38°S, 67°W) which is important for growing apples and peaches. The other is the Mendoza area important for grapes and which is about 5° north of the Alto Valle del Rio Negro and Neuquen area.

For the Alto Valle Del Rio Negro and Neuquen area, a general forecast of minimum temperature is made by the central forecast station in Buenos Aires employing conventional synoptic practices. By means of a hygrometric formula, a specific local forecast is made for Neuquen and the Valley. The procedure claims 75 per cent accuracy for \( T_M \leq 6°C \).

Fernandez (1970) and Almejum (1970) reported on the method used in Mendoza, region located in the first eastern ranges of the Andes. Because of the topography, local differences in \( T_M \) are strongly displayed by their mean values. The difference, \( \Delta T \), between the mean value for a given location and for the reference forecast point was used to correct the value of \( T_M \) for the reference point, forecast from the equation:

\[
T_M = a + bT_W
\]

where \( T_W \) is the wet-bulb temperature at 1800 GMT, and \( a \) and \( b \) are constants empirically derived.

As a refinement they stipulated five different synoptic patterns which may produce frost in the Mendoza area. For each a different correction was statistically developed to obtain a total correction \( C_1 \), defined as

\[
C_1 = \Delta T - a_y \sqrt{1 - r^2}
\]

where \( y = T_M \), \( a_y \) is the standard deviation of \( T_M \) and \( r \) is the correlation coefficient between \( T_M \) at the reference forecast point and another location. This was found to be a significant improvement, as \( C_1 \) incorporated a factor dependent upon the wind speed forecasts for the different synoptic regimes. Results from one season (1962-1963) for five different stations showed that average errors ranged from 1.2 to 1.5°C where \( C_1 \) was applied, as opposed to 1.9 to 2.3°C when \( \Delta T \) was used alone. Only nights when \( T_M < 8°C \) were selected for verification.

3.2 Australia

The techniques applied in Australia may be represented by those of the Victoria Regional Office for Meteorology; they essentially involve synoptic considerations or empirical equations.

*For more detail and information the reader is referred to an excellent work by Schnieder (1963) and to a Technical Note by Blanc et al. (1963).
The synoptic considerations are:
(a) $T_d < 6^\circ C$ – the possibility of frost;
(b) $T_d < 0^\circ C$ – the probability of frost;
(c) $T_x > 18^\circ C$ – frosts unlikely;
(d) A wind between SW and SE is particularly favourable for frost.
(e) The increase or decrease of cloud overnight is unfavourable and favourable for frost, respectively;
(ff) Substantial overnight pressure rises with resultant clearing skies and decreases in wind speed are favourable for frost;
(g) Presence of moisture aloft, even without cloud, will hinder nocturnal radiation.

The empirical equations which vary from place to place depending on local influences, may be represented by sets of nomograms. A typical set developed for predicting the overnight $T_M$ at Mildura and Lemnos (located in two of the major fruit-growing areas) include the following variables:
(a) The forecast surface pressure gradient for the following morning;
(b) The forecast overnight cloud cover, defined as that part of the sky obscured by low or middle cloud plus one half of the remaining sky obscured by high-level clouds;
(c) The current day’s $T_x$;
(d) The mean of the current day’s noon and 1500 LMT $T_d$ values for Mildura; the 1500 $T_d$ for Lemnos.

3.3 Canada

The Canadians have apparently been quite active and several of their works differing from the main body of techniques will be noted.

3.3.1 Empirical formulae

O’Neill (1968) reported on results for Goose Bay, Canada, using a slightly modified formula developed by McKenzie (1959) for Aberdeen, Scotland (about the same latitude as Goose Bay). McKenzie’s formula is:

$$T_M = 1/2 (T_x + T_d) - C$$

where $T_d$ is the average overnight value of $T_d$, $C$ is a correction factor based on average overnight wind speed and cloud cover (see Table 1). For 345 cases in 1964, when no marked overnight frontal passages occurred, the mean absolute error was $1.4^\circ C$, the mean was $0.4^\circ C$ and the standard deviation was $1.9^\circ C$. The positive bias in forecast errors was found to be real (99 per cent confidence level) when the mean error was tested statistically to determine if it differed significantly from the value of zero expected for an unbiased forecast. O’Neill points out that errors in the predicted values of $T_x$ and $T_d$ do not have as much effect on the predicted $T_M$ as might first appear, due to the averaging process, however the 2200 LST predictions give noticeably better results because $T_x$ is then known and an improved estimate of $T_d$ is more likely obtained.

A very large percentage of the various formulae for $T_M$ used sunset or post-sunset data, for many applications a frost or freeze warning issued at these times is timely enough to be effective. However, longer advance warnings of impending critical temperatures are often desirable, sometimes essential. Korven (1964) described an equation for Penhold, Alberta, applicable several hours before sunset:

$$T_M = T_{17} + (t + 1/2 (T - T_d)_{17})$$
where $T_{10}$ is the air temperature at 1700 LST, $t$ is the number of hours from 1700 to sunrise to the nearest half hour. Tables 2 and 3 show results for the six warm and six cold months, respectively. Table 4 presents a comparison between $T_M$ calculated at 1700 and at sunset.

3.3.2 Graphical method

Lamont (1957) described a technique for forecasting the minimum temperature on clear nights in Hamilton, Ontario, during May when frosts were important. He used as one parameter, the difference between the maximum air temperature $T_X$ and the normal temperature of western Lake Ontario. He felt that there was a rough correspondence between this difference and the difference between temperatures at the soil surface and several centimetres below. This would serve as a quantitative measure of the soil heat flux in the nocturnal cooling process. From historical data he constructed a scatter diagram of:

$$(T_X - T_{\text{Lake}}) \text{ vs } (T - T_d)_{1330 \, \text{EST}}.$$  

Values of $\Delta T = (T_X - T_M)$ were marked beside each point plotted. Best-fit isopleths were then drawn to construct Figure 1. Wind corrections ($k_v$) are applied to the predictions from this graph depending on the estimated value of surface wind speed ($v$) at 0730 EST (Figure 2). $k_v = 0$ for $v < 0.9$ mps and is a constant for $v > 5.0$ mps.

Finally a correction for advection ($k_a$) based on a subjective appraisal of the synoptic situation is added:

$$T_M = T_X - (\Delta T^1 - k_v - k_a)$$

where $T^1$ is the first approximation of $T$ taken from Figure 1. Table 5 shows results of some tests comparing this method with official forecasts.

3.3.3 Brunt’s and Reuter’s formulae

Fley (1961) simplified Reuter’s formula and developed two nomograms for rapid solution. The simplified form is:

$$\Delta T_o = \frac{2}{\sqrt{C_x} \rho_s K_s} \sqrt{\frac{T}{A \rho}} \sqrt{\frac{t}{F \cdot E \sqrt{t}}}$$

where $A$ is the coefficient of eddy conductivity of the air (considered constant on any given night) and $E$ is the net outgoing radiation. Following Brunt he found $E \approx 0.55 (0.56 - 0.08 \sqrt{e})$. Reuter’s value of $A = 65 U$, where $U$ is the mean wind speed (MPH) was used and $\sqrt{C_x} \rho_s K_s$ was determined empirically from observed value of $\Delta T_o$ for nights which had radiational cooling alone and has a mean value of $0.290 \text{ cal} \text{ cm}^{-2} \text{ min}^{-1/2}$. For rapid calculation $F$ was defined as above; two nomograms were constructed: one to find $F \cdot E$ for various combinations of relative humidity and sunset temperatures (Figure 3), and another to obtain $\Delta T_o$ from $F \cdot E$ for any date from April through September (Figure 4). Table 6 gives some independent results from observations that fit the assumptions.

Fley concluded that this method should have practical value but applied only when the ground is dry, since $\sqrt{C_x} \rho_s K_s$ increases with very wet soil. Also the temperature of the ground should be used but is not commonly available.

Kagawa (1968) evaluated Brunt’s formula for several prairie locations in Canada. He rearranged it to make $C = \rho_s C_s \sqrt{K_s}$ the dependent variable and established values for $C$ from past observational data. He found that $C$ had great variability. However, when the values were grouped into a histogram, the distribution had a peak value and this was selected. For cloudy skies the author followed Reuter (1951) to calculate $S(0)_{n}$, the flux of terrestrial radiation with $n$ tenths of cloud:

$$S(0)_n = S(0)_{0} (1 - K_n)$$

where $K_n$ is a constant depending on cloud type: 0.031 for cirrostratus; 0.063 for altostratus; 0.085 for stratus; and 0.099 for nimbostratus.
If the soil parameters are considered constant for any locality, the Brunt formula can be simplified and rearranged for quick solution as follows:

\[ T = C \cdot S(0) \cdot 2.03\sqrt{t} \]

where \( S(0) \) and \( 2.03\sqrt{t} \) are found from nomograms (Figures 5 and 6) and \( S(0) \) is adjusted for cloudiness as discussed. Table 7 shows some results.

3.3.4 Multi-regression

Yacouwar (1968) derived a set of multiple-regression equations where maximum and minimum temperatures were dependent variables and various sets of predictors were the independent variables, including atmospheric parameters from 850 to 500 mb as well as for the surface (for example, snow). This rather complex technique is hardly suited for the routine prediction of frosts or freezes, but may be used at the larger meteorological centres, which may soon be able to provide the local forecaster with valuable guidance.

3.4 Finland

Franssila (1948) reports that the formula derived by Ångström for calculating \( T_M \) is probably the best, at least for Finland:

\[ T_M = C_1 T_W - C_0 T - K \]

where \( C_1, C_0 \) and \( K \) are constants which depend upon the time that psychrometric measurements are made, the season, cloudiness and other local factors. Ångström's values for \( C_1 \) varied between 0.83 and 1.12 and for \( C_0 \), between 0.12 and 0.15 but Franssila's values of \( C_1 \) were significantly higher. Finally he obtained:

\[ T_M = T_W - \frac{T}{4} - K, \]

which he further simplified and then determined values of \( K \) by month vs. observation time and cloud cover, and introduced a factor dependent on wind speed. In tests of the formula, with and without the wind correction term, the standard deviation for the error was never greater than 0.2°C.

Franssila concluded that if no change in air mass occurs from the time psychrometric observations are made until the following morning, then the accuracy of \( T_M \) computed by Ångström's formula is not significantly dependent on the observation time. This would appear to have a definite advantage over other types of empirical equations which require input from later hours.

In private correspondence, P. Jarvi (member for Finland of the WMO Commission for Agricultural Meteorology) noted that Ångström's method as such is not suitable for practical frost forecasting because it gives a value of \( T_M \) for a height of 2 m, whereas values between the minima for grass and screen have to be taken into account.

For practical purposes another method has been developed, i.e., to use nomograms in which the occurrence or non-occurrence of frost is depicted as a function of the 1400 LST values of \( T \) and \( T_d \). The graphs were constructed from observations at the Jokioinen Meteorological Observatory to predict frost for south Finland. When the surface temperature the following night falls below 0°C, the point \( (T, T_d) \) is marked (X); otherwise (0). The distributions of (X) and (0) show the probability of frost. This technique is much the same as the one used in Jordan with \( T_d \) and H. (See Figures 7 and 8).

3.5 France

The national Meteorological Services have perfected a method of forecasting the minimum temperature of the free air 10 cm above the ground based on a simplified form of Brunt's equation:

\[ \Delta T = -K (a - b\sqrt{c}). \]
K represents a "lumped" constant which apparently includes the effects of soil-moisture, initial temperature and length of the night, i.e., two terms in the numerator and denominator of the Brunt equation. Thus K is an independent variable with different values from night to night, but constant for any given night.

No verification has been made but may be available when the technique is published as a notice of instruction to meteorological offices.

3.6 Greece

In Greece it is reported that the general synoptic forecasts are supplemented with local frost-prediction aids using empirical formulae for predicting $T_M$ at screen level. Independent variables are $T$ and $T_d$ observed at 2000 LST on the previous day. A similar formula, which includes upper-air data, has been developed. Neither method has been completed or tested sufficiently to provide results.

3.7 Israel

The Israeli Meteorological Service has issued frost advisories for relatively large areas of the country for many years. Recently they have attempted to provide more detailed frost forecasts for part of the central coastal region.

The scheme employs topoclimatological maps, which are based on several years of data, and depict for various regions, as a continuum, the expected frequency of temperatures, $0^\circ C$ or below, and the expected number of hours with $0^\circ C$ and below. Also shown are the locations of all topoclimatological stations and the average departures of their minimum temperature from that at a base station (for example, Yad Hanan) for nights with radiational cooling.

As a forecast tool the maps are used to make specific predictions for areas represented by the different topoclimatological stations simply by adjusting the value of the minimum predicted for the base station. Preliminary results indicate that in 80 per cent of the cases the forecasts have been within $\pm 1^\circ C$.

Conclusions based on the results of three seasons are:

(a) Topoclimatological maps provide an excellent guide for interpreting general forecasts for specific areas;

(b) Provided that the synoptic forecast is accurate, detailed predictions are possible with an acceptable degree of accuracy;

(c) The main climatic element responsible for inaccurate forecasts is light wind.

3.8 Japan

Kuribayashi (1957) derived an equation between $T_W$ at 1500 LST and subsequent $T_M$ for application in the Echime Prefecture of Japan when mulberry orchards are frequently damaged by spring frosts:

$$T_M = 1.09T_W - 4.34.$$  

He established a similar relationship between the minimum temperature of the Earth's surface, $T_s$, and $T_M$ at shelter height:

$$T_s = 1.17T_M - 4.36.$$  

The average value of $T_M - T_s$ was $3.2^\circ C$. 
Imada and Hirano (1957) devised a seemingly unique technique for objectively refining a hygrometric relationship. Recognizing the importance of radiation and realizing that for identical combinations of $T_W$ and $T_d$ the subsequent $T_M$ may be quite different from that given by formula, they modified their formula:

$$T_M = \frac{1}{3} (T_W + T_d).$$

to take into account the mean specific humidity from the surface up to 700 mb. They divided the cases when frost was a threat ($T_M < 3^\circ C$) into three groups according to atmospheric pressure. Each group had a different mean specific humidity, implying a different atmospheric transmissivity. Then the results given by formula were adjusted by subtracting amounts that ranged from 3.5$^\circ C$ for the group with the lowest specific humidity to 2.0$^\circ C$ for the group with the highest. The basic forecast is for Tokushima, whose minimum temperature may be related to various other locations in the Prefecture to predict the probability of frost.

3.9  Jordan

The Agrometeorological Division of the Jordan Meteorological Department is undertaking an extensive programme in order to establish accurate frost prediction methods, particularly for the Jordan Valley where winter agriculture is practised. Two techniques are currently used. The graphic method consists of plotting 1200Z air temperature vs. the 1200Z relative humidity and recording the grass minimum temperature $(T_g)$ at that point. After considerable data have been collected a line is drawn separating the negative values from the positive. A second line is drawn separating the $T_g$ values between $0^\circ C$ and $-1^\circ C$ from those less than $-1^\circ C$. Areas on the graph then denote the likelihood of frost or no frost and are labelled as such. Figure 8 is a graph for the Baqura Agricultural Meteorological station in Jordan. Similar diagrams can be prepared for different regions according to their local characteristics and may then be used as forecast tools. The graphs are only used when: (a) the synoptic situation implies some possibility of frost and; (b) certain predetermined limits of surface temperature, 850 mb temperature and height and 500 mb thickness are satisfied at 1200Z. This method verified correctly for 70-80 per cent of all cases when frost occurred.

A second method involves a relationship:

$$T_{(1800Z)} = (T_{(1200Z)} + T_M)/2$$

which was applied daily for various locations in the Jordan Valley. After it has been empirically established which minimum temperature (grass or air) gave best results, the equation may be used as a forecast tool by solving for $T_M$.

This method produced about 75 per cent accuracy. To improve this, wind was taken into account via a regression equation developed to produce a correction $Y = 0.35X + 0.03$ where $X$ is the mean wind speed expected during the night in km h$^{-1}$.

3.10  New Zealand

A number of local studies have been made by meteorologists in the New Zealand Meteorological Service to test prediction formulae such as Brunt's. They found reasonably good results provided there was no change in the general weather conditions. However, frost forecasts are mainly made by the National Weather Centre using conventional synoptic practices. The major problem in frost prediction is to forecast changes in cloud cover and the onset of wind.

3.11  Portugal

It is reported that frost forecasting in Portugal is based on climatology and synoptic meteorology almost exclusively. Although frost can occur in most regions all year round, it is mainly in spring but also in autumn that forecasts are most important. Therefore the synoptic situations which pose a threat of frost have been classified for each of the months September through November and March through May.
September: There are two main synoptic situations that account for the occurrence of frost in Portugal: when the Azores anticyclone centred over the north of the islands develops with its main axis oriented into N - S or NE - SW directions, or when an anticyclone is centred over the Bay of Biscay. In both cases the advection of maritime polar air has a strong meridional component.

October: There are three main situations: (a) an anticyclone centred to the south or southwest of the British Isles that transports continental polar air; (b) an anticyclone centred over the North Sea or the Scandinavian peninsula that produces the advection of a continental polar air mass; (c) an anticyclone centred west of Cape Finisterre transporting maritime polar air.

November: There are two main situations: (a) an anticyclone centred north-west of the British Isles that brings maritime polar air into Portugal; and (b) an anticyclone centred north-east of the Azores with a ridge over Central Europe causing the advection of continental polar air into Portugal.

March: Situations favourable for frost formation are associated with the Siberian anticyclone, centred over the Scandinavian peninsula, or Germany, which advects continental polar air; or an anticyclone centred between Iceland and the Azores that transports maritime polar air into Portugal. In the first case, with a polar air mass, frost may occur anywhere; in the other, frosts occur only in Algarve (south Portugal) because over the remainder of the country the weather is usually cloudy, with rain in some localities.

April: When the Azores anticyclone develops a ridge that penetrates over the north of Europe, the associated circulation brings continental polar air into Portugal.

May: With an anticyclone centred north-west of Cape Finisterre an invasion of modified maritime polar air associated with intense nocturnal radiation is a very favourable condition for frost.

3.12 Switzerland

Primault (1971) discussed the risk of frost and its prediction especially for spring frosts. Using Kammernann’s rule (see paragraph 2.1), he arranges the data so as to handle better situations with changing air masses. Because of climatological variations in Switzerland, he divided the region of interest into eight different zones and developed regression equations for each zone valid for the months of April and May and for April and May combined:

\[ y = a + bx \]

where \( y \) is the fall in nocturnal temperature and \( x \) is the sum of the cloud amounts for two different times of day. Correlation coefficients of \( x \) on \( y \) for the 24 relationships ranged from \(-0.473\) to \(-0.953\). Although this technique was not as simple to use as Kammernann’s rule it was certainly more precise and better adapted for Switzerland.

3.13 United States of America

There are five areas of the United States where cold protection for agricultural crops is practised to a significant degree: the far West, the North-east, the Great Lakes Region, Texas and Florida. Workers in these areas have been mainly responsible for the frost prediction techniques presently used.

3.13.1 Empirical formulae

Of all the techniques tested for many years Young’s (1920) has been the most widely accepted (see paragraph 2.1). This formula or variations of it are in general use in the fruit-growing regions of California, Washington,
Oregon and Arizona, and in the majority of cases it has an absolute error less than 1.7°C. An alternate version derived by Allen (1957) has also apparently been favourably accepted and is currently in wide use. He obtained $V_d$ and $V_h$ in a different way to get a simpler equation:

$$T_M = \frac{2T_d}{3} + \frac{98}{12}H$$

where $T_d$ and $H$ are observed at 1645 LST. Further simplification seemed desirable to circumvent the need for computing $T_d$ and $H$. Allen generated a family of $T_M$ values for ranges of $T$ and $T_d$ which normally precede frost in the San Joaquin Valley. He plotted $(T_W - T_M)$ vs. $T$ and chose the prediction equation from the line of best-fit through the scatter diagram:

$$T_M = T_W - \frac{1}{4} (T+16).$$

This quick and convenient route to $T_M$, devised in 1942, is referred to as the “short cut” Young method. It has been used for many years and found to differ from calculations using the complete formula by less than ±0.3°C on nights with frost.

Hagood (1967) described a technique that apparently produces very good results both in the lower Rio Grande Valley of Texas where considerable amounts of fruits and vegetables are produced, and for Brownsville, Texas where the agricultural weather forecasting facility is located. He established (via climatological records) the maximum cooling that can occur at a given location under ideal radiation conditions, i.e., the greatest difference between the maximum temperature on one day and the minimum the following morning in the same air mass. The basic equation is:

$$T_{M1} = T_X - M_c + M_c \left[ \frac{1}{2} (\bar{V} + \bar{v})/100 \right]$$

where $M_c$ is the maximum cooling (e.g. −1°C over Brownsville);

$\bar{V}$ is the average wind speed from 1 to 1525 m taken from the 1800Z sounding (in knots);

$\bar{v}$ is the average surface wind speed expected during the night (in knots).

Certain criteria must be met to use equation (1): (a) $\bar{V} < 10$ knots, (b) $\bar{V} < 20$ knots, (c) $T_d < T_{M1}$. If the wind criteria are exceeded equation (1) is modified:

$$T_{M2} = T_X - M_c + M_c [\bar{V} + \bar{v})/100].$$

If the dew point criterion is not satisfied, a third equation is used:

$$T_{M3} = T_M + (T_d - T_M) \left(1 - \frac{\bar{V}}{100} \right)$$

where $T_M$ is computed from either equation (1) or (2). Table 8 gives the results of 75 forecasts over a broad range of minimum temperatures.

3.13.2 Graphical method

Soderberg (1969) developed a graphical technique for an important agricultural area in south-west Michigan by incorporating the following parameters: 1600 LST air temperature, dew point, low or middle cloud cover, and the expected change in the 24-hour 850 mb temperature. Figure 9 may be used for practical forecasts of $T_M$. For example, if at 1600 LST, $T$ and $T_d$ are 15.5 and −2.2°C respectively, cloud cover at 5000 ft. is 3/10 and no change in 850 mb temperature is expected, then $T_M$ equals 3.3°C. If the expected 24-hour temperature change due to advection is −21°C then a further empirically derived correction of 21.6°C would be made, so that $T_M$ would be −0.5°C.

Table 9 shows the frequency distribution of error for 26 forecasts during the spring of 1967 by range of error and according to type of 850-mb advection and cloud cover.
3.13.3 Semi-objective (radiometer) technique

Using an economical net radiometer (Suomi and Kuhn, 1958; Tanner et al., 1969), Georg (1970) devised a semi-objective method of predicting the local $T_M$ from radiometer data observed two hours after sunset. The fall in air temperature at shelter level is determined mainly by the difference between the radiating temperatures of two "black" copper plates, one facing the sky, the other the ground, insulated from each other and shielded from advective heat transport by transparent polyethylene. The top of the instrument is ventilated to prevent dew and frost from interfering with radiative exchange. When sky and wind conditions are expected to be reasonably uniform throughout the night, observations of the temperatures of the top and bottom sensors $T_L$ and $T_B$, respectively, are made two hours after sunset. A scatter diagram is plotted of $T_L - T_B$ vs. $T_B - T_M$ and two best-fit lines are drawn: one line for those cases where $T_L < 0^\circ C$, the other for those where $T_L > 0^\circ C$. The equations of the lines are then used to forecast subsequent $T_M$. These instruments are easy to build and use, and have been rather popular with some growers and agriculturalists for predicting their local $T_M$ for purposes of cold protection. The data also provide a valuable feedback to the central forecasting office in Lakeland, Florida which is responsible for issuing a final minimum temperature forecast for all of Florida at 2300 IST. Figure 10 is the frequency distribution of errors for 131 forecasts made for Madison, Wisconsin over several years during the months May to October. The mean of the distribution is 17.7°C and the standard deviation 1.8°C. Approximately 75 per cent of the errors are within one standard deviation of the mean and 94 per cent, within two. Figure 11 shows the distribution of errors for 97 radiometer forecasts made at Bartow, Florida for the months of November to March over the period 1963 through 1966. The mean of this distribution is 18.7°C and the standard deviation 1.6°C. Approximately 79 per cent of the errors are within one standard deviation of the mean and 98 per cent within two.

Table 10 shows a comparison of radiometer, hygrometric formula and Brunt formula verifications at DeLand, Florida. The radiometer forecasts were compared with the subjective forecasts for a site in Central Florida over a four-year period and the histogram of Figure 12 shows the results in terms of total seasonal error. There is a strong inference here that the method is superior to subjective short-range forecasts, i.e., 12 hours or less.

The quality of these objective forecasts varies significantly, and appears to depend on the care with which the original observations are made, screened and fitted to a prediction line. Some results are considerably better than those presented here, some are worse.

3.13.4 Application of Brunt's formula

Brunt's formula has been routinely used to predict $T_M$ in portions of the Florida peninsula for over a decade. To circumvent the problem of determining the soil parameters, mean values of the term ($\rho_s C_s \sqrt{K_s}$) were found from solutions of the equation after the fact, for good radiation nights only. In some cases the mean values of this term were unrealistic, while others were quite acceptable. Although there is no problem in finding suitable density and specific heat values, the thermal diffusivity limits the equation's usefulness. Following Taylor and Jackson (1965), Burleson and Georg (1972) determined values of $K_s$ for several Florida soils of different water content, for example. Figure 13 for Lakeland Sand. Once such curves are established it is relatively simple to measure the water content and then compute realistic values of $\rho_s C_s \sqrt{K_s}$. Such a procedure although untested, should prove the usefulness of the Brunt equation better than a method using empirically derived values of $\rho_s C_s \sqrt{K_s}$, particularly for areas where the soil water content is highly variable. However, if this procedure is to be followed, it must be verified for values at the surface.

Where it is inconvenient to measure the volumetric soil water content, reasonable values of the thermal diffusivity may be found directly from soil temperature profiles. Leber (1968) made many determinations of soil thermal diffusivity ($K$) by graphical means using soil temperature profiles and the classical heat conduction equation:

\[
\frac{\partial^2 T}{\partial t^2} = K \frac{\partial^2 T}{\partial z^2}
\]
where $K = \frac{K_s}{\rho_s C_a}$

The necessary derivatives were obtained from plotted curves of the soil temperature profiles and the equation was solved for $K$. The results were good: they reflected variations in soil water content and were physically acceptable.

Table 10 gives some results for the method applied in Florida and are representative of other results for Florida and Wisconsin. Figure 14 is a graphical solution for Gainesville, Florida (Davis, 1967).

3.13.5 Multi-regression equations

Using a computer, Wallis and Georg (1972) constructed multi-regression equations for some 300 fruit-frost temperature survey stations on the Florida peninsula: the minimum temperature at each fruit-frost station was correlated with the minimum temperature at three "key" stations using a sample of 40 nights covering a three-year period (winter season only). The criterion for selecting a night was that it had to be a "cold night", defined as a night when the minimum temperature was $2.2^\circ C$ or lower somewhere on the peninsula. "Key" stations are sites with some means of obtaining the nocturnal minimum temperature quickly on a daily basis. There are a total of 14 "key" stations, most of which are National Weather Service Offices or Agricultural Experiment Stations of the University of Florida.

Correlation coefficients for these equations range from 0.77 to 0.99: 87 per cent are $>0.90$; standard deviations of errors range from $0.55^\circ C$ to $2^\circ C$. The histogram in Figure 15 shows the distribution of errors for 5423 computations, — the mean is zero and the standard deviation, $1.4^\circ C$. Ninety-five per cent are within two standard deviations of the mean.

The equations serve two important purposes in providing excellent estimates of, first the peninsula-wide minimum temperature picture within minutes of occurrence, and second, the minimum temperature in many groves and fields when forecasts for the 14 "key" stations are reasonably accurate. The latter introduce a significant amount of objectivity into the general forecasts of the minimum temperature range for the heterogeneous fruit-frost districts of the state.

3.13.6 Boundary-layer model

Georg (1971) recently used boundary-layer theory to model the lower surface layer of the atmosphere in an attempt to calculate the nocturnal air temperature profile from 1.5 to 24 m. Input parameters are: the measured net radiation; the ambient air temperature at the reference level ($T_R$), 1.5 m; the wind speeds at 9.0 and 18.0 m; maximum and minimum soil temperatures for the day at $i = 0, 5, 10, 20,$ and 50 cm; percentage of water in the soil on a volume basis and dew-point temperature at initial time.

Essentially the programme computes a temperature profile up to 24 m with $T_R$ as base, and then a new value for $T_R$ one time-step into the future to serve as the base for the second profile. This process is repeated (cf. model described in the Appendix).

The flux of latent heat due to condensation and sublimation is an important term in the energy balance at the Earth's surface at night. The model makes no provision for this flux per se, but does account for it implicitly. At any point in the computations when the new $T_R \leq T_d$, then that and all succeeding temperature changes with respect to time are reduced by one-half. This prevents the model from computing temperatures so far below $T_d$ that they exceed the extreme limits observed in nature. Also the normal change in temperature with time is approximated much more closely.

The computed values of $T_R$ were compared with actual 0700 EST observations for 45 cases (Figure 16). The comparison is good and leaves one with the impression that strict objectivity using the theory may be the best approach to a universal method of minimum temperature and frost prediction.
3.14 Zambia

Frost (1968) applied his formula successfully to a very rare event in Zambia, June 1968. However, it is observed that the method is only useful as a guide and is not strictly applicable to any other month or year. The most frequent techniques for frost and minimum temperature prediction are:

(a) Synoptic meteorology;

(b) Maintaining charts of the deviations of ground temperature minima from seasonal normals. Centres of deviation move in a coherent manner, loosely controlled by low-level wind flow;

(c) Quantitative relationships (for ground frost) based on parameters, such as the previous day's temperature, dew point, wind speed and cloudiness conditions at 1200Z, and ground minimum temperature.

These methods appear to have merit but sometimes a "frost" or "no frost" forecast is beyond their scope and failures must be expected occasionally.
CHAPTER 4

"SURFACE" TEMPERATURE FORECASTS

It appears that very little verification has been done on the forecasts of minimum surface temperature; most schemes are verified for some standard height, usually 1.5 m above the ground. Probably the most important reasons for this are the lack of a suitable definition of "surface" and the difficulty of exposing a sensor so that its reading is representative of the area concerned.

Surface temperature is usually measured by simply placing a minimum thermometer horizontally on the surface or a few centimetres above. Baer and Edey (1970) have reported on the seasonal and spatial variances between grass minima (thermometers exposed a few centimetres above short-cut grass) and standard screen minima at various locations in Canada (Table 11). Geiger (1965) discussed the differences between the temperature of the surface and air immediately above or at standard shelter level. The coldest temperature at night is not always the radiating surface which may even be warmer than the air immediately above under certain conditions. Georg and Wallis (1968) made extensive comparisons between temperatures at the surface of bare soil and the air temperature 5 cm above, using thermocouples and sensitive anemometers. One anemometer was exposed so that its cups just cleared the surface. When the surface wind speed was equal to or less than 1.5 km h⁻¹ the soil-surface temperature was warmer; for speeds greater than this the opposite was observed – results in very close agreement with those of Raschke (cf. Geiger, 1965).

Franklin (1919) concluded that the surface temperature of an open cultivated field fell rapidly at the beginning of a clear, calm night until it was far enough below the value of 10-cm depth to cause heat conduction upward sufficient to balance radiation at the surface. He also (1920) gave a formula for forecasting the minimum soil-surface temperature and compared it to the air temperature immediately above. On 28 nights when the soil was not frozen he found that the minimum temperature of the air followed very closely that of the surface with an overall departure of 0.4°C.

Most practical forecasters make no attempt to forecast a specific value for the minimum surface temperature, whether this surface is bare soil or short-clipped grass in a meadow or the canopy of an orchard of fruit trees. They usually seek a method for objectively forecasting the minimum at standard shelter height and then subjectively adjust this prediction according to the nature of the "surface" and an estimate of the nocturnal inversion. If these considerations indicate that the radiating surface will reach a dew-point temperature at or below freezing, then frost would be predicted.
CHAPTER 5

SUMMARY AND CONCLUSIONS

From what has been reported there is considerable interest in, and need for, accurate minimum temperature and frost-prediction techniques in many agricultural areas of the world. Empirical, semi-empirical, theoretical, semi-theoretical, and ordinary subjective techniques are presently employed to answer the problem. Generally, each claims as much success as the others when applied on the local level and using the verification system prescribed for the technique.

It appears that scant progress has been made for many years and that little application of theory or adaption of older well-known cooling formulae have been attempted. Most techniques still involve regression-type formulae of which the hygrometric type seems to be the most popular.

Few of the present methods are totally objective, since they depend on certain criteria which must be forecast subjectively.

The state-of-the-art of predicting minimum temperatures and frost is not sufficiently developed to meet present or future demands, and is generally not much better than many years ago. Improvement may not occur until empirical and subjective approaches are replaced by a method combining theory and statistical climatology.

Acknowledgements

The author wishes to express his gratitude to all those experts who provided valuable information on the methods of frost prediction in their countries.
### TABLE 1

Values of the correction factor $C$ for various values of average overnight wind speed and cloud cover (after McKenzie). Values of $C$ are in degrees C.

<table>
<thead>
<tr>
<th>Average overnight wind speed mps</th>
<th>Average overnight cloud cover in fractions (ignoring Cirrus)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>8.3</td>
</tr>
<tr>
<td>0.5 - 1.5</td>
<td>7.2</td>
</tr>
<tr>
<td>1.6 - 3.4</td>
<td>4.4</td>
</tr>
<tr>
<td>3.5 - 5.5</td>
<td>3.9</td>
</tr>
<tr>
<td>5.6 - 8.4</td>
<td>3.3</td>
</tr>
<tr>
<td>8.5 - 10.9</td>
<td>2.2</td>
</tr>
<tr>
<td>11.0 - 13.5</td>
<td>2.2</td>
</tr>
</tbody>
</table>

*In the original formula, average amount of low cloud only was considered. Initial testing of a few cases suggested that, for Goose, middle cloud cover was sufficiently important in the nocturnal radiation budget to warrant its inclusion. In consequence, the above table was amended slightly to include both low and middle cloud in the calculation of average overnight cloud cover. (After O'Neill)

### TABLE 2

Mean and extreme variations between observed and calculated minimum temperatures using 1700 hour readings, April to September

<table>
<thead>
<tr>
<th>Month</th>
<th>Number of cases</th>
<th>Average difference observed – calculated minimum deg. C</th>
<th>Extreme variations between observed and calculated minimum deg. C</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>7</td>
<td>1.7</td>
<td>-2.8 to +2.2</td>
</tr>
<tr>
<td>May</td>
<td>12</td>
<td>1.2</td>
<td>-1.7 to +2.8</td>
</tr>
<tr>
<td>June</td>
<td>13</td>
<td>0.9</td>
<td>-1.1 to +1.7</td>
</tr>
<tr>
<td>July</td>
<td>14</td>
<td>1.4</td>
<td>-2.2 to +2.2</td>
</tr>
<tr>
<td>August</td>
<td>26</td>
<td>1.0</td>
<td>-2.2 to +1.7</td>
</tr>
<tr>
<td>September</td>
<td>27</td>
<td>1.0</td>
<td>-2.8 to +1.1</td>
</tr>
<tr>
<td>All cases</td>
<td>99</td>
<td>1.2</td>
<td>-2.8 to +2.8</td>
</tr>
</tbody>
</table>

(After Korven)
### TABLE 3
Mean and extreme variations between observed and calculated minimum temperatures using 1700 hour readings, October to March

<table>
<thead>
<tr>
<th>Month</th>
<th>Number of cases</th>
<th>Average difference observed – calculated minimum deg. C</th>
<th>Extreme variations between observed and calculated minimum deg. C</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>21</td>
<td>1.3</td>
<td>-3.9 to +3.9</td>
</tr>
<tr>
<td>November</td>
<td>13</td>
<td>1.8</td>
<td>-2.8 to +3.9</td>
</tr>
<tr>
<td>December</td>
<td>11</td>
<td>1.9</td>
<td>-2.2 to +3.9</td>
</tr>
<tr>
<td>January</td>
<td>7</td>
<td>1.1</td>
<td>-1.1 to +3.9</td>
</tr>
<tr>
<td>February</td>
<td>8</td>
<td>2.2</td>
<td>-5.0 to +2.8</td>
</tr>
<tr>
<td>March</td>
<td>9</td>
<td>1.3</td>
<td>-1.1 to +3.9</td>
</tr>
<tr>
<td>All cases</td>
<td>69</td>
<td>1.6</td>
<td>-5 to +3.9</td>
</tr>
</tbody>
</table>

(After Korven)

### TABLE 4
Comparison of observed and calculated minimum temperatures from 1700 hours and from sunset (deg. C)

<table>
<thead>
<tr>
<th>Date</th>
<th>H</th>
<th>( T )</th>
<th>( T_d )</th>
<th>( T_d )</th>
<th>Calculated minimum from 1700</th>
<th>Observed minimum</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 April 62</td>
<td>13</td>
<td>14.4</td>
<td>10.6</td>
<td>2.8</td>
<td>2.8</td>
<td>1.1</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1700</td>
<td>sunset</td>
<td></td>
</tr>
<tr>
<td>20 May 63</td>
<td>11½</td>
<td>15.0</td>
<td>10.6</td>
<td>-0.6</td>
<td>-0.6</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>26 June 62</td>
<td>11½</td>
<td>22.2</td>
<td>16.7</td>
<td>1.1</td>
<td>0.6</td>
<td>5.0</td>
<td>4.4</td>
</tr>
<tr>
<td>12 July 61</td>
<td>11 ¼</td>
<td>23.9</td>
<td>21.1</td>
<td>8.9</td>
<td>6.7</td>
<td>10.0</td>
<td>9.4</td>
</tr>
<tr>
<td>11 August 61</td>
<td>12</td>
<td>27.2</td>
<td>22.2</td>
<td>4.4</td>
<td>6.7</td>
<td>8.9</td>
<td>8.9</td>
</tr>
<tr>
<td>4 September 62</td>
<td>13 ½</td>
<td>22.8</td>
<td>18.3</td>
<td>3.3</td>
<td>5.6</td>
<td>5.6</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.8</td>
<td>2.8</td>
<td>Clear S 2.8</td>
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</table>

(After Korven)
### TABLE 5
Results of test of semi-objective technique and comparison with original official forecasts (deg. C)

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Observed $T_{min}$</th>
<th>Objective $T_{min}$</th>
<th>Official $T_{min}$</th>
<th>Objective error</th>
<th>Official error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>14</td>
<td>4.4</td>
<td>3.9</td>
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<td>-0.5</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>5.6</td>
<td>5.6</td>
<td>10.0</td>
<td>0</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>3.9</td>
<td>2.2</td>
<td>4.4</td>
<td>-1.7</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>3.3</td>
<td>1.7</td>
<td>4.4</td>
<td>-1.6</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>5.0</td>
<td>2.8</td>
<td>3.3</td>
<td>-2.2</td>
<td>-1.7</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>6.1</td>
<td>5.0</td>
<td>4.4</td>
<td>-1.1</td>
<td>-1.7</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>8.9</td>
<td>7.2</td>
<td>7.2</td>
<td>-1.7</td>
<td>-1.7</td>
</tr>
<tr>
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<td>23</td>
<td>7.8</td>
<td>6.1</td>
<td>7.2</td>
<td>-1.7</td>
<td>-1.7</td>
</tr>
<tr>
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<td>26</td>
<td>2.8</td>
<td>4.4</td>
<td>7.2</td>
<td>1.6</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>5.0</td>
<td>5.0</td>
<td>4.4</td>
<td>0</td>
<td>-0.6</td>
</tr>
<tr>
<td>1955</td>
<td>4</td>
<td>12.2</td>
<td>11.1</td>
<td>15.6</td>
<td>-1.0</td>
<td>3.4</td>
</tr>
<tr>
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<td>6</td>
<td>7.2</td>
<td>7.8</td>
<td>10.0</td>
<td>0.6</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>3.9</td>
<td>3.9</td>
<td>10.0</td>
<td>0</td>
<td>6.1</td>
</tr>
<tr>
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<td>10</td>
<td>4.4</td>
<td>4.4</td>
<td>1.1</td>
<td>0</td>
<td>-3.3</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>7.8</td>
<td>7.2</td>
<td>6.1</td>
<td>-0.6</td>
<td>-1.7</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>12.2</td>
<td>10.0</td>
<td>7.8</td>
<td>-2.2</td>
<td>-4.4</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>5.0</td>
<td>5.6</td>
<td>2.2</td>
<td>0.6</td>
<td>-2.8</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>5.0</td>
<td>3.3</td>
<td>5.9</td>
<td>-1.7</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>10.6</td>
<td>6.1</td>
<td>8.3</td>
<td>-4.5</td>
<td>-2.3</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>3.3</td>
<td>4.4</td>
<td>4.4</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>5.6</td>
<td>7.2</td>
<td>6.7</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>10.0</td>
<td>12.8</td>
<td>8.3</td>
<td>2.8</td>
<td>-1.7</td>
</tr>
</tbody>
</table>

Standard deviations of forecasts from observations 1.7 2.7

(After Lamont)

### TABLE 6
Results of simplified Reuter technique for computing the sunrise temperature at Winnipeg, Canada

<table>
<thead>
<tr>
<th></th>
<th>June 13-14</th>
<th>July 30-31</th>
<th>Sept. 7-8</th>
<th>Sept. 6-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunset temperature °C</td>
<td>11.7</td>
<td>21.1</td>
<td>16.1</td>
<td>18.3</td>
</tr>
<tr>
<td>Sunset relative humidity %</td>
<td>43</td>
<td>61</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Average wind mps</td>
<td>2.3</td>
<td>4.5</td>
<td>4.5</td>
<td>2.3</td>
</tr>
<tr>
<td>$F\times E$ from Figure 3</td>
<td>0.51</td>
<td>0.36</td>
<td>0.39</td>
<td>0.43</td>
</tr>
<tr>
<td>$T_o$ from Figure 4</td>
<td>11.1</td>
<td>7.7</td>
<td>9.4</td>
<td>9.4</td>
</tr>
<tr>
<td>Computed sunrise temperature °C</td>
<td>0.6</td>
<td>13.3</td>
<td>6.7</td>
<td>5.6</td>
</tr>
<tr>
<td>Actual sunrise temperature °C</td>
<td>2.2</td>
<td>12.8</td>
<td>7.8</td>
<td>6.1</td>
</tr>
<tr>
<td>Error °C</td>
<td>-1.6</td>
<td>0.6</td>
<td>-1.1</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

(After Eley (1961))
TABLE 7
The predicted minimum temperatures (Tm) compared with the observed values as,
\[ \varepsilon = \frac{\sum |Tm \text{ obs.} - Tm \text{ forl}|}{n} \]
and the root-mean-square deviation was computed from the formula, RMS deviation
\[ \sqrt{\frac{\sum (Tm \text{ obs.} - Tm \text{ forl})^2}{n}} \]

<table>
<thead>
<tr>
<th>Location</th>
<th>No. of cases</th>
<th>Mean ABS error</th>
<th>RMS deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calgary</td>
<td>43</td>
<td>1.7</td>
<td>2.2</td>
</tr>
<tr>
<td>Edmonton</td>
<td>37</td>
<td>1.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Winnipeg</td>
<td>36</td>
<td>1.6</td>
<td>2.1</td>
</tr>
<tr>
<td>Saskatoon</td>
<td>36</td>
<td>1.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Regina</td>
<td>29</td>
<td>1.3</td>
<td>1.6</td>
</tr>
</tbody>
</table>

TABLE 8
Average forecast error for various ranges of minimum temperatures

<table>
<thead>
<tr>
<th>Observed minimum temperature deg. C</th>
<th>Number forecast days</th>
<th>Average forecast error deg. C</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.6 - 20.6</td>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>10.0 - 15.5</td>
<td>18</td>
<td>1.1</td>
</tr>
<tr>
<td>4.4 - 9.9</td>
<td>31</td>
<td>0.8</td>
</tr>
<tr>
<td>-1.1 - 4.3</td>
<td>15</td>
<td>0.4</td>
</tr>
<tr>
<td>-6.7 - 1.2</td>
<td>1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

(After Hagood)

TABLE 9
Frequency distribution of the absolute error during 1967

<table>
<thead>
<tr>
<th>Type of temperature change</th>
<th>Range of error in deg. C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-1.1</td>
</tr>
<tr>
<td>850 mb cooling</td>
<td>2</td>
</tr>
<tr>
<td>850 mb warming</td>
<td>2</td>
</tr>
<tr>
<td>No temp change</td>
<td></td>
</tr>
<tr>
<td>Cloud cover 0 through 5/10</td>
<td>3</td>
</tr>
<tr>
<td>Cloud cover 6/10 through 10/10</td>
<td>4</td>
</tr>
</tbody>
</table>

(After Soderberg)
TABLE 10
Verification of local forecast schemes during 1966-1967 season (DeLand, Florida)
(Departure of forecasts from actual minimum)

<table>
<thead>
<tr>
<th>Date</th>
<th>Minimum temperature</th>
<th>Deg. C</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Radiometer</td>
<td>Hygrometric</td>
</tr>
<tr>
<td>3.11.66</td>
<td>1.7</td>
<td>-3.3</td>
<td>-3.9</td>
</tr>
<tr>
<td>25.11.66</td>
<td>6.1</td>
<td>-1.7</td>
<td>-1.7</td>
</tr>
<tr>
<td>28.11.66</td>
<td>3.9</td>
<td>-3.3</td>
<td>-7.2</td>
</tr>
<tr>
<td>29.11.66</td>
<td>2.8</td>
<td>-0.6</td>
<td>-2.8</td>
</tr>
<tr>
<td>30.11.66</td>
<td>2.2</td>
<td>-1.1</td>
<td>-5.0</td>
</tr>
<tr>
<td>1.12.66</td>
<td>1.1</td>
<td>0.0</td>
<td>-0.6</td>
</tr>
<tr>
<td>2.12.66</td>
<td>2.8</td>
<td>-1.7</td>
<td>-0.6</td>
</tr>
<tr>
<td>3.12.66</td>
<td>2.8</td>
<td>-0.6</td>
<td>-1.1</td>
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<tr>
<td>14.12.66</td>
<td>7.2</td>
<td>-4.4</td>
<td>-3.9</td>
</tr>
<tr>
<td>15.12.66</td>
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<td>-2.2</td>
<td>-1.1</td>
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<td>19.12.66</td>
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<td>-1.1</td>
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<td>20.12.66</td>
<td>7.8</td>
<td>-2.2</td>
<td>-2.2</td>
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<td>21.12.66</td>
<td>5.6</td>
<td>-3.9</td>
<td>-2.2</td>
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<tr>
<td>24.12.66</td>
<td>-2.2</td>
<td>+1.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>25.12.66</td>
<td>-1.1</td>
<td>-2.8</td>
<td>-2.8</td>
</tr>
<tr>
<td>29.12.66</td>
<td>2.8</td>
<td>+1.1</td>
<td>+2.2</td>
</tr>
<tr>
<td>4.167</td>
<td>1.7</td>
<td>+0.6</td>
<td>-0.6</td>
</tr>
<tr>
<td>5.167</td>
<td>0.0</td>
<td>-0.6</td>
<td>-1.1</td>
</tr>
<tr>
<td>11.167</td>
<td>4.4</td>
<td>-3.3</td>
<td>-2.8</td>
</tr>
<tr>
<td>16.167</td>
<td>7.2</td>
<td>-5.6</td>
<td>-4.4</td>
</tr>
<tr>
<td>28.167</td>
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<td>+1.7</td>
<td>0.0</td>
</tr>
<tr>
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<td>1.1</td>
<td>-0.6</td>
<td>+1.1</td>
</tr>
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<td>-2.8</td>
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<td>-5.6</td>
<td>-5.0</td>
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<td>+1.1</td>
<td>-1.1</td>
</tr>
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<td>-5.0</td>
<td>-7.2</td>
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<td>26.267</td>
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<td>-2.8</td>
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<tr>
<td>Average error</td>
<td>2.6</td>
<td>2.6</td>
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### TABLE 11
Location, soil and climate description of selected weather stations

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude N</th>
<th>Longitude W</th>
<th>Altitude M</th>
<th>Soil</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fredericton</td>
<td>45°55'</td>
<td>66°37'</td>
<td>39.65</td>
<td>Sandy loam</td>
<td>Maritime</td>
</tr>
<tr>
<td>Ottawa</td>
<td>45°24'</td>
<td>75°43'</td>
<td>79.30</td>
<td>Loam</td>
<td>Semi-humid</td>
</tr>
<tr>
<td>Swift Current</td>
<td>50°17'</td>
<td>107°45'</td>
<td>762.20</td>
<td>Clay loam</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Fort Vermilion</td>
<td>58°23'</td>
<td>116°03'</td>
<td>286.75</td>
<td>Sandy loam</td>
<td>Sub-arctic</td>
</tr>
</tbody>
</table>

Accumulated percentage frequencies of daily deviations of grass minimum from screen minimum temperatures

<table>
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<tr>
<th>Station</th>
<th>Month</th>
<th>Years</th>
<th>&lt;0</th>
<th>1-2</th>
<th>3-4</th>
<th>5-6</th>
<th>7-8</th>
<th>9-10</th>
<th>11-12</th>
<th>&gt;12</th>
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<tr>
<td>Fredericton</td>
<td>May</td>
<td>3</td>
<td>12</td>
<td>52</td>
<td>87</td>
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<td>31</td>
<td>90</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
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<td>18</td>
<td>76</td>
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(After Baier and Eddy, 1970)
FIGURES

Basic data are thirty-eight cases of clear nights during May 1951, 1952 and 1953 at Hamilton.

$T_m - T_1$ (afternoon maximum temperature minus normal daily lake temperature)

Figure 1 – Showing overnight temperature drop on clear nights at Hamilton, Ontario, in May
Figure 2 – Showing correction, $k_v$, to be subtracted from predicted overnight temperature drop for various surface wind speeds

<table>
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Figure 3 – Graphic solution of $F \cdot E$ for wind (After Eley, 1961)
Figure 4 – Nocturnal cooling (sunset to sunrise) at Winnipeg (After Fley, 1961)

Figure 5 – Graph to find $S(0)$, the net long-wave radiation from the Earth's surface from temperature and dew point $S(0) = T (1 - 0.4T - 0.09 \sqrt{T})$ (Brunt's equation) (After Kagawa)
Figure 6 — Plot of $2 \cdot 03 \sqrt{\text{h}}$ vs. Date for 50 degrees ——— and 54 degrees ——— latitude. "h" is the number of hours between sunset and sunrise (After Kagawa, 1968)

Figure 7 — The probability of frost in south Finland as a function of temperature and dew point (Private communication Järvi)
Figure 8 – Possibility of frost in the following night, according to the combined situations of temperature and humidity at 1200 GMT, Baqura Station

Figure 9 – Graph of minimum temperature in °C for non-advective nights when the cloud cover at 1600 LST ranges from 0 through 5/10. Based on data 1962 through 1966 (April 15 to June 10)
Figure 10 — Distribution of radiometer forecast errors at Madison, Wisconsin

Figure 11 — Distribution of radiometer forecast errors at Bartow, Florida

Figure 12 — Seasonal comparison of total errors of radiometer forecasts with subjective forecasts
Figure 13 — Thermal diffusivity of Lakeland sand as a function of percent water by volume

Graphical solution of Brunt's formula in the form
\[ \Delta T = \frac{\Delta T'}{T'} \left( 2.26 - \frac{32}{T} \right) \text{ for } \frac{\Delta T'}{T'} = 0.077 \]

Figure 14 — Graphical solution of Brunt's formula (Courtesy G. R. Davis)
Figure 15 — Distribution of errors for 5423 computations of $T_M$ using multiple regression for 300 fruit-frost stations on the Florida peninsula.

Figure 16 — Scatter diagram of computed v. observed 0700 air temperature at standard shelter level for 45 cases.
ANNEX

TEMPERATURE PROFILE PREDICTION MODEL

The soil is assumed to be homogeneous. Its volumetric heat capacity, \( C_v \), is computed by the formula

\[
C_v = \rho_B (c_s + PW/100)
\]

where \( \rho_B \) 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\(^{-1}\).

In order to find the projected change in temperature with respect to time at each level of measurement within the soil an equation by van Wijk (1965) was used

\[
T(Z, t) = T_A + AT_o \exp \left(-\frac{Z}{D}\right) \sin \left(wt + C_o \frac{Z}{D}\right)
\]  \( (1) \)

where \( T_A \) is the average soil temperature: \( \text{Max} + \text{Min} \)/2. \( T_A \) is often the same at all levels within the depth of diurnal temperature change,

\( AT_o \) is the amplitude of the soil surface temperature,

\( D \) is the damping depth where the amplitude of the temperature wave has decreased to 1/e of its value at the surface,

\( C_o \) is a constant which depends upon the choice of the zero point on the time scale, and

\( w \) is the radial frequency, \( 2 \pi/P \), where \( P \) is the period.

To approximate the real conditions more closely, a different value of radial frequency was used for the period after 1800 LST than that from the time of maximum temperature to 1800 LST. This technique had the effect of stretching the time from maximum to minimum so that the minimum occurs near 0700 LST or the time of sunrise in Florida during the winter months. Using derivations of \( (1) \) the soil heat flux across the earth's surface was computed from

\[
S(0) = \int_0^Z (\rho_s C_v dT_s/dt) dz
\]  \( (2) \)

The net radiation was assumed to be constant throughout the forecast period and the horizontal and vertical divergences of heat flux were assumed to be zero. The convective heat flux was taken to be

\[
F_h(0) = R_n(0) - S(0).
\]

An approximation of the friction velocity was computed from the log wind profile equation

\[
U_* = (\overline{U}_2 - \overline{U}_1) k/\ln 2
\]

where \( k \) is von Karman's constant, 0.40.

These values of \( U_* \) and \( F_h \) are then used to find the Monin-Obukhov (1954) scaling length, \( L \), by

\[
L = \left(U_*^2 c_p \overline{T}/kg F_h\right)
\]

where \( g \) = acceleration due to gravity. Similarly they were used to find the scaling temperature defined by Lumley and Panofsky (1964) as:

\[
T_s = -F_h/kU_* c_p \rho
\].
This completes the necessary input for solving the profile equation

$$T_Z = T_R + T_\infty \left( \frac{1}{n Z / Z_R + \alpha Z / L} \right)$$

where $\alpha = 8$ was arbitrarily chosen from numerous values in the literature which range from 3 to 10 for the stable régime, e.g., McVehil (1962) recommends $\alpha = 7$ for stable air. From the profile, $dT/dZ$ at the reference level (150 cm) was computed and used with $F_h$ to find the exchange coefficient

$$K_h = -F_h(0) / \rho c_p \frac{dT}{dZ}$$

and the eddy conductivity ($\lambda$) was computed as

$$\lambda = K_h \rho c_p.$$

Finally an equation due to Brunt (1941) is solved to find the projected change in temperature at 150 cm during the subsequent hourly interval in order to establish the value of the reference temperature for the next iteration of the program:

$$T(Z, t) = 2F_h / \lambda \left[ (K_h t/\pi)^{1/2} \exp \left( -Z^2 / 4K_h t \right) - \frac{Z}{2} \operatorname{erfc} \left( Z / \sqrt{4K_h t} \right) \right].$$
REFERENCES


Gröen, P., 1947: On radiational cooling of the Earth’s surface during the night, especially with regard to the prediction of ground frosts. Mededelingen en Verhandelingen, Serie B, Deel 1, No. 9, 35 pp.


PART II (a)

METHODS OF COLD AND FROST PROTECTION (U.S.A.)

by J. F. Gerber
# CONTENTS

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SUMMARY

Methods employed for frost protection in the United States of America are discussed. Theoretical bases for the methods employed are also presented where applicable.

Economic consequences and desirability of protecting against cold and frost are reviewed.

RÉSUMÉ

Les méthodes appliquées aux États-Unis pour la protection contre le gel sont étudiées dans cette partie. Les principes théoriques sur lesquels sont fondées ces méthodes sont également exposés, le cas échéant.

On y examine également les conséquences économiques de la protection contre le froid et le gel et l'opportunité de prendre des mesures en ce sens.

ПЕРІОМЕ

Излагаются методы, применяемые в Соединенных Штатах Америки, для защиты от заморозков. По мере возможности представлены также теоретические обоснования применяемых методов.

Дается обзор экономических результатов и желательности защиты против морозов и заморозков.

RESUMEN

En esta parte se estudian los métodos de protección contra las heladas empleados en los Estados Unidos de América. Cuando procede, también se presentan las bases teóricas de los métodos utilizados.

Igualmente, se examinan las consecuencias económicas y la conveniencia de adoptar medidas de protección contra el frío y las heladas.
CHAPTER 1

INTRODUCTION

Fruit and tender annual horticultural crops are subject to damage from freezing weather. Freeze damage of annual crops is less insidious than that of perennial fruits because the former can often be replanted quickly and still be harvested the same season. Damage to fruit trees not only causes loss of the crop for one year, but also produces tree damage ranging from reduced production to loss of the tree or orchard.

Almost all perennial fruits are subject to cold-weather damage. Deciduous fruits are hardy while dormant, but can be damaged by low temperature in spring. Fruit buds are especially subject to damage at this time (References 11, 70, 95). Blossoms and young fruit can even be damaged by temperatures only slightly below freezing. Evergreen tropical fruits (citrus, avocados, mangoes, etc.) are subject to damage from sub-zero temperatures; the critical temperature varies from near-freezing to \(-7\)°C depending on the cultivar. Some fruits, however, sustain physiological damage even above freezing temperature (bananas and mangoes).

1.1 Impact of climate

The fruit-grower faces an annual cold-weather problem in the temperate and subtropical climates and at high altitudes in the tropics. Cold weather in temperate zones is mainly preceded by advection and air-mass changes, followed by calm, clear nights with intense nocturnal radiation. This pattern is repeated in subtropical latitudes, but the systems move more slowly. Cold spells in spring and autumn in temperate latitudes tend to be frequent and of short duration, a few hours on one or two nights. At lower latitudes cold weather may not occur annually, but two to four cold nights in succession are common, and periods of below-freezing temperatures, eight to ten hours long may occur.

Frost in temperate climates usually occurs in spring and autumn while cold-weather damage in the subtropics is most severe during midwinter (References 36, 73, 103). The Mediterranean-type climates, usually on the western shores of continents, have intense nocturnal inversions during cold weather, mainly caused by subsidence. The climates in the interiors and along eastern shores of continents have weaker inversions and more advective freeze except where orographic features such as mountain ranges or large bodies of water serve as buffers against cold-air outbreaks.

Net nocturnal-radiation heat losses tend to be larger at low latitudes (\(-0.1\) to \(-0.2 \text{ \,Jy/min}\)) because the soil is warmer and the skies are colder than at higher (temperate) latitudes (\(-0.05\) to \(-0.1 \text{ \,Jy/min}\)). Since cloud cover modifies radiation cooling more dramatically than any other single factor, climates with persistent nocturnal cloudiness may therefore be suitable for fruit production even at high latitudes.

Horticulturists have commonly identified and classified cold weather as “white frost” and “black frost”. White frost occurs when freezing weather is accompanied by a high dew point. When the temperature falls, white hour-frost forms on exposed parts of plants, buildings and other objects colder than the dew point. High dew-point temperatures are characteristic of air masses that contain water vapour and are not extremely cold. Therefore, white frost is commonly thought to be less damaging than black frosts which occur with extremely low dew-point temperatures in air masses that originate over the Arctic and polar regions. These air masses are intensely cold and, because of their low vapour pressures, are conducive to large nocturnal-radiation losses. White frosts rarely occur with advection because mixing keeps temperatures in the boundary layer near but above dew point and effects a lower limit of minimum temperature. Black frosts which occur in very strong advection are usually more damaging than those in calm conditions because increasingly colder air is advected during the night.
1.2 Strategies for cold protection

The strategy of cold protection may depend upon how the produce is marketed. Fresh fruit must not be frozen or it will deteriorate rapidly and become unsuitable for sale and consumption. Spring frosts cause peel blemishes which lower the quality of the exterior but not the interior. Fruit which is processed has less exacting surface-texture requirements. For example, oranges can even be made into entirely satisfactory frozen orange juice concentrate several weeks after the fruit has been frozen (Reference 68).

Practitioners of cold protection methods attempt to maintain the temperature just above the damaging level. This conserves energy and should therefore be feasible theoretically because the temperature difference between the protected and non-protected area is as small as possible. To achieve this result the temperature should be maintained constant. For conceptual purposes it is helpful to consider the orchard or vineyard as enclosed in an imaginary box which includes the plants (Figure 1). The heat balance of this box can be approximated by the following equation:

\[ C \frac{dT}{dt} = O = Q_{\text{rn}} + Q_s + Q_k + Q_h + Q_{\text{le}} \]

Where:
- \( C \) = the sum of the heat capacities of the air and objects in the imaginary box
- \( T \) = temperature
- \( t \) = time
- \( Q_{\text{rn}} \) = net radiation
- \( Q_s \) = soil heat flux
- \( Q_k \) = convective heat flux
- \( Q_h \) = heat flux added for cold protection
- \( Q_{\text{le}} \) = latent heat flux.

The heat balance of individual trees or leaves may be considered in the same way (Figure 2). The amount of heat required, \( Q_h \), would maintain a constant temperature and protect from damage by freezing. When fuel is burned, fires are used as heat sources and then \( Q_h = Q_{\text{rn}} + Q_s + Q_{\text{le}} + Q_k \). Since \( Q_{\text{le}} \) is usually small at night, \( Q_h \) is approximately equal to \( Q_{\text{rn}} + Q_s + Q_k \). Since \( Q_k \) is strongly dependent upon wind, \( Q_{\text{rn}} \) upon effective surface and sky temperature while \( Q_s \) is a very conservative parameter, \( Q_h \) is related primarily to \( Q_k \) and \( Q_{\text{rn}} \). On clear, calm nights when \( Q_{\text{rn}} \) is nearly invariant, \( Q_h \) must not vary much either. However, the temperature benefit in protected orchards from heating varies greatly from night to night. In fact, increasing \( Q_h \) often has only marginal effects upon the temperature difference between the protected and non-protected area. This can be best understood by viewing the convective heat flux in a simple one-dimensional equation.

\[ Q_k \propto U(\Delta T/\Delta Z) C_p \rho. \]

Really, \( Q_k = K_h (\Delta T/\Delta Z) C_p \rho. \)

Therefore, \( K_h \), the eddy coefficient of vertical exchange, is proportional to the wind.

Where:
- \( U \) = wind velocity
- \( C_p \) = heat capacity of the atmosphere
- \( \rho \) = density.

However, when cold protection is successful, \( (\Delta T/\Delta Z) \) is large in the heated area, i.e., \( K_h \) approaches zero. When cold protection is marginal, \( K_h \) approaches a very large number and the vertical heat transport becomes the controlling factor in achieving successful cold protection.
On calm, clear nights heat is lost from the surface by radiation to the cold sky. Consequently, the soil and plant surfaces become colder than the atmosphere and are a sensible heat sink for the air. The atmosphere near the surface cools and becomes denser so that a stable stratification occurs and a nocturnal inversion is formed. The air near the ground becomes significantly colder than at 15 or 20 m. Mixing in the stable layer increases the convective heat flux and raises the surface temperature.

Several methods of protecting plants from cold and frost depend upon effective use of natural heat sources to produce favourable changes in the heat fluxes from the soil and the air. The soil heat flux can be modified by two management practices—clean cultivation and irrigation and compaction of the soil. These practices increase the soil conductivity and heat storage capacity; consequently, the increased heat flux at night slows the rate of cooling and raises the minimum temperature. The use of wind-breaks and removal of air dams increase the downward heat flux in the absence of natural convection.

1.3 Methods of cold protection

Frost and cold damage can be averted by using both active and passive methods to modify low temperatures. Most protection systems are not solely of one type. Active methods usually modify the nocturnal microclimate directly either by releasing heat by burning fuels and freezing water or by increasing the turbulence to change the heat balance with the use of various machines and other devices. These methods pose special problems because a high level of technology is required to implement them and because natural physical principles mitigate against their complete success. For example, the heat released from fires produces hot buoyant gases which tend to rise up and out of the area protected and are therefore lost. Wind increases the vertical transport and blows the gases away.

Passive protection methods involve the use of moist, compact, cultivated soil to produce a favorable heat balance; earthen mounds or insulating wraps around trees to cover bud unions; trenches and covers to protect individual plants from exposure to low temperature; paints to increase the hardiness of plants by lowering the maximum temperatures during the daytime hours. Warm, sunny days tend to decrease the hardiness of perennial fruits by stimulating growth of buds and blossoms in evergreen tropical and subtropical fruits.
CHAPTER 2

PASSIVE METHODS OF COLD PROTECTION

Firm, moist, cleanly cultivated bare soil will absorb and store more solar energy during the day because its heat capacity and the conductivity are both increased. Conversely, it will release more heat at night, and, most importantly, the surface remains warmer. The temperature advantage commonly ranges from 1 to $2^\circ$C (References 18, 47, 89). Organic or peat soils present a special night-frost problem since their heat capacities and thermal conductivities are very low, especially when dry. Sometimes irrigation during the day preceding a cold night can successfully modify the thermal properties of such soils and prevent damage, for example, in the United States (References 18, 51). However, the irrigation must be timed so that the surface is dry before sunset; otherwise evaporative chilling would cause the soil to be colder than if it were dry and unirrigated. Cranberry bogs are commonly flooded at night to prevent cold damage (Reference 52).

Soils which are moist usually are easy to compact. Sprinkler irrigation or rain often provide enough compaction to improve the thermal properties. Citrus grown on mineral soils irrigated prior to cold weather has survived with little damage, while orchards which had not were damaged (Reference 107). This demonstrates the importance of maintaining soil thermal properties to take advantage of solar heat.

In the United States soil mounds or “banks” are formed around the root-stock and scion of young citrus trees prior to cold weather in the autumn (Reference 53). The tops of these trees may be damaged, but the bud union is protected. Soils in Florida are sandy and well-drained, and fungus problems are not serious.

Throughout most of the world, soils are too heavy and retain enough water to cause fungi problems so that wraps of fibreglass, newspapers, straw or corn stover are used instead. Any good insulating material will usually suffice even in very cold weather. From physical principles it is apparent why soil is effective. The heat capacity is great and the conductivity reasonably small. Insulating materials have a low conductivity, but the heat capacity is so low that protection may be marginal, especially if well-ventilated in windy conditions. Another feature of insulators, which meteorologists may tend to overlook, is the effect the material may have upon the physiological activity of the tree trunk. They dampen the diurnal temperature oscillations and reduce high temperatures so that the trunk of the tree is kept hardy. This same effect is often obtained by using highly reflective paints which are commonly applied to the trunks of deciduous fruit trees.
CHAPTER 3

ACTIVE METHODS OF COLD PROTECTION WHICH UTILIZE LATENT HEAT OF FREEZING AND HEAT STORED IN THE ATMOSPHERE

3.1 Sprinkling

Overhead sprinkler irrigation has been successfully used to protect low-growing crops and deciduous fruit blossoms and buds during spring frost, but has been less successful for evergreen subtropical fruits.

When water freezes, heat is released keeping the temperature of the ice-water mixture near 0°C. If the mixture is maintained the temperature will remain near 0°C; otherwise it will fall and may reach the wet-bulb temperature. The water must supply enough heat by freezing to compensate for all heat losses by radiation, convection and evaporation. Radiative and convective heat losses are approximately the same for a wet or a dry plant; however, the evaporative heat loss from a wet plant is much greater than that from a dry plant. Since the latent heat of evaporation at 0°C is approximately 7.5 times as great as the latent heat of fusion, at least 7.5 times as much water must be frozen as evaporated. Unless this condition is met, the temperature of the wet plant will fall below that of the dry plant.

The sprinkling required to irrigate for cold protection can be formulated theoretically by considering the heat balance of a single horizontal leaf (Figure 2). Businger (Reference 31), Gerber and Harrison (Reference 59), and Pogrell and Kidder (Reference 87) have investigated the effect of irrigation on the heat balance. The heat balance of the leaf is the algebraic sum of all the heat transfers,

\[ C \frac{dT}{dt} = Q_{nr} + Q_k + Q_{lc} \]

where \( C \) is the heat capacity of the leaf or plant part. Radiative transfer may be calculated by assuming that the leaf is at air temperature and then correcting for the difference between leaf and air temperature. This technique is valid for small differences [Brunt (Reference 29), Raschke (Reference 91) and Sutton (Reference 102)] i.e., the first terms of a Taylor series are included:

\[ Q_r = Q_{ra} + h_r(T_a - T_l) \]

where:

\[ \left( \frac{dQ_r}{dT} \right) = h_r = 40eT^3 \]

\( Q_r \) = radiant heat flux

\( Q_{ra} \) = radiant heat flux at ambient air temperature

\( e \) = Stephen-Boltzman constant

and \( T_l, T_a \) are leaf and ambient air temperatures, respectively. The coefficient, \( h_r \), is not a heat-transfer coefficient but has the same dimensions. Because the sprinkled leaf will be wet, the heat loss due to evaporation may be developed in a similar manner. It is assumed that the vapour pressure of the leaf is saturated at air temperature. As for \( Q_r \) the latent heat loss may be expanded in a Taylor series in which the derivative of saturated vapour pressure with respect to temperature is calculated at the average temperature. This equation can then be transformed from a vapour-flux to a heat-flux equation with the use of a coefficient "\( a \)" to adjust vapour gradients to temperature differences and vapour fluxes.

\[ Q_k = Q_{ke} + 2(T_a - T_l)h_e \]

\[ h_e = \frac{de}{dT} \frac{d\theta_v}{\theta_v} = (ah_v i_0/(R_w T^2)) \]
where: \( Q_{le(a)} \) is the latent heat loss if the vapour pressure is saturated at the air temperature

\[ R_w \] is the specific gas constant for water vapour

\[ e \] is the vapour pressure

\[ le \] is the latent heat of vaporization

\[ h_c \] is the engineering convection heat transfer coefficient,

and \( de/dT \) can be obtained from the Clausius/Clapeyron equation. The coefficient of latent transfer \( h_c \) is approximately equal to one-half the convective heat transfer coefficient.

Sensible heat transfer may be estimated by the familiar convective heat transfer equation:

\[ Q_k = 2h_c(T_l - T_a) \]

By appropriate substitutions and combinations, a satisfactory heat-balance equation can be obtained for the leaf.

The assumptions have been shown by Gates and Benedict (Reference 46) and Raschke (Reference 91) to be satisfactory. Busiging (Reference 31) compared values for cylinders and spheres and found that in the range of Reynolds numbers commonly encountered in conditions when cold protection is required the convective coefficients varied by less than 15 per cent. The heat balance is written with the substitution, \( T_m \), as the lowest permissible leaf temperature instead of \( T_l \), the temperature of a dry leaf, and since the change in temperature with time is zero at equilibrium it may be set equal to a similar equation using \( T_l \) as leaf temperature. By subtracting these two equations and adding \( Q_{lf} \) as the heat released through freezing of water, there is obtained

\[ Q_{lf} = -2(h_c + h_r + h_e)(T_m - T_l) \]

The constant 2 occurs throughout all equations since the leaf has two sides. If this equation is divided by the latent heat of fusion, \( l_f \), the depth of water required per unit time is

\[ I = \frac{-2}{l_f} (h_c + h_r + h_e)(T_m - T_l) \]

If sprinklers are distributed uniformly, if all the leaves are equally exposed, and if all the water remained on the plant parts, then \( I \), the sprinkling rate, would produce the required heat. Instead, a variable multiplier \( \alpha \) must be included to adjust for systems, crops and locations. Values of \( \alpha \) ranging from 1 to 1.5 have been observed in field experiments (Reference 60). Meteorological factors, such as change of wind speed with height, convective coefficient as well as leaf orientation, size and exposure are included in \( \alpha \). The appropriate sprinkling rate becomes

\[ I = \alpha h_e(T_m - T_l) \]

where: \( h_e = -2/l_f (h_c + h_r + h_e) \).

By using standard engineering heat-transfer coefficients for plates it is possible to compute the values of \( h_i \) for the various wind speeds and temperatures shown in Table 1. The lowest value of \( I \) in this table, 0.254 cm h\(^{-1}\) does not follow from theory, but reflects the influence of natural convection and evaporation, and is therefore quasi-theoretical.

Since sprinkling for cold protection is commonly obtained by using rotating sprinklers which distribute small drops of water, it is necessary to consider the longest permissible time between re-wettings of the leaf to determine the rotation period. Water that is delivered to the sprinkler near 22\(^\circ\)C is cooled to near 0\(^\circ\)C by the time it reaches the plant (Reference 59). Cooling of the leaf between periods of wetting determines the longest interval between sprinkling and can be calculated by using standard cooling formula. The length of time required to freeze the film of water adhering to the leaf which has a minimum thickness, \( \delta \), of approximately 0.03 mm can be estimated from:

\[ t = k(l_f2\delta)/(T_o - T_a) + (C/l_f\delta) \ln(T_o/T_m) \]
where $k$ is assumed to be $14 \text{ cm}^2 \text{ min}^{-1}$, and $T_0$ is the freezing temperature of water. The air temperature and the minimum permissible leaf temperature are the important parameters. The value of $T_m$ for a given crop can be determined in advance while the lowest expected air temperature must be known for design purposes. Rotational periods are usually between 1 and 2 min.

This general theory should provide guidance for field experimentation as well as for design if leaf temperature, wind speed and sprinkling rates are known.

Systems like this have been operated in Florida, U.S.A., for various purposes including the protection of mature citrus trees. Although there have been no known failures in protection at the irrigation rates given in Table 1, mature citrus trees have suffered disastrously because: (a) Ice accumulation on foliated evergreen trees can cause breakage and severe damage; (b) Citrus leaves are more vulnerable to cold damage when wet than when dry; dry leaves will commonly withstand temperatures in the range of $-4.5^\circ\text{C}$ to $-6.5^\circ\text{C}$ without damage in their hardened state, but when wet from sprinklers will be damaged at $-4.5^\circ\text{C}$; this temperature should not occur if enough water is used; (c) Insufficient water leads to evaporative chilling to near the wet-bulb temperature and increases damage. Under advective conditions, very high sprinkling rates are required, usually higher than can be achieved.

A simple field check for an adequate sprinkling rate is the icicles with clear ice encasing all parts of the plant. When the rate is sufficient to maintain an ice-water mixture, some of it drains from the leaves forming the icicles. If these fail to form, if the ice is milky instead of clear or if the plant is not completely encased, the sprinkling rate is too low and disastrous results will occur, especially with citrus.

Overhead sprinkler irrigation has been used successfully on low-growing crops including citrus nursery stocks and on truly tropical fruits such as avocados, mangoes and limes for which it is used to protect from frost rather than freezing.

Sprinkling should begin at or near the freezing point if damaging temperatures are anticipated. Once started, it cannot be stopped until the wet-bulb temperature has risen above the damage level. Equipment failure or insufficient application of water during the cold period will increase the damage; with citrus almost all the exposed parts of the tree may die. Consequently, the design criteria must anticipate the worst possible condition. Also horticultural considerations must include soil and root conditions. Only if the plants can tolerate the irrigation rates should sprinkling be considered. Sprinkling may be stopped when the wet-bulb temperature equals $0^\circ\text{C}$; otherwise there is a waste of energy and water. Further sprinkling may hasten melting of the ice but does not raise its temperature. It is not uncommon to find recommendations that sprinkling should be continued until all the ice is removed, but this practice simply ignores the physics and meteorology of ice formation. A shaded wet-bulb thermometer ventilated at approximately the same rate as the plant would give a good indication of the time when sprinkling can be stopped.

Sprinkling has many advantages. It consumes small quantities of energy in comparison to heating, it is non-polluting and provides nearly complete crop protection when practised properly with good design. Also an overhead sprinkling system may be utilized to supply irrigation water during the growing season. Its use for deciduous fruits is most attractive than for citrus, especially for apples and other fruits that have sturdy frames or that have been trained to withstand ice-loading. Tree damage usually does not result from failure to apply enough water to deciduous fruit; however, complete loss of buds and fruit will occur. Sprinkling of vineyards is popular in the western United States (Reference 96), where vines are commonly trained and trellised to support the ice load.

Layout and design of a sprinkler system requires competent engineering knowledge (Reference 65). Most properly designed systems have specially designed sprinklers, pressure controls, and approximately 100 per cent overlap of patterns for adequate distribution of water.

### 3.2 Wind machines

Wind machines provide protection by mixing air in the lowest part of the atmosphere to obtain more efficient utilization of the heat stored in the air. The first studies of wind machines were undertaken in California, U.S.A., in
the early 1920s. Baker (Reference 8), Moses (Reference 84), and Young (Reference 117) reported that none of them was very effective and could not penetrate more than 15 m against wind drift. In 1928, a wind machine (Reference 103) was described which was mounted on a 7.5-m tower and rotated through 360° every four minutes. It appeared to be the prototype of the modern tower-mounted machines. A description of heat transfer by wind machines is given by Brooks et al. (References 27, 28) under conditions for California, U.S.A.

The first Australian field trials were reported by Shaw and Redlich (Reference 99) about 1946. Their machine was powered by a 5-horsepower engine with a 3.6-m fan mounted on a 3.6-m tower. Angus (References 2, 3, 5, 6, 7) covers in detail the results of the Australian field-trial results which generally agree with those obtained in the United States. He pointed out that: (a) the performance of the wind machine varies markedly with the strength of the inversion; (b) the penetration of the jet is greater with drift than against it; (c) the size and speed of the air jet determines its penetration which is mainly controlled by buoyancy; (d) the air jets should be directed slightly downward, between 10 and 20° below the horizontal; and (e) the area covered increases as the rotation speed is decreased.

Wind machines were first used in Florida in the early 1950s, and field results generally agree with those in California and in Australia. In particular these tests showed that on a clear, calm night with an inversion a wind machine in the 100-horsepower class is capable of modifying the temperature over an area of 2 to 4 hectares and that when the natural air movement becomes greater than 1.3 or 2.2 m s⁻¹, natural mixing predominates and the machine is of little additional value.

Wind machines in the United States and Australia are mainly powered by gasoline or electricity. Electrically-powered units can be operated with automatic thermostats but usually have lower power and cover smaller acreages; these are used mostly in California. The majority of the gasoline-powered types consist of a tower 9 to 10.5 m tall and a propeller 3 to 4.5 m in diameter inclined downward 3 to 7° below the horizon, with speeds varying from 500 to 750 r.p.m. The propeller makes one complete revolution about the tower every four to five minutes. A slower rotational rate reduces the effectiveness of the machine because cold-air stratification develops following mixing. The gasoline-powered machines are commonly in the 100-brake horsepower class. The power unit may either be mounted on the ground or on top of the tower. It is not uncommon for two power units and two propellers to be mounted on one tower (Figure 3), which increases the effective coverage by approximately 50 per cent. This type is less efficient than two units mounted on separate towers, but there is an obvious advantage in lower construction costs and maintenance.

Mixing a stable atmosphere has been investigated from both the theoretical and experimental standpoint. Redlich (Reference 92) determined that approximately 12.4 brake horsepower per hectare was required for adequate mixing. Ball (Reference 9) calculated that the power needed to mix the lowest 15 m of the atmosphere under clear, calm conditions would be only 0.62 horsepower per hectare. At present, wind machines of the 85 to 100 brake horsepower class will protect 5.5 to 6.5 hectares. It is apparent that wind machines are relatively inefficient, expending much energy for work other than mixing.

Theoretical examinations of the wind machine were made by Baker (Reference 8), Ball (Reference 9) and Leonard (Reference 77), but have not been helpful in design because the analysis led to two opposing conclusions. A small-core, high-speed jet will provide protection over the greatest area, but a large-core, slow-speed jet will produce the greatest temperature modification. Angus (Reference 6) designed a series of experiments in which the down-angle was varied from nearly-vertical to horizontal in order to test whether the designs used in the United States could be surpassed, but little improvement was achieved.

Wind machines provide protection in a pattern, roughly circular, with the machine located near the centre (Figure 4). The amount of protection depends upon the strength of the inversion, but very often the temperature can be modified by an amount equivalent to one-half of the temperature difference between 1.5 and 15 m. Research at the University of Florida (References 30, 53, 58, 61, 93) indicates that the area as well as the amount of pro-
tection can be predicted from the inversion strength (Figure 5). Wind has a pronounced effect on wind machines (Reference 97): it usually elongates the area of protection (Figure 4); but most importantly it destroys the nocturnal inversion so that little additional protection can be expected.

Crawford (Reference 38) was able to show that the area of modification produced by a slowly rotating wind machine is given by

\[ A = \frac{25}{v_a} \left( \frac{F}{\mu w} \right) \]

where: 
- \( A \) = area influenced
- \( v_a \) = minimum value of average cross-sectional velocity for adequate mixing
- \( F \) = thrust.

Wind machines protect against the cold through ingenious utilization of the heat stored in the air; nevertheless, their success is highly dependent upon cold weather conditions which may not be suitable in many areas because either the nocturnal inversion is too weak or advection occurs frequently. Obviously for effective use the inversion strength should be measured.

Machine effectiveness depends very much on proper propeller speed and thrust, for example, a 10 or 20 per cent reduction in speed may reduce thrust by 30 to 40 per cent. Therefore, wind machine operational speeds should be checked frequently. Also effectiveness as compared to the inversion should be determined. If a strong inversion is present and little protection is obtained, the operating speed of the machine should be determined immediately. One of the easiest methods of determining the operating speed is to observe the time required for the machine to make one complete revolution around the tower. If this is greater than the specifications, the machine is almost certainly operating at less than rated power. Unless corrected, very little cold protection will be obtained. Wind machines should be operated periodically during the cold season to make sure they are in good running condition and can be started when needed. They should not be operated in high winds unless the manufacturer has specifically indicated that such operation will not damage the machine. Machines equipped with teetering hubs will tolerate moderate wind speeds; those without will vibrate excessively and mechanical failure may result to either the gear box or the propeller. Power units of wind machines should either be of the original design or should be adapted by a competent engineer to ensure proper performance. An adequate maintenance programme should be established to reduce the possibility of failures on cold nights.

Since wind machines protect a roughly circular area, they will not give complete protection for square or rectangular orchards. The protection pattern changes as the wind changes in both speed and direction. For maximum protection on clear, calm nights location should be near the centre of the area and slightly upwind to the direction of the prevailing drift. Multiple machine locations often produce synergistic effects in the overlapping areas of their influence, where the combined protection is commonly greater than that for an individual machine.

To maintain the temperature as high as possible, wind machines should be started early in the evening or whenever the temperatures are near the freezing point or as soon as protection is needed. Numerous reports (References 17, 20, 22, 23, 24, 43, 44, 45, 49, 50) state that it is difficult to regain a previous temperature if the wind machine is stopped. Exposed leaves are colder than the ambient air and may approach critical temperature levels on calm nights before the air reaches the freezing point. Early starting is necessary before low temperatures are reached.

Although numerous wind machines have been designed which add heat to the propeller, most have been singularly unsuccessful (References 24, 25, 63). One design utilizes ram jets as power units on the tips of the propellers. It is claimed that the heat produced by the ram jets will be entrained into the jet from the wind machine and give additional protection; however, in practice this causes the jet to rise very quickly above the tops of the trees.
3.3 Helicopters

Helicopters can also be used to mix the lowest layers of the atmosphere in radiation frost conditions. They simulate the action of the wind machine and are very effective because the air is mixed by a large moving vehicle rather than by the moving jet of air. Effectiveness and size of the area protected are proportional to the helicopter’s thrust. Large helicopters (4 500-k or heavier) can protect an area of 80 to 400 ha under calm, stable conditions. However, cost precludes their use exclusively for cold protection so that they are used mainly in support of other means of protection or in their absence.

3.4 Wind-breaks

Wind-breaks have been used to protect plants from cold-air advection and are usually constructed of lumber or other locally produced materials but commonly are formed by various living trees and plants. However, their effectiveness is often marginal because they may enhance the stratification and accumulation of cold air near the surface on calm nights and produce colder conditions than those in open areas. Their behaviour and design have been investigated by Woodruff (Reference 113) mostly as a means of preventing wind erosion. However, the principles also are applicable to cold and frost protection.

There are compounding influences since tall wind-breaks partially shield the plants immediately adjacent from the cold-sky radiation. Date palms have been shown to prevent or mitigate damage under radiation frost conditions in citrus orchards. Most living wind-breaks are complex systems which modify not only wind speed and radiation but also compete for water, nutrients and sunlight. Thus, they have a physiological effect upon the adjacent plants, so that the grower has difficulty in deciding their merits. Very few living wind-breaks are used for prevention of frost in the United States, but rather for protection from wind erosion and wind scarring of fruits.

3.5 Insulating foams

Insulating foams have been investigated as a means of protecting from cold weather. They are primarily insulating blankets that reduce the thermal conductivity and protect by utilizing the heat stored in the plant and the soil. The first reported use of foam, which was similar to firefighting foam, was by Shear and Barrows (Reference 100). More recently protein-based (purified protein or gelatin) foams (Reference 13) have been used to give protection to low-growing crops (Figure 6). Experimentally, foam has been used on trees with a supporting matrix for retention. They must be applied prior to the cold period and must have sufficient physical strength to persist during the cold.

Foams have several advantages: they provide complete protection; are non-polluting; and require rather low quantities of energy. Their main disadvantages are: the length of time and the specialized equipment required to apply them and the rather high cost of the stabilizing chemicals.

3.6 Clouds and fog

It has long been known that clouds and fog modify minimum nocturnal temperatures. On clear nights the back radiation from the atmosphere is so much less than the radiation from the surface that the air near the surface is cooled and can produce frost and freezing temperatures. Clouds prevent the loss of surface radiation and produce enough back radiation to raise the surface temperature and keep it warmer. Most of the energy that is lost from the surface occurs in the 8- to 12-μm radiation band, called the “atmospheric window”. Water droplets of the proper size can also decrease the radiation loss through this window sufficiently to ameliorate cold damage.
Brooks (Reference 18) performed experiments to determine the effectiveness of oil-fog clouds that were generated primarily for military purposes as a means of closing the atmospheric window. He found that a steam/oil cloud, while very opaque to visible radiation, did not attenuate radiation in the window because of droplet size. However, if the droplet size and number were increased sufficiently to close the window, toxicity resulted from accumulation of excessive amounts of oil. De Boer's work encouraged further research into the production of water droplets for cold protection. Essentially two techniques have been used. Water is vaporized and then condensed into droplets (Reference 15) or mechanically separated into small droplets. Neither technique is efficient in producing an appropriate droplet size. Small droplets tend to evaporate rapidly because of their increased vapour pressure. Since they must be produced in extremely dry atmospheres, evaporation is a serious problem. Attempts have been made to coat water droplets with chains of monomolecular films to reduce the vapour pressure and the evaporation (Reference 85). However, in most instances this has not succeeded because of the low efficiency in producing droplets and coatings. Currently, the most successful systems produce droplets of appropriate size by impinging water against metal needles under high pressure. The fog is spread by diffusion. Usually there is an immediate drop in temperature by evaporative chilling around the fog emitters, but evidence indicates that a substantial modification in the radiation balance can be achieved (Reference 15) as well as some cold protection. However, the amount of water used per unit area shows that the efficiency of producing droplets is low.

Fog has several advantages, namely it utilizes the heat stored in the soil, requires rather small amounts of energy to produce and is non-polluting. But fog has a number of serious disadvantages. Success depends upon its vapour pressure and the diffusion processes. Under strong advection it is unlikely that any benefit would result and even further evaporative cooling might occur. If the droplet size is too large, they fall quickly to the surface and accumulate on plants where, of course, they freeze and may provide some protection by releasing the latent heat of fusion. However, at some distance from the emitters not enough water will be present so that the plants may be cooled through sublimation. Trees near the emitters may be broken by ice accumulation. Finally, in urban areas artificial fog on highways may interfere with commerce.

Artificial fogs are still in the research and development stage, but because they offer the possibility of utilizing stored soil heat they will continue to receive attention. Undoubtedly, there are situations for which they are uniquely suitable, and therefore can provide satisfactory protection at low cost. Also they may be useful for suppressing heat during summer months when prevention of high temperatures can enhance fruit quality and yield (References 33, 62, 110).
CHAPTER 4

ACTIVE METHODS OF COLD PROTECTION REQUIRING HIGH ENERGY INPUT

4.1 Introduction

Fire is one of the oldest means of cold protection and one of the best (References 1, 32, 34, 47, 72, 118). The kind of fuel or heater used does not greatly influence the protection obtained with the important exception that devices which produce radiant heat are more effective under cold-advection conditions. While heater placement and fire size are important, most other features are matters of convenience and operational reliability. Smoke production and air pollution do not directly relate to effectiveness, but should be avoided if possible.

The important factors which influence heating efficiency and effectiveness are: inversion strength, size of fire, size of the protected area, wind speed, plant height and heater placement. Inversion strength and fire size determine the depth of the heated layer. Small fires do not heat as deep a layer as large fires even if total heat produced is the same. Strong inversions tend to confine the heat to the lower layers of the atmosphere. Small orchards or fields require more heat per unit area than large ones because heat is lost around the edges and the air is changed more rapidly. Tall plants restrict the wind and retain the heat in the lower air layers, but the tops of tall trees are vulnerable in windy, advective freezes. Orchards which are sufficiently dense generally can be heated more easily than those which are open and allow free passage of the wind.

4.2 Heat balance calculations

Investigation of the heat balance of the lower atmospheric layers specifically for cold protection was begun in the late 1940s and early 1950s by Ball (Reference 10), Priestley (References 88, 89) and Priestley and Ball (Reference 90) which described the fate of energy released in the lowest layers of the atmosphere under typical cold, freezing conditions. A general theory of convective plumes proposed by Priestley (Reference 88) and confirmed in the model studies by Crawford and Leonard (Reference 39) demonstrated that the rise of the heated plume could be computed for a stable atmosphere. Crawford (Reference 37) used this information and classical micrometeorological theory to calculate the heat requirements for cold protection under specific meteorological and heating conditions, and he corrected many misconceptions about cold protection. In his technique the orchard was imagined to be enclosed in a box; the heating requirement was calculated from the heat fluxes flowing through the sides of the box. The depth of the heated layer was estimated from the calculated plume height. Radiation flux was obtained from general relationships between net radiation, surface temperature and humidity. The solution of the equations for specific parameters, namely, fire size, inversion strength, wind speed, orchard size and surface temperature was published in nomograph form (Reference 37). Gerber (Reference 56) used a numerical method combining Crawford’s concepts with the engineering heat transfer approach to obtain a solution. Crawford’s ideas have been further developed by Martsolf and Panofsky (Reference 81) using the classical equations of continuity and thermodynamics to formulate the three-dimensional mass- and energy-balance of an orchard.

Several features of most techniques used to compute the heat required for cold protection aid in comprehending the heating problem and the following associated enigma. A review of field experimental data reveals that more variations in heating effectiveness occur between nights than between the orchards, vineyards or fields which are being protected. Thus, synoptic micrometeorological influences are stronger than site influences. Net radiation, soil heat, and convection have been measured and are the major heat fluxes. Shifts in these fluxes should control
the heat balance. During a clear, cold night, net radiation and soil heat flux are stable with little variation. From night to night they show only small seasonal changes; therefore convection should be nearly constant, yet heating effectiveness varies greatly between nights.

Heating requirement effectiveness is usually expressed in terms of the temperature modification and fuel burned because these are of the most importance to the practitioner. Any analytical framework should relate these to the meteorological situation. Analysis of one-dimensional heat flow shows the convective vertical flux, \(Q\), is proportional to the product of an exchange coefficient, \(K_h\), and the vertical temperature gradient, \(dT/dZ\). In order for there to be a temperature difference between a heated and non-heated open area, the temperature gradient \(dT/dZ\) must be different. Increasing \(Q\) by burning more fuel may have only a small effect if \(K_h\) is large. The extra heat released by the fires can be transported vertically with only a slight change in \(dT/dZ\) and only a small temperature response.

Since convective vertical heat flux is difficult to estimate or measure, the computational techniques usually assume it is zero by choosing a height for the imaginary box at which the flux vanishes. Implicit in this assumption is that all convective heat loss will occur in the horizontal direction. The height chosen is usually determined by the plume-rise theory which assumes that heat is lost from the plume by radial dissipation from its center-line. The height at which vertical convection vanishes is determined by the inversion profile, but measurements over heated orchards, including citrus, indicate that the temperatures aloft over “heat islands” are cooler than those over the surrounding area at the same height. The reasons are related to flow trajectories which almost certainly change the height at which the vertical convection vanishes and therefore casts doubt on the validity of this computational approach. Vertical heat convection, even at a low velocity, can transfer more heat than horizontal advection except for very small areas. Crawford's techniques (Reference 37) overestimate the heat requirements for small areas and probably underestimate them for large areas due in part to the implicit assumption that convection is basically horizontal. The most likely significant improvement in heating effectiveness would result from the reduction in vertical exchange and modification of the radiant heat loss.

4.3 Practical heating methods

Numerous field experiments have been conducted on heating for cold protection (References 54, 55, 56, 69, 75). Their general features and recommendations are summarized below.

4.3.1 Open fires

Heating was first accomplished with open fires of wood, coal, coke or other fuels (Reference 72), which were effective under many conditions. The heat was released near the ground and radiation was emitted by the flame as well as the cinders and ash. Open fires had several disadvantages. The fuel was exposed to rain and was often difficult to light and could not be regulated. If not burned the fuel usually was removed from the orchard in the warm season. Smoke was produced which was a nuisance to neighboring areas. The early literature (Reference 119) indicated an association between smoke and effectiveness. Therefore the use of manures and wet straw to increase the smoke was recommended, but was based upon an erroneous conclusion drawn from observation, i.e., when smoke lingered in the orchard the fires were effective. But the conclusion that the smoke was the effective agent failed to separate the heated gases and smoke. If the smoke remained in the orchard, the heating was indeed effective because the heated gases remained there as well. If the smoke were blown away, then obviously the heated gases were also blown away.

4.3.2 Open containers

Petroleum fuels were introduced and used in open buckets and containers for cold protection in Europe, the United States and Australia (References 4, 32, 34, 38, 115). These fuels were inexpensive, the containers could
be covered from rain, the oil was easy to store and refuel, and their heat content was high, allowing them to burn for longer periods than solid fuels. However, coke heaters (essentially open containers) were also effective because coke burned at a high temperature and in addition to the convective gases produced radiant heat from the glowing metal container. The main disadvantages of open buckets and pails were the production of smoke, the inability for regulation in any controllable way, and in general the production of mostly convective heat with very little radiation.

4.3.3 Stack heaters

Coke heaters with their rudimentary combustion chambers lead to the refinement and development of oil-fired stack heaters for orchards. The best (Figure 7) were developed in California (Reference 78) in the 1930s to reduce air pollution and have proved to be excellent. Two of the foremost are the university return-stack and the large cone stack (Figure 8). Fire in the bowl heats the oil and vaporizes it so that complete combustion can occur in the stack where additional vents are installed to increase combustion efficiency and reduce smoke production. In the “return-stack” a portion of the fuel-rich gases are recycled into the reservoir to reduce the amount of fuel in the mixture and allow for complete combustion. Both the “large cone” and “return-stack” can be operated in the United States to meet the ambient air pollution regulations, for example, in California, emission is limited to one gram of unburnt carbon per minute, but in Florida, to one-half gram. In addition to the superior properties of these two heaters, from an air pollution standpoint, they are easily lit and regulated. The draft setting allows regulation from approximately 1 to 4 litres per hour. Radiant heat is a function of the stack temperature but ranges between 20 and 30 per cent of the total heat output. Under advective conditions, trees or plants exposed to the hot glowing stacks also benefit from the radiation. A satisfactory placement of heaters for optimum utilization of heating and for most effective protection is shown in Figure 9. For radiant heat to be effective, part of the tree or plant must be in a direct line of sight with the stack and not shaded from it. Thus heater placement is important and as many trees as possible should be adjacent to a heater. This arrangement is also very effective in distributing the hot, convective gases.

4.3.4 Petroleum wax or coke

One other way of improving the distribution of heat is to use a large number of small fires. Heaters composed of petroleum wax or coke have been developed for this purpose (References 55, 79, 98), are partly or completely combustible (Figure 10), and can produce a small, open fire which may be placed either directly beneath or near the canopy of the tree. The heated plume of convective gases rises directly through the canopy and warms the trees. The effective cold protection characteristics of various heaters are compared in Table 2. The advantage of a larger number of fires is demonstrated by the greater increase in leaf temperature per unit of heat. However, wax heaters have proved very difficult to use, spillage has been a serious problem, and the cost of the solid fuel is usually higher than oil. In orchards where several frosts can be expected annually they are probably more expensive than the oil heaters. At the same time they eliminate the need for expensive heaters and fuel storage tanks.
CHAPTER 5

ENVIRONMENTAL, ENERGY AND ECONOMIC CONSIDERATIONS

5.1 Field results

If all the heat released by combustion could be kept in the orchard, heating for cold protection would be very effective and efficient. Unfortunately, most of the heat is lost directly by radiation to the cold sky, by convection above the plants and by flux at borders and edges. Convective heating requires that the hot gases be warmer than the plants. If convection supplied all the heat then the heat gained by the plants must equal the heat lost by radiation to the sky assuming that the temperature remains constant. For many years, about the only estimates of the heat required for cold protection were found from general rules based on experiments conducted (References 72, 76, 82, 105, 120) to determine the heat production and the amount of protection expected.

Field experiments in Australia (References 4, 89, 90) and in the United States (References 12, 18, 38, 56) confirmed that the heat needed for cold protection varies from 1.5 to 4 times the net radiant heat loss, depending upon meteorological conditions. This would require 85 to 100 heaters per hectare, each burning 3.5 litres of oil per hour; such a complement of stack heaters would make the most successful system. Additional heaters are needed on the borders, especially on the upwind sides. Small heaters beneath the canopy increase heating efficiency and effectiveness. Maximum temperature-response with small fires occurs closer to the ground (Figure 11). Radiant heating from stacks provides protection under windy, advective conditions even though there is virtually no modification of the ambient air temperature. Since the amount of radiation warming is roughly inversely proportional to the square of the distance from the stack, only those plants within several metres receive enough to be protected.

Heaters or fires should be lit before the temperature of the exposed leaves or fruits reaches dangerously low levels. The temperature of exposed leaves and fruits should be measured by remote-indicating thermometers, for example, with thermisters or thermocouples, but if these are not available, a minimum-indicating thermometer exposed in the orchard on top of a flat surface 1 to 1.5 m above the ground may serve as an index of exposed leaf temperature. To forecast lighting time, the exposed thermometer of leaf, bud or fruit temperature recorders should be read at sunset and hourly thereafter. If temperature is plotted against time (Figure 12) and a line connecting the points is drawn, the earliest time that firing is required can be estimated. This is not precise and usually predicts a time earlier than actually needed, but this extra time is useful for alerting firing crews and assembling equipment and personnel.

It is often desirable to have the maximum amount of heat available at the coldest time, for example, near sunrise. Heaters should be lit in advance so that maximum heat production can occur during this period. However, if the total amount of equipment is limited, lighting may be delayed until temperatures are dangerously low. The time for lighting also depends on the fuel supply. Heaters should not be operated at excessively high burning rates. Rates greater than about four litres per hour reduce efficiency. It is better to increase the number of heaters than the burning rate (References 11, 61). High burning rates also shorten the life of the heater by oxidation and subsequent rusting of stacks. Best heating conditions can usually be accomplished with heaters that produce few flames above the top of the stack.

5.1.1 Care and maintenance of heaters

Equipment is needed for refuelling heaters after night-time use and for removing oil at the end of the cold season. Heaters should be given good care and maintenance. The tops should be securely closed to exclude rain-water,
which causes operating difficulties, otherwise proper burning cannot be obtained. Oil floats on the water and after ignition causes it to boil. Escaping steam will either extinguish the heater, reduce the burning rate, or occasionally cause the stack to be blown off.

If heaters have been operated at high burning rates or for several nights, the galvanized stack will be oxidized. Unless these stacks are treated with a rust preventive, severe rusting will occur. Since the regulation of the heater depends upon proper alignment and tight fitting of tops, drafts and stacks, it is important to maintain them in good condition; otherwise considerable wastage of fuel will occur.

5.1.2 Hazards

Crews who light and refuel heaters should be impressed with the need to keep dry and free of oil. Normal body temperature will warm oil so that it becomes easily ignited. Oil-soaked clothing is a great fire hazard in the presence of open flames from lighting torches. Most torches used in the United States have flame screens in their spouts to prevent flames from striking back into the reservoir. Lighting mixtures are commonly one part heater oil and one part gasoline to increase the flammability. Unless the screen is kept in place, the torch is a fire and explosion hazard.

Lighting a hot heater is a hazard, the grey vaporized oil cloud is flammable and will ignite easily. Since heaters must be lit in this condition occasionally, the vapour should be ignited first, with the operator remaining as far from the heater as possible because flash ignition will occur. If possible, the heater should be allowed to cool before lighting is attempted.

Because of the difficulty in refuelling heaters and in regulating them quickly, systems have been designed which supply oil through pressurized pipelines to the heaters which burn the oil from a furnace-type nozzle. The advantages of this type of heater are that they are clean burning if properly designed, easily regulated and extinguished, and have fewer labour requirements. Most of these heaters have the disadvantages of higher cost and the need for careful maintenance of pipes, filters and nozzles. Most of the pipes used in the United States are polyvinyl chloride or polyethylene.

5.2 Wind machines and heaters

The fuel costs for operating wind machines are much lower than those for heaters since they consume 9.35 and 200-400 litres per hectare per hour respectively. There are occasional nights when the meteorological conditions are not favourable for wind machines, namely moderate winds, weak inversions, or simply temperatures which are too cold. Consequently, there is an incentive to combine heaters and wind machines for cumulative or synergistic effects. The combination system has been investigated under field conditions mainly in Australia (Reference 4) and in the citrus-producing regions of California (References 38, 39) and Arizona (Reference 71).

Field experiments reveal that this combination not only produces sizable savings in fuel but also increases the efficacy of both components of the system, the number of heaters needed is reduced by 60 to 70 per cent. The heat sources must not be located too close to the wind machine or the heat will lift the machine’s jet above the ground. These sources should be dispersed mainly in peripheral areas of the wind-machine’s protection pattern. Burning rates in excess of 3 litres per hour are not as beneficial as lower rates of burning. For a particular night the response obtained from the dual system is usually greater than the combined response of the separate devices. With wind speeds in excess of 2.5 m s\(^{-1}\) very little additional benefit can be obtained by using the machine. When wind machines and heaters are used together flexibility is added to the system so that protection may be gained under conditions when the machine alone would give marginal or no benefit. In terms of energy saving and efficiency, a wind machine/heating system consumes about 140 litres of fuel per hectare as compared to 200-400 for a heating system alone.
5.3 Economic considerations

Frost and cold protection equipment must be simple, relatively inexpensive and durably constructed for economy and operation. To save money, open fires, fires in pails and cans, have been used to burn old tyres, discarded railroad ties and nearly every other combustible material. Most of these produce heavy palls of smoke which are not only disagreeable but soil buildings and clothing and aggravate respiratory ailments and allergies increasing health risks. Smoke has no known benefits and should be avoided if at all possible. Although it indicates incomplete combustion and loss of efficiency, copious smoke can even result from 95 per cent combustion. Fortunately, cold weather is transient so that heating is not required on many nights during the year. Oil-fuelled stack heaters and petroleum wax coke and charcoal heaters produce little air pollution if managed properly. The "large cone" and "return-stack" heaters can meet air pollution standards for emissions of less than one-half gram of solid carbon per minute. Most of the pressurized systems which burn atomized oil can pass this same test. Manufacturers should be required to supply data on emissions as related to burning rates.

Wind machines, irrigation systems, fogs, foams, and helicopters can be considered to be non-polluting methods of frost and cold protection, and therefore should be used if possible, especially in densely populated areas which have a normal high burden of air pollution. These methods require the least energy (fuel) and labour but may be more expensive to install. Economic studies (References 1, 114) have been made but they are of minor importance due to the rapidly changing prices of fuel, manufactured products, fruits and other agricultural products.

Several principles can serve as guides for decisions about the economic consequences and desirability of protecting against cold and frost. The added capital cost for equipment must be borne by the crop being protected. This cost can be amortized over the expected life of the equipment (for heaters, five to ten years; for sprinklers and wind machines, ten to twenty years). From climatological records, the annual number of operational hours can be estimated. Using expected costs of labour and fuel, the total annual costs including capital and operations can then be determined. This must be balanced against the total added income generated through the increased number of crops harvested, the changes in yields and differences in quality. In addition, the cost of lost production, the damage to trees and orchards and the lost economic opportunity from the inability to produce a cold-sensitive crop must be considered. Usually prices for fruit or vegetables which are cold-sensitive are much higher following cold periods or seasons because supplies are reduced. Because of differences in local cost and availability of labour and the prices of produce, almost all evaluations must be made on a local basis.

Frost and cold protection methods have been practised for many, many years. It would appear, on the basis of a superficial examination, that the need for such protection simply indicates the producers' insistence on using sites which are climatically unsuited for the production of cold-sensitive crops. However, closer examination of the reasons for growing crops in areas with occasional cold weather reveals that this choice is often deliberate and is sometimes caused by competition to obtain more desirable sites for non-agricultural purposes. Elevations above the surroundings in the local topography tend to be warmer sites during radiation frosts and are therefore particularly well-suited for fruit production but are also attractive for construction of houses. Those sites are often prized by fruit growers as the most desirable sites available since the cool night temperatures enhance fruit quality; other climatic and soil factors may also be highly beneficial for production.

It is unlikely that the need for cold and frost protection will diminish. In fact, there is evidence that it will increase as increasing urbanization and land values force fruit production into more marginal areas. In a very real sense, agricultural meteorologists have a role to play in indicating the value of "warm" sites for utilization as fruit production sites. They provide the most desirable, economical and reliable natural method for frost and cold protection. Unfortunately, policy-makers who are instrumental in determining zoning and land-use planning regulations are not always sufficiently cognizant of these facts.
# TABLES

## TABLE 1
Precipitation rate (cm h\(^{-1}\)) necessary for cold protection

<table>
<thead>
<tr>
<th>Temp. (°C) of a dry leaf*</th>
<th>0 to 45</th>
<th>89 to 178</th>
<th>224 to 358</th>
<th>447 to 625</th>
<th>805 to 983</th>
<th>1341</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.78</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.76</td>
</tr>
<tr>
<td>-3.33</td>
<td>0.25</td>
<td>0.25</td>
<td>0.36</td>
<td>0.51</td>
<td>1.02</td>
<td>1.52</td>
</tr>
<tr>
<td>-4.44</td>
<td>0.25</td>
<td>0.41</td>
<td>0.76</td>
<td>1.02</td>
<td>2.03</td>
<td>4.06</td>
</tr>
<tr>
<td>-5.55</td>
<td>0.30</td>
<td>0.61</td>
<td>1.27</td>
<td>1.52</td>
<td>3.05</td>
<td>4.57</td>
</tr>
<tr>
<td>-6.67</td>
<td>0.41</td>
<td>0.76</td>
<td>1.52</td>
<td>2.03</td>
<td>4.06</td>
<td>6.10</td>
</tr>
<tr>
<td>-7.78</td>
<td>0.51</td>
<td>1.02</td>
<td>1.78</td>
<td>2.54</td>
<td>5.08</td>
<td>7.62</td>
</tr>
<tr>
<td>-9.44</td>
<td>0.66</td>
<td>1.27</td>
<td>2.29</td>
<td>3.30</td>
<td>6.60</td>
<td>10.16</td>
</tr>
<tr>
<td>-11.67</td>
<td>0.86</td>
<td>1.78</td>
<td>3.05</td>
<td>4.32</td>
<td>8.64</td>
<td>12.70</td>
</tr>
</tbody>
</table>

*The temperature of a dry leaf is the expected minimum temperature of an unprotected leaf. This will range from 0.5°C below air temperature on nights with light winds, to 1.5 - 2°C on very calm nights.

## TABLE 2
Mean cold protection obtained with petroleum coke and return-stack heaters

<table>
<thead>
<tr>
<th>Heater</th>
<th>Leaf temperature (°C)</th>
<th>Air temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.5 m</td>
<td>3 m</td>
</tr>
<tr>
<td>Petroleum coke</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 2.7-kg units/tree</td>
<td>2.17</td>
<td>1.51</td>
</tr>
<tr>
<td>1 1.8-kg units/tree</td>
<td>1.67</td>
<td>1.22</td>
</tr>
<tr>
<td>8 1.8-kg units/tree</td>
<td>3.67</td>
<td>2.22</td>
</tr>
<tr>
<td>Return-stacks(^{3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>86/hectare</td>
<td>0.5</td>
<td>0.36</td>
</tr>
</tbody>
</table>

\(^{1}\) 173 trees per hectare.

\(^{2}\) Mean burning rate = 91 litres/hour.
FIGURES

Figure 1 – An orchard enclosed in an imaginary box. The heat flows and energy balance can be visualized as separable components. The arrows represent net radiant loss, $Q_m$, advective loss, $Q_k$, soil heat, $Q_s$, latent heat loss, $Q_{le}$, and heat added from heating, $Q_h$.

Figure 2 – The heat balance for a leaf can be formulated by considering the radiant flux (soil and sky) $Q_r$ and the conductive, $Q_k$, and latent heat, $Q_{le}$, transfers.
Figure 3 – Wind machines with power units in the 100 brake horse-power class. Upper left, a ground-powered single unit. The tower is 9.1 m high, the propeller 4.5 m in diameter. The down-angle is approximately 7°. The machine will protect about 4 hectares. Upper right, a double machine with power units mounted on the tower. Total power is approximately 200 horse-power. Area of protection about 6 hectares. Lower centre, machine in operation.
Figure 4 — The protection pattern from a 100 brake horse-power wind machine under calm conditions, and with 1.75 m s⁻¹ wind measured at 2 m height. Note the distortion of the pattern by the drift.
Figure 5 - The relation between the area of protection and the inversion strength (1.5 and 15 m) for a wind machine in the 100 brake horse-power class.

Figure 6 - Protein stabilized water foam used to protect strawberries. The entire plant and soil surface is covered.
Figure 7 — Stack heaters used for frost and cold protection. (1) Heater designed to burn rubber tyre debris, (2) "Braden" heater designed to burn atomized oil, (3) "Spot" heater designed to burn atomized oil, (4) return stack oil fuelled, (5) short stack oil fuelled, (6) coke heater, and (7) large cone oil fuelled.

Figure 8 — Two of the most successful oil-fuelled heaters (left, large cone; right, return-stack). These heaters can produce 20 to 30 per cent radiant heat, can be regulated from one- to four-litre/hour burning rates and produce less than 1 g of unburnt carbon per minute.
Figure 9 - A heater placement scheme for maximum efficiency of both radiant and convective heat distribution. Note the higher heat density on the edges (top and left). It is assumed that the orchard continues on the bottom and right sides, and that cold air advection is predominately from the north and west.

Figure 10 - Experimental petroleum wax heaters (above) and petroleum coke heaters (left). The first two wax heaters on the right burn completely, the other two have containers. The refills are shown to the right of the heaters. The petroleum coke heaters also burn completely and are sealed in polyethylene waterproof bags. Heat production varies from 6000 to 12000 kcal h⁻¹ for the wax heaters; that for the coke heaters is 2500 kcal h⁻¹.
Figure 11 – Generalized temperature profiles from two types of heaters. The stack oil-burning heater produces about 25,000 kcal h\(^{-1}\). The small petroleum coke heaters produce 2,500 kcal h\(^{-1}\). These profiles demonstrate the effect of fire size and the cooling aloft over the heated area which are especially noticeable with the stack heaters.

Figure 12 – A method for estimating the earliest time firing will be required. Heaters are to be lit at \(-4^\circ\). Temperatures are read hourly and plotted when \(-1^\circ\) is reached. Lines joining these hourly temperature plots intersect the \(-4^\circ\), when projected, at estimated earliest time for firing.
REFERENCES


PART II (b)

METHODS OF COLD AND FROST PROTECTION (EUROPE AND ASIA)

by A. Bagdonas
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SUMMARY

The report enumerates both direct and indirect methods employed for protecting plants from frost in Europe and Asia. The results of extensive research on the subject are analysed and the effectiveness of different methods evaluated. A bibliography is appended.

RÉSUMÉ

Ce rapport énumère les méthodes tant directes qu'indirectes utilisées en Europe et en Asie pour protéger les plantes du gel. Les résultats des importantes recherches faites à ce sujet sont analysés et l'efficacité des diverses méthodes évaluée. Le rapport comporte en appendice une bibliographie.

PEZIOME

В этом отчете перечислены прямые и косвенные методы, применяемые в Европе и Азии, для защиты растений от заморозков. Дается анализ результатов обширных научно-исследовательских работ по этому вопросу и оценка эффективности различных методов. Библиография приведена в приложении.

RESUMEN

En el presente informe se enumeran los métodos directos e indirectos utilizados en Europa y Asia para la protección de las plantas contra las heladas. Se analizan los resultados de amplios trabajos de investigación sobre este tema y la eficacia de los diferentes métodos evaluados. Se adjunta como apéndice una bibliografía.
CHAPTER 1

INTRODUCTION

This report has been prepared with the support of the scientific staff of the Hydrometeorological Service of the Lithuanian S.S.R. It has been compiled mainly from literature published since 1965, but includes a number of prior works which were not included in the well-known publication “Frost Protection in Plant Growth”* edited by Mr. Schnelle, and WMO Technical Notes Nos. 51 and 118.

This survey presents a brief classification of protection methods against frost, together with a bibliography. While this report cannot be considered an exhaustive document, the wide range of material used enables quite a thorough examination of the existing methods of frost protection and permits an assessment of their application to agricultural practices.

All units of measurement in the text are given in the same form as in the original sources.

Agriculture is different from other branches of the economy in that it is heavily dependent on factors stemming from the external environment, whose effects can be either beneficial or damaging. Frost is one of the harmful factors which cause partial or full destruction of plants, as well as a retardation or premature cessation of vegetation and crop formation. Frost is particularly dangerous for growing vegetables, flowers, vines, citrus fruit, etc. Even average-intensity frosts can cause great damage. For example, according to Radomski (Reference 755) the May frosts of 1952 caused damage amounting to more than 7 million zlotys in the region of Oleśnica (Poland) alone. The publication “International Fruit World” (1966) (Reference 629) contains references to the frost of 1965 which destroyed more than 800,000 orange trees in Hungary. According to Groenwold (Reference 658), the grape-juice harvest from vineyards in Wurtemberg (Federal Republic of Germany) showed an average decrease of 400 litres per hectare in years with frosts (1953, 1957, 1959) and Foltyn (Reference 639) estimated that the May frosts from 1936 to 1956 reduced the annual grape harvest in Unterfelder (Federal Republic of Germany) by 20 per cent. The list of damage from frost could be continued for most heat-loving crops. Thus frost protection methods are important and should be implemented.

*Fritz Schnelle, Frostscherz in Pflanzenbau, BLV Verlagsgesellschaft, Munich, Basle, Vienna.
CHAPTER 2

CLASSIFICATION OF FROST PROTECTION METHODS

All the present day methods of protecting plants from frost fall into two main groups: direct or active methods and the indirect or passive methods (References 587, 652, 669, 789, 795). However, they are also classified as preventive and protective (References 352, 655, 808); continuous (long-term) and temporary (Reference 195); group-based and single-plant (Reference 79).

The present survey uses the first group of classification, namely direct and indirect methods.

Direct methods are mainly aimed at improving the thermal régime of the surface layer of air at the ground and at decreasing the radiation from the soil and from plants; they require accurate weather forecasting. Direct methods of protecting plants from frost can be divided into three sub-groups:

(a) Methods by which radiation (cooling) from the surface of the soil or from plants can be decreased, including use of different types of cover, smoke and the creation of artificial fog clouds;

(b) Methods which can be used to raise the temperature of the surface layer of the air or of the plant by open-air heaters and infra-red radiation or by using the latent heat released in condensation (sprinkling, irrigation); and

(c) Methods of raising the temperature of the surface layer of air by mixing it with the higher and warmer layers by means of fans and other wind-generating mechanisms.

Since direct methods are costly, present-day research is chiefly aimed at finding ways of mechanizing and automating the protection techniques capable of providing maximum effectiveness for minimum outlay.

Indirect methods are mainly more preventive in nature, and may be roughly subdivided into biological and ecological techniques. The former is based on increasing plant hardness to frost by direct toughening, by selecting and developing new, more frost-resistant swift-ripening varieties and by artificially holding back plant growth, etc. The latter makes use of artificial means to alter the environment in which plants live, for example, by changing the plants' nutritional régime in respect of minerals, by properly selecting the location and soil for crops and by employing many other conventional agricultural techniques.

Methods for protecting agricultural crops from frost are dealt with as follows:

Direct methods of frost protection for plants:

1. Protective covers:
   (a) Plastic or film covers without supporting framework;
   (b) Low plastic tunnels and forcing-beds;
   (c) High plastic tunnels and hot houses;
   (d) Other forms of cover.

2. Smoke-generation and artificial fogs:
   (a) Smoke clouds;
   (b) Combustion of chemicals.
3. Open-air heating of plants and areas:
   (a) With liquid-fuel heaters;
   (b) With solid-fuel heaters;
   (c) Gas heaters.

4. Irrigation and sprinkling.

5. Mixing air.

*Indirect methods of frost protection for plants:*

1. Biological methods:
   (a) Hardening;
   (b) Treatment of seed with trace-elements and other chemicals;
   (c) Selection and grading of frost-hardy strains;
   (d) Development of new frost-hardy varieties;
   (e) Regulation of bud development.

2. Ecological methods:
   (a) Control of mineral nutrition;
   (b) Crop site selection, taking relief into account.

3. Other agricultural techniques.
CHAPTER 3

DIRECT METHODS OF PROTECTING PLANTS FROM FROST

3.1 Protective covers

Covers are used to prevent heat loss from soil and plant surfaces into the atmosphere. They do not create heat but help to regulate the daily variations in air and soil temperatures. The most commonly-used substances for this purpose are transparent paper or glass. In recent years the development of the chemical industry has led to a great increase in the use of plastics, particularly different kinds of sheeting. It has been reported (References 283, 729) that the total world area of crops grown under plastic sheeting amounts to more than one hundred and sixty thousand hectares. The largest areas are found in Japan, U.S.S.R., Federal Republic of Germany, Austria, Israel and France. Experiments conducted in different climatic conditions for a variety of crops have demonstrated that polythene sheets are more transparent than conventional glass and are particularly sensitive to ultra-violet radiation. In clear weather newly developed sheets transmit 78.5 per cent of the ultra-violet radiation, PVC, 53.6 per cent, while glass, only 29 per cent (Reference 192). During daylight hours the thermal régime under plastic cover is also better than under glass. The advantages of polythene consist in its low cost, the ease with which sections can be joined, and its ability to withstand temperatures ranging from −40 to +90°C. It is not only waterproof but easily transmits oxygen and carbon dioxide. However, plastic sheets have many shortcomings, as shown by most covers which are used to protect plants from advection and weak radiation frosts; whenever these are used during heavy radiation frosts the air temperature beneath can fall even lower than the ambient temperature, due to the intense radiation of heat through them. Polythene sheeting is particularly unfavourable since it is transparent to infra-red radiation. All coverings must therefore be warmed additionally by using matting or supplementary heat sources to protect them from radiation frosts. Moreover, polythene sheeting is broken down by the action of ultra-violet radiation and therefore does not have a long life. Plastic covers quickly get dirty, with a consequent further reduction in transparency, by the condensation which forms on the inner surfaces of the sheets. The properties of polythene and other plastics have been reported by many workers (References 125, 192, 296, 318, 529, 553, 564, 568, 591, 594, 605, 638, 648, 674, 686, 688, 704, 726, 729, 753, 784, 793, 814, 821, 822, 825, 830-832, 834). Nevertheless, the disadvantages of plastic sheeting are outweighed by the advantages, and it has recently come to be widely used in agriculture for temporary and permanent covering. A number of workers consider that polyamide sheeting is more suitable for covering vegetable crops (References 13, 79, 128, 146, 170, 314, 400, 448, 521, 657, 814). PVC is used most widely in Japan (Reference 440). Perforated sheeting is mainly used in certain other countries (References 545, 665, 785, 800).

There are many ways of using sheeting as covers: without any supporting structure, with simple supporting frames, with high supporting frames; also for forcing-beds and hot houses.

3.1.1 Plastic or film covers without supporting framework

The simplest method of using sheeting is as a direct covering for plants. Nowadays, sheet-covering machines are used to set such covers in position. Many experimenters have referred to the high cost-effectiveness of this method since not much labour is involved and since the net income from early ripening of vegetable crops is high (References 47, 65, 223, 489, 524, 525, 531, 607, 704, 799). Perforated sheeting is even better as it ensures ventilation for the plants and allows the passage of rain-water (References 545, 665, 800).
Unsupported covering is also utilized in vine-growing; plastic sheets or matting are hung on the wires used for training the vines. This method protects grapes from frosts down to -4°C, but is very costly (References 581, 677, 740, 741), and expenditure amounts to about 22-25 000 francs per hectare.

Plastics have also been successfully used to produce individual hood-covers; since wherever plants are set widely apart, covering the entire area under cultivation is not cost-effective. Hoods are usually of different shapes and dimensions (References 77, 79, 80, 269, 336, 402, 541, 614, 635, 666, 710, 758, 766, 776, 777). One author (Reference 614) has made an interesting suggestion about the use of corrugated PVC hoods, and considers them to be more cost-effective than tunnel coverings or hothouses because they do not require much labour. The overall cost for protecting plants amounts to 150 000 lire (240 dollars) per hectare; in addition the crop can ripen from 20 to 25 days earlier. Vineyards in Italy are also protected by polythene "sleeves" which are mounted on the dry vertically bound vine stems. These will protect from frosts down to -2 or -3°C (Reference 565).

In fruit-growing, small-mesh polythene nets are used for the same purpose. They are stretched on frames and mounted on posts of different heights (References 487, 624, 648). Polythene sheeting is also employed for soil mulching which improves the root development and the growth and general development of plants, therefore increasing their resistance to frost. Black polythene sheeting gives the most effective results (References 37, 77, 78, 153, 172, 181, 203, 217, 263, 271, 272, 316, 323, 333, 373, 388, 400, 422, 432, 463, 540, 552-554, 562, 626, 635, 644, 677, 650, 663, 667, 678, 680, 683, 687, 694, 708, 709, 722, 742, 745, 768, 779, 828).

3.1.2 Low plastic tunnels and forcing-beds

Research in many different countries has proved the tunnel shape to be the best form for temporary covering (References 14, 36, 70, 77, 79, 83, 91, 125, 154, 187, 201, 202, 222, 223, 250, 251, 293, 297-300, 318, 367, 371, 440, 443, 491, 499, 524, 534, 551, 573, 583, 584, 597, 601, 611, 615, 628, 664, 675, 676, 688, 696, 701, 703, 705, 706, 711, 725, 736, 747, 760, 766, 771, 778, 806, 811, 832, 833). The primary advantage of the tunnel-type of covering is that its shape reduces the wind resistance per unit area, and therefore increases its stability and resistance to wind. Moreover, temperature conditions are improved, since its shape hampers air stagnation and cooling: the air flows down the walls. Another great advantage of its shape stems from the lower requirements for labour and materials during installation which has recently been mechanized (Figure 1) (Reference 778).

Tunnels can have different lengths, but for the best use (convenience of operation and optimum ventilation) should not be longer than 25-50 m. Depending on the size of the crop to be protected, the length of time that the tunnel is to be used and the width of the plastic sheeting, the tunnel-widths usually vary from 0.6 to 1.5 m and heights from 0.2 to 1 m. The bow-shaped supporting structures for the tunnels are made of wire, plastic and aluminium tubing, etc. The plastic is stretched across the top, one of its edges is covered by soil and the other is left open for ventilation (Figure 2). Perforated plastic sheeting is now used to improve ventilation (References 37, 146, 293, 681, 785, 800). It is still more profitable to make movable covers for growing a variety of crops (References 318, 617, 706). According to some authors (References 155, 222) tunnel covers are between 51 and 96 per cent more economical than growing crops in the open, and the cost of making them is 5-7 times cheaper than for glass forcing-beds. Additional heating is required to protect plants from heavy frosts. In Japan it has been established (Reference 194) that the highest minimum temperatures were to be found under PVC tunnels covered with matting (Figure 3) which is produced from straw, rushes, reeds and cane, canvas, paper, bast, sacking and other locally-produced materials (References 31, 79, 177, 261, 267, 400, 432, 463, 510, 636, 655, 677, 713). Mat-weaving machinery has been designed to speed up manufacture. Glass forcing-beds or heated planting beds are also covered with matting (Figure 9).

Forcing-beds of various designs (flat or pitched, movable or permanent) for covering early vegetable crops, can produce the temperatures which they need much earlier than those which occur in natural conditions, and can
also protect the crops during freezes (References 11, 69, 79, 107, 108, 206, 207, 218, 327, 346, 428, 461, 462, 471, 479, 480, 490, 506, 529, 530, 632). But because of the advantages mentioned above, glass in the forcing-bed frames has recently begun to be replaced by plastics. Expenditure on laying out and operating such forcing-beds is much lower, and the quality of vegetables and heat-loving crops is much higher than under glass (References 47, 62, 79, 117, 132, 151, 263, 346, 399, 401, 411, 448, 530, 711). Forcing-beds are normally heated by biological fuels or by technical appliances.

3.1.3 High plastic tunnels and hot-houses.

Great difficulties are encountered in providing ventilation to grow vegetables under low tunnels, since cultivation of the crops cannot be mechanized. This has led in recent years to a great expansion in the building of high plastic tunnels and hot-houses. These tunnels are usually 4-5 m wide and 1.5-2 m high, and have the advantage that they possess better temperature conditions for plant growth and development. Pressure in the plastic sets up an air space which prevents the cold air outside and the warm air inside from mixing too quickly. A temperature difference of 2-3°C is established, reducing expenditure on heating by 20-25 per cent (Reference 830). High tunnels can also be equipped with ventilators and all the cultivating operations can be mechanized. Provided the plastic sheeting is of good quality and the support structure is well designed, they can be used for up to three years: this has led to their increasing in many countries (References 73, 79, 293, 386, 387, 389, 399, 425, 480, 488, 508, 561, 564, 567, 572, 602, 626-628, 641, 654, 682, 688, 69, 704, 707, 708, 711, 730, 750, 756, 757, 797, 800, 815-818, 820, 830). Spring hot-houses are usually heated by sunlight and biological fuel. The economic effectiveness of this type of hot-house can be considerably increased by heating the air or soil, which enables them to be used all the year round. They are normally heated in the same way as glass hot-houses (References 263, 319, 495, 584, 778) i.e. by steam, hot water, warm air or electricity. The most common method in many areas of the U.S.S.R. is by means of hot water passed through asbestos-cement pipes (References 8, 124, 280, 328, 329, 416) or by steam (References 18, 71, 175, 243-245, 248, 249, 262, 326, 328).

Electricity has recently been used for this purpose (References 71, 185, 380, 392, 493, 494, 502, 532, 538, 617), by passing current through a heating coil or special cables set in asbestos-cement, ceramic pipes or hotplates. Other methods have been used, since current at the voltage necessary to heat the forcing-beds and hot-houses (particularly those under plastic sheeting) is not always available. The most widespread method is to heat the air and to pass it through perforated pipes to warm the air or soil (References 270, 283, 407, 480, 491, 521, 557, 631, 688, 819). One heating system worthy of note is the contact-gas system (Reference 344), where the source consists of two combined heating and ventilation units. These give complete combustion of gas and deliver a mixture of combustion products and fresh air to the cultivation site.

Different artificial materials, which are not only good light transmitters and heat insulators but are also wind and corrosion-resistant and not subject to any other action by the environment, are used in addition to plastics in making different kinds of cover for conservatories and hot-houses. Rigid polyester, PVC and other synthetic materials (Figure 4) are also utilized (References 279, 379, 387, 415, 586, 704, 767, 784, 829, 838). Covers of this kind, as well as glass hot-houses, are usually industrially produced (References 457, 826, 827).

3.1.4 Other forms

Other forms of covering, using different materials besides plastics, are employed, to protect plants from frost in various countries. For example, in subtropical areas of the U.S.S.R., grapes are protected by building lean-to shelters roofed with three-ply gauze, sacking, straw, sedge or other materials. During heavy frosts the shelters are heated (References 10, 150, 190, 205, 320, 377, 391, 398, 464). The trench-method of grape-growing is used in many areas of the U.S.S.R.; at night the trenches are covered with glass frames or matting (References 10, 12, 39, 103, 264, 406). Because earth is a poor conductor of heat, temporary earth covering is sometimes used to protect plants. Even an extremely thin layer of earth, 2-3 cm deep, is sufficient for protection down to -4, -5°C. This
can preserve the shoots of potatoes, other wide-row crops as well as grape-vines. Special combine machinery (References 53, 64, 75, 77, 79, 221, 291, 305, 455) can be used for all work needed to cover plants by this method.

Foam covering has recently been tried out to protect plants. Stable foams are poor heat conductors and also act as a protective layer; some foams are made from PO-6 and "Volna" powders (Reference 142); three per cent concentrate of hydrolyzed albumen in water containing one per cent gelatine (Reference 558); and protein. The latter is the most stable and long-lasting (References 625, 762). The difference between the temperature beneath the protein foam and that above it can reach 12°C, but the foam is very costly to produce in terms of money and manpower.

If the different methods of covering are compared with respect to their thermal efficiencies, plastic high tunnels are best, since they create the best micro-climates. The air under plastic sheeting is more strongly heated by radiation than in the open. Some of the heat surplus persists during the night and air temperatures under this kind of covering can therefore be 2-3°C higher than over unprotected ground, even without heating. High tunnels are stable and provide good protection against cold winds and advection frosts, particularly if constructed with a double sheet of plastic. The small droplets of condensation forming on the inner walls of these tunnels further increase their thermal insulation at night, even though such condensation can hamper the transmission of light during the day. These tunnels allow for ventilation and mechanization of all cultivation work. High tunnels can be even more effective by being equipped with heating systems for use throughout the entire year to grow any kind of vegetable. Even where heating systems are installed, it costs much less to build tunnels of this kind than glass hot-houses or forcing-beds, since their frames can be industrially manufactured.

Low movable tunnels are the most cost-effective in growing early vegetables which are not so demanding in warmth. The key to this lies in transferring the plastic covering from vegetables that do not require so much heat to the more heat-loving varieties. For example, in early spring they can be used for growing lettuce, kohlrabi, and radishes; then the covering can be transferred to tomato, pumpkin or cucumber seedlings; after the early vegetables have been picked, pepper seedlings can be grown. Cultivation methods of this kind yield a greater return than cultivation under glass covering.

3.2 Smoke-generation and artificial fog

The night-time temperature reduction occurring in the surface layer of air when clouds are absent and winds light is normally accompanied by high radiation efficiency at the ground. The chief heat losses through radiation occur in the 8-12 μm radiation band. The thermal radiation from the ground is highest in this part of the spectrum where the atmosphere is almost completely transparent (References 46, 47, 256, 257). Methods of frost-fighting that can reduce nocturnal radiation are therefore of particular importance.

Smoke- and fog-generation methods which are designed to counteract the nocturnal radiation by means of an aerosol screen are widely used in many countries. Such a screen, whose thickness depends on the smoke material, reflects part of the radiation back to the surface of the soil, while absorbing the remainder. Moreover, heat (whose amount depends on the calorie content of the combustion material) is released by combustion as well as by condensation of steam (References 49, 77, 79, 277, 451, 488, 748, 808). Another factor of particular importance occurs when frosts cease in the early morning hours; the smoke cloud then acts as a screen, hindering light rays from reaching the plant directly. Under cover of the smoke the plants gradually come back to life, i.e., undergo a defrosting process (References 49, 628). However, it should be noted that there are great differences between the requirements for smoke-screens designed for frost-fighting at night and those for masking in the morning. The former must have a maximum thermal effect — their greatest absorptive capacity in the spectral region beginning at about 10 μm. For masking purposes, absorption in the visible part of the spectrum is mainly important. An increase in the attenuation coefficient is accompanied by a reduction in effective radiation, but depends on the size of
aerosol particles. For maximum attenuation the optimum particle-size is nearly equal to the wavelength (References 46, 47, 49, 257, 451, 488, 748, 808).

3.2.1 Waste heaps

Smoke can be produced from unused remnants of produce and waste matter. The principle is described in many articles (References 49, 85, 115, 129, 220, 256, 296, 338, 487, 500, 510, 644, 659, 775). Experience has shown that the desired results can be best achieved when the combustion material creates a stable heavy smoke close to the soil in a continuous and constantly maintained layer over the entire area requiring protection. In orchards it is essential for smoke to cover trees completely (Reference 628). In recent years, cheaper substances (waste from the timber industry, coal and oil products, oil and grease wastes, petroleum residues, turf, tern of different kinds) have come into use (References 49, 487). Mixtures of sal-ammoniac and lime (Reference 628) or tar and naphthalene (Reference 256) can be added to the heaps.

The thermal effect of these heaps is low while the consumption of material is high. Some authors (References 256, 500) have even reported that this method yields an increase of only 1-2°C in air temperature. To obtain this increase over an area of one hectare in calm weather (wind speed of less than 1 m s⁻¹) experiments have shown that more than a ton of damp fuel must be used per hour, distributed over 60 to 150 waste heaps (References 49, 84, 85, 115, 129, 336, 628). Depending on the heat content of the material, the duration of the frost, and the sensitivity of the plants, the total outlay of fuel must amount to 15-20 metric-tons per hectare (References 49, 219, 257). It is therefore more effective to generate smoke during the evening, when a considerably lower fuel outlay can cause a significant decrease in the strain induced by solar radiation in plants which are gradually thawing (Reference 47).

3.2.2 Combustion of chemicals

Chemical substances — zinc, phosphorus, sulphate compounds, ammonium chloride, smoke powder and the like — are nowadays used to produce smoke screens and fogs. It is usual to employ substances releasing aerosols by means of chemical reactions or combustion. The prime requirement for these kinds of fog and smoke is that they be harmless to crops and human beings. Smaller quantities of chemical substances are needed to produce chemical smoke screens than combustion clouds, while their protective effect is almost identical to that obtained through the traditional methods. The thermal increase from NH₄Cl amounts to 2.3°C and occurs with light winds and high atmospheric humidity (Reference 256). Phosphorus fog reduces the effective ground radiation by 40-60 per cent and raises air temperatures up to 2.4°C (References 467, 500). Red phosphorus is the best of the known smoke-makers (Reference 49); it is not toxic but is relatively safe to use. On combustion, it forms phosphorus pentoxide which actively combines with water or steam. Other materials reported as being harmless to plants include ammonium chloride (NH₄Cl), naphthalene, ammonium sulphate (NH₄)₂SO₄ and certain mineral oils (References 115, 332, 486, 773, 808). Some are less effective, for example, silicon tetrachloride (SiCl₄) and titanium tetrachloride (TiCl₄) contain significant amounts of chlorine, and plants can be damaged if they are used for very long. White phosphorus forms unstable smoke clouds and burns easily on coming into contact with air, thus presenting a fire hazard. Oil clouds are also not very effective, since the aerosols quickly settle on plants and the soil surface; because they form unbroken toxic films, they are harmful to plants (References 50, 628). Experiments at volatilizing ammonium chloride to form smoke-screens resulted in a reduction of effective radiation by only 14-28 per cent (Reference 403).

Specially designed fog-generating systems have been developed to ease and speed up the production of smoke-screens and artificial fog (References 49, 268, 569, 628, 774, 808). The equipment is largely transportable or mobile. A single appliance can protect plants over areas of up to 600 ha. One device worthy of note produces a heavy white smoke (ammonium sulphate) formed immediately through a reaction of sulphur dioxide and ammonia (References 49, 576, 628, 808). By continuous refuelling its production can be regulated and the fog can be made to
last for whatever period is required. The equipment has a high output: one unit is sufficient for an area of some 400 ha.

The smoke-pot (References 48, 79, 84, 85, 196, 341, 354, 628) is another device for making smoke-screens, using such substances as ammonium chloride, coal tar and amphathene, with potassium nitrate (KNO₃) or potassium chlorate (KClO₃) as oxidizers. These burn to form a thick layer of black or white smoke whose stability largely depends on the wind speed. In calm weather the screen lasts 15-20 min and the thermal effect of burning 100 pots ha⁻¹ h⁻¹ amounts to 2-2.5°C. If smoke piles are used in combination with smoke-pots (Reference 628), the smoke-screen can be made to last up to 3-4 hours, with about the same thermal effect. The manpower requirement in using smoke-pots to protect plants throughout the freezing period is 1.5-3 persons per hectare.

Another composite method of smoke-making is practised by open-air burning of oil in ditches. A thin layer of turf or cool dust is sprinkled onto the oil (References 38, 330). It is evident from the foregoing that smoke-generation is not very effective as a means of frost protection (see Table 1).

Table 1 shows that the greatest thermal effect of the different methods only occurs in weak radiation frosts, and varies from 2 to 3°C. With a wind speed of 1 m s⁻¹, a smoke-screen will move 60 m in a minute (Reference 419). Therefore, the only solution for greater wind speeds is to organize continuous smoke production, but this is very expensive, requiring a great outlay of material and manpower. Moreover, it is difficult to use smoke screens in hilly country. Finally, now that atmospheric pollution is a world-wide problem most of the smoke-generating techniques referred to cannot be used for protecting plants against frost in densely populated areas or countries.

3.3 Open-air heating of plants and areas

The open-air heating of orchards, plantations and groves is based on the use of fuel-burning heat sources to raise the temperatures of plants and the air surrounding them. The heat sources are normally different kinds of heaters and stoves. The effectiveness of the heating method, as well as the efficiency of heaters, is in direct proportion to the height of the inversion layer and its temperature profile (References 45, 49, 414, 644, 649, 669, 748). Even a comparatively weak breeze is sufficient to break up the inversion layer, thereby reducing heater efficiency, in which case direct radiational heating of the plant acquires prime importance. Research has shown that the leaves of plants affected by radiation have a higher temperature than that of the surrounding air. They thereby become heat sources themselves and form convection currents (Reference 245).

A great variety of heater and stove systems are in use in different countries; but they are of two basic types: (a) firepots and stoves for open-air burning; and (b) heating and heat transfer by means of thermal conductivity (Reference 649). Heaters may also be subdivided by the type of fuel used—liquid, solid. Economic considerations result in different types of fuel being used in various countries.

3.3.1 Heaters with liquid fuel

As shown in Table 2, fuels do not release the same amount of heat (Reference 79). Those of oils, petroleum wastes, and coal have the greatest heat content. This is the explanation for the popularity of liquid fuel heaters, particularly in the U.S.S.R., the Federal Republic of Germany, and France. The most widespread type are the so called “California” heaters, but in the U.S.S.R. the Nikiforov type is used; in the Federal Republic of Germany, the “Stahl” and “Schrotte”, while in France, the common open-air-flame heaters, the “Garonne”, “Seppie”, “Breetag”. Heaters used in the U.S.A. and New Zealand are shown in Figures 5 and 6.

Heaters using liquid fuels normally consist of a fuel tank with a capacity of 10-201 with or without chimneys, along with a flame- or heat-and-fuel consumption regulator. Heaters with chimneys are preferred, since they consume
less fuel, produce less smoke, have the best heating effect and as reported by Bouchet (Reference 598), have the highest thermal efficiency for useful activity. In selecting heaters, attention must be paid to their output. Tabard (Reference 598) reported that their highest output tends to be towards the end of the night, after operating for several hours (See Table 3).

Since it is expensive to operate oil heaters (e.g. the Nikiforov type), the fuel used in most countries is petroleum residue. A large number of experiments have shown that, depending on the microclimatic features of the area to be heated, the heaviness of the frost and the type of crop to be protected, the maximum heating effect produced by different kinds of heater is about 3°C for 100-250 heaters per hectare (References 559, 576, 598, 617, 643, 658, 684, 692, 717, 733, 748, 789, 790, 792, 795, 808). A heating effect of up to 5°C can only be obtained by means of Nikiforov-type oil heaters provided that the number per hectare is as high as 400-500 (References 35, 56, 49, 84, 200). Different kinds of heaters consume differing amounts of fuel. Practical experiments have shown that from 200 to 600 kg ha⁻¹ h⁻¹ of petroleum waste are required depending on the severity of the frost, the location of the orchard and the heater output. The Nikiforov heaters consume up to 700-800 kg ha⁻¹ h⁻¹. Savings in fuel can be made by increasing the number of small heaters, but this requires increased manpower thereby adding to the total cost.

Plantation heating costs are very high; in France (depending on the region) expenditure amounts to 4-10000 francs or more per hectare (References 643, 790, 792), while in the Federal Republic of Germany, about 7-8 000 DM (References 639, 643, 769). Since this kind of heating also requires the use of large amounts of manpower, some countries have permanent central equipment which feeds liquid fuel from a central tank (Figure 7) to the heaters through underground piping systems (References 647, 649, 669, 748, 790, 808). The annual cost of operating a complete heating system amounts to some 13 000 francs per hectare (Reference 647). Despite its high cost, this system is efficient because it can be easily started and its other operations are automated.

### 3.3.2 Solid-fuel heaters

Solid fuel in the shape of briquettes which may be burned with or without special heaters are used alongside liquid fuel for open-air heating in many countries. The briquettes are manufactured from coal, semi-coke, turf, oil-waste mixtures and the like (References 79, 294, 326, 579, 769, 782). Special briquettes weighing 1-2 kg are widely used in the Federal Republic of Germany (References 464, 577, 579, 580, 639, 658, 781). Depending on the severity of the frost, 700-900 briquettes (costing 1-1.2 DM each) per night will be required to heat one hectare. A different kind, capable of burning for up to 6-8 hours, is used in Japan (Reference 689). Konakahara et al. consider that these briquettes are much more efficient even than gas heaters, but nevertheless much more manpower is required to set them out in the orchards.

The paraffin "candle" has come into use during the last decade. The heater consists of a container, lid and wick filled with solid paraffin. Candles come in a variety of sizes weighing about 6 kg capable of burning 8-10 hours; they are easily lit and transported, and are weather-resistant (Figure 8). The candles are mainly used to protect citrus plants and vines and are placed beneath the trees (References 49, 580, 589, 629, 639, 718, 748, 763, 781, 789, 791, 808). Heat disperses in all directions, forming a kind of protective cone around a tree. In the opinion of some workers (References 629, 748), four such candles located beneath a single tree can protect it from a frost as severe as -8°C or -9°C. Others (References 763, 789, 791) claim that 350 candles per hectare are needed to raise the air temperature by 1-2°C, 450, by 2-3°C; and 550 by 3-4°C. Depending on the frost severity and the location of the site, 400-600 paraffin candles per hectare are required. Heating expenses vary considerably in each country because of the cost of paraffin. According to most of the literature referenced, heating by candles is a very costly procedure, in spite of its operational advantages, compared with heating by liquid fuel. It is therefore recommended only for use to protect the most valuable crops against frost. An exception occurs for the U.S.S.R. where heating by paraffin candles costs only half as much as heating by oil because paraffin is so inexpensive (Reference 49).
3.3.3 Gas heaters

Combustion of liquid or solid fuel releases a great deal of smoke and soot, creating an atmospheric pollution problem. Therefore, experimental workers in many countries have started to use gas for heating (References 49, 66, 271, 390, 395, 559, 578, 581, 588, 589, 608, 616, 624, 673, 717, 763, 789, 792, 808, 833). Experiments have demonstrated that this method has other advantages besides the insignificant atmospheric pollution it produces: the combustion products are harmless to plants, and the method requires minimum manpower since it can be fully automated. Liquid propane is commonly used for heating. Tabord (References 789, 792) has reported detailed test results. Usually the equipment consists of a fuel storage tank, and twelve outlet points which are attached to the heaters. Each outlet point has a pressure regulator and consumption is regulated at a central point. By heating the liquid propane, the gas is formed which is conveyed under pressure to the heaters. From 1000 to 1200 heaters are required per hectare; 200 kg ha\(^{-1}\)h\(^{-1}\) of gas must be used to raise the temperature of the environment by 2°C. More heaters per unit area must be added to raise the temperature to 3°C or higher. Including expenditures on materials and repair work, the overall cost amounts to 8 500-9 000 francs per hour. Expenditure on fuel is almost identical to that for other techniques. The system is considered valid for crops having a high monetary return. As an example, the cost of this system in Italy amounts to 1.2 million lire ha\(^{-1}\)h\(^{-1}\) (References 616, 808).

Gas can be used to warm plants as well as to heat the surface air layer by means of the long-wave radiation from the heater. Gas is normally passed from the central container through plastic pipes set up between the branches along rows of trees. Such a system can raise the temperature of plants 5-6°C higher than the ambient air (References 578, 581). In the U.S.S.R., infra-red radiation heaters are used for this purpose (References 49, 66, 271, 390, 395), while in France infra-red grids (References 559, 789, 792) are suspended over the vegetation. Although the cost of the latter techniques is great, it is not higher than that of classical equipment.

A method of warm-air heating using fans or propellers merits more attention (References 578, 639, 647, 788, 792). The fan or propeller is attached to the fuel tank where the air is heated by combustion, and then is directed by means of the propeller or fan towards the area to be protected. About 20 l h\(^{-1}\) of fuel is consumed. The usefulness of this method is limited because of the high equipment cost, but is very effective, heating the air by 8°C or more. In the U.S.S.R. and in the Federal Republic of Germany, electric stoves are also used for heating plants but their high cost makes them unsuitable for wide use.

In the U.S.S.R. and some other countries the ground is also heated by means of warm water (References 49, 243, 245, 249, 481, 759, 809) and steam (References 143, 175, 528, 628, 758, 813), from the excess heat produced at industrial installations. The heated soil produces large amounts of evaporated moisture, maintaining high humidity in the surface air layer. During radiation frosts, this method of heating can counteract temperature falls of 5-6°C without any covering, as compared to unheated areas. Smoke or fog-generation is sometimes used in conjunction with heating (References 49, 277, 419), but has not shown any significant increase in air temperature.

To sum up, although the cost of different heating methods can be considerable, nevertheless proper selection of heating equipment and fuel, combined with careful planning and layout, can produce quite reliable and cost-effective heating to protect valuable crops from radiation frost, down to -4°C. The damage done by frost is sometimes much greater than the expenditure on equipment (References 639, 658). To prevent atmospheric pollution, preference must be given to heating methods using warm air, gas or electricity. But these are not universally available and are still in the trial stage, so that it would be inadvisable as yet to recommend them for general use.

3.4 Irrigation and sprinkling

The amount and distribution of water vapour in the atmosphere is particularly important in the nocturnal radiation process. A reduction in the amount of vapour increases the effective radiation, making it easy for frost to form and increasing its severity. For this reason irrigation has been used since ancient times as a means of fighting
weak radiation frosts—a technique based on the high heat capacity of wet soil and changes in its thermal conductivity. The soil's thermal conductivity increases with dampness so that when the soil is warmed during the day, heat travels more quickly to lower layers. On the other hand, at night the movement of heat from moisture and deeper layers increases. It has been demonstrated that the temperature at the surface of moist soil is 1.6-2.6°C lower in daytime and 0.9-1.3°C higher at night than at the surface of dry soil (References 77, 79). Moreover, the dew-point temperature of a watered site rises because of the increase in humidity, and latent heat is given off when the water vapour condenses. The net effect is to delay frost occurrence on an irrigated site. Warm sunny days before a frost guarantee that preventive watering would be worthwhile, but the method only protects plants against weak radiation frosts, not lower than –3°C (References 5, 31, 49, 77, 79, 85, 115, 254, 296, 359, 543, 594, 619, 764). Many of the above-mentioned studies state that it is essential to irrigate 2-3 days before a frost in order to accumulate heat in the soil. If this is done the day before a frost, heat is lost through increased evaporation and frost damage can even increase as a result of evaporative super-cooling. Hence, accurate weather forecasting is essential, if irrigation is to be successful.

Irrigation is normally used to protect low-standing plants and crops from frost: early potatoes, peas, tomatoes, flowers (References 5, 49, 57, 79, 115, 129, 296, 482, 588, 619, 764). Good results were obtained in the Central Asian Republics of the U.S.S.R. to protect cotton against autumn frosts, for example, at a watering rate of 1000 m³ ha⁻¹ produced a rise in air temperature of 2.3°C (References 32, 49, 115, 528). In Japan, deep-water irrigation is practised on rice paddies, where the unripe ears of rice lie completely under water at 19-20°C.

Sprinkling has become widespread as the most effective method of protecting plants and crops (vegetables, potatoes, berries, citrus fruits and flowers) against frost. This has been confirmed for frosts of varying intensity by many research workers and farmers in Belgium (Reference 765), Bulgaria (References 5, 96, 100, 254, 354, 404, 487), Federal Republic of Germany (References 580, 641, 653, 659, 662, 724, 770, 836), France (References 619, 647, 752, 763, 788-790), Italy (Reference 808), Japan (Reference 195), New Zealand (Reference 669), Norway (Reference 764), Poland (Reference 606), Romania (Reference 628), Switzerland (Reference 377), United Kingdom (References 588, 589, 596, 612, 702, 712, 721, 734, 807), U.S.S.R. (References 29, 49, 56, 77, 79, 87, 129, 163, 164, 208, 245, 360, 497, 510, 514, 533).

Like irrigation, sprinkling relies on the latent heat released as water freezes. Experiments have shown that air temperatures on sites where sprinkling was carried out were 4°C higher than on control plots (Reference 49). Chicasov (Reference 498) reported that this difference may reach 0.7-5.6°C with above-zero temperatures, and 2.6°C with below-zero temperatures. As the air temperature drops below 0°C, the sprinkler water freezes as it falls on the plants which gradually become covered with a solid sheath of ice; many investigators claim that the temperature beneath this sheath remains in the +0.5 to –1.0°C range (References 5, 29, 52, 164, 195, 254, 487, 497, 595, 606, 628, 659, 752, 764, 765, 808), since latent heat is released to the plant as the water freezes (80 cal g⁻¹). It has been demonstrated (Reference 628) that heat absorbed by the plant helps to maintain temperature beneath the ice-sheath 2-4°C higher than the ambient temperature. The continuously-forming ice acts as an insulation layer protecting the plant against cooling. Uninterrupted sprinkling and ice-formation also help such temperatures to be maintained under the ice covering throughout the sprinkling period. Most vegetables incur no damage beneath the ice-sheath at temperatures down to –1°C (Reference 594), since their freezing threshold lies at about –2°C. The threshold depends on the type of plant and its vegetation, for example it was noted (Reference 164), that the freezing threshold is –5.8°C during the green bud phase, –4.2°C during the pink bud phase, –3.8°C during the blossoming period, –2.7°C during germination, and –2°C when there is green fruit.

A key factor for successful sprinkling to protect most agricultural crops from frosts is continuous ice formation, i.e., by uninterrupted sprinkling. If sprinkling ceases, there is a risk of considerable plant damage since the temperature beneath the ice would fall quickly. Sprinkling effectiveness also depends on how the sprinklers are used—they must rotate at a steady speed and must produce fine droplets of spray. Different designs of sprinklers are used: modern equipment for protecting plants against frost must meet a range of specifications. The system must be capable of uninterrupted sprinkling throughout a frost (References 5, 29, 49, 254, 295, 497, 498, 589, 594, 613, 653, 716, 721, 788-790, 807). The sprinkling rate must be high enough for reliable protection. A conflict of opinion
exists in the literature – some authors (References 5, 254, 613) consider a sprinkling rate of no less than 2 mm h⁻¹ essential, while others (References 606, 628) consider a rate of 1.5 mm h⁻¹ adequate for protecting trees, and 2.5-3 mm h⁻¹ for low-growing plants and crops.

Číčasov (Reference 498) considers that the sprinkling rate, which depends on the rotation rate of the nozzle, should correspond to the severity of the frost. To protect low-growing crops at a wind speed of 0.5 m s⁻¹, various sprinkling rates are required (see Table 4).

The relationship of sprinkling rate to wind speed has also been reported (Reference 724). A sprinkling rate of 2.7 mm h⁻¹ enables plants to withstand frosts down to -3, -5 and -7°C if the wind speed does not exceed 1, 0.5 and 0.4 m s⁻¹ respectively. Goedeche (Reference 653) and Veronesi (Reference 808) consider that a mean sprinkling rate of 2.8-3.5 mm h⁻¹ ensures protection against frosts down to -6°C but, according to other experiments (References 195, 487, 497, 716, 764, 765, 788, 790), reliable protection against frost requires a sprinkling rate of 3-5 mm h⁻¹, depending on frost severity and the kind of crop. Thus the sprinkler system must have a rate of about 2.5 mm h⁻¹, depending on wind speed, degree of frost and type of crop to be protected.

The system must be able to produce a spray with a fine droplet structure and an even spread. Many modern designs (Figure 11) meet the above criteria. The so-called “slow sprinkling” type, i.e. with spraying by means of a fine jet, have recently been introduced for this purpose: its sprinkling rate of 0.08 mm min⁻¹ neither breaks down the soil aggregates nor harms the plants. Sprinkling equipment (MOIDC-0.5 and JDP-30 C models), with such a rate, has been successfully used in Soviet orchards and citrus groves (References 208, 295, 360).

A mobile system employing plastic hosing instead of metal pipes has been designed in the Federal Republic of Germany (References 548, 575). On the chassis frame are mounted three drums, reels and a reduction gearbox. Two drums are set on either side of the chassis frame while a third is fixed at the front; 1.9 and 2.5-cm plastic hoses are wound around the side drums while a 7.6-cm hose is coiled around the front one. Each individual drum is wound via the reduction gearbox. In moving the mobile chassis over the ground, first of all the 7.6-cm hose is unwound and serves as the main pipe. Then the smaller hoses are unwound and are linked into the junctions set along it. Sprinklers are mounted on the ends of the hoses. The system is served by one person. The author considers that this system considerably reduces the labour required for dismantling, moving, and assembling equipment and shortens the watering time, and ensures even sprinkling. After eight years of operation, the plastic hosing was still capable of further use.

Other mobile sprinkling equipment is used including the “Rollehle Beschneigung” manufactured by the “Perro” Company (Federal Republic of Germany), the “Juterborg” (German Democratic Republic). On these the water pipe also acts as the axle on which the wheels are mounted. Fitted with medium-flow sprinkler jet equipment, the system operates from a fixed position and moves by means of a small petrol engine (Reference 424). Many firms produce a range of metal and plastic sprinkler apparatus, carrying out radial and area watering (driven by the reactive power of the water jet); some have pipes, propeller systems, or rocker arms rotating vertically and horizontally; some have hydraulic vacuum drive systems; others are of the “cannon” type, mounted on the fixed water hydrants and pipes of movable sprinkler systems and equipment. In many countries, sprinkler systems have been developed using automatic devices responsive to wind strength and air temperature. An Austrian system has closed pipes used for pre-frost watering of orchards, gardens and vineyards, which may be as large as 1000 hectares; there are 18 sprinkler sets per hectare for slow sprinkling (0.03 mm min⁻¹). In Bulgaria medium-intensity sprinkler systems include the Di-600, Marica 40, Marica 45, as well as mobile equipment with a 1-2 min nozzle rotation rate (Reference 497). Rutter (Reference 404) describes a sprinkler method developed in France using perforated unmovable piping, fixed in position above the soil along the furrows.

Different workers disagree about the times for switching the sprinkler system on and off. Some consider that sprinkling must be begun while temperatures are still above zero and stopped when the air temperature is steadily maintained above 0°C under conditions of high air humidity (References 5, 254, 295, 354, 497, 498, 643, 724, 807). Others consider that to conserve water, the system can and must only be switched on at lower, sub-zero
temperatures, depending on the freezing threshold for different types of plants; for example, a few workers (References 195, 721, 789, 808) claim that it is advisable to switch on sprinkling equipment at an air temperature of \(-1.7^\circ C\), since the critical temperature for most fruit-bearing plants is \(-2^\circ C\). However, this question requires further study, as a delay in switching the equipment either on or off can cause great frost damage in the crops.

Water supply is a major problem which becomes particularly acute where there are no natural sources. In such places tanks must be located having sufficient water for three consecutive nights of sprinkling. Calculations (References 254, 613) indicate that 550 m\(^3\) of water is required for three nights each with nine hours of sprinkling, at 2 mm h\(^{-1}\); 250-300 m\(^3\) ha\(^{-1}\) of water are used at 3-5 mm h\(^{-1}\) (Reference 716), the amount needed is 30-35 m\(^3\) ha\(^{-1}\) h\(^{-1}\) at a rate of 3-3.5 mm h\(^{-1}\) (Reference 808). Additional money is required to provide a tank holding such a large amount of water, for example a water tank holding 6.5 million gallons has been estimated to cost 360 pounds sterling (Reference 589).

Hewett (Reference 669) compares sprinkling costs using a tank and natural water supplies. It is therefore necessary to determine the minimum amount of water needed to protect plants against frost. To save water it has been recommended (References 721, 789) that the number of waterings be limited and the duration of sprinkling be curtailed, with the equipment being switched on when the air temperature falls to about \(-2^\circ C\). The limitation on the number of irrigations is made during the early phases of fruit-plant development, when the freezing threshold is quite low.

Large capital investments are required to install fixed or mobile sprinkling systems and they also entail high operational costs. Also, particularly where soils are heavy, drainage systems must be laid out. Despite all these high costs involved most workers consider that sprinkling is the most effective method for protecting plants against frost, and recommend using it for large areas and valuable crops. Avramov and Kreovski (Reference 5) have demonstrated that a fixed sprinkling system pays for itself completely if once used successfully to protect crops. Over a period of 30 to 50 years it would pay for itself several times over. Hewett (Reference 669) shows that frost-fighting with sprinkler systems is economically much more worthwhile than those with open-air heating by means of firepots (Figure 12).

A number of authors (References 337, 593, 671, 672) describe a sprinkling system where frost protection is provided by sprinkling glass or polythene covers with water rather than the plants themselves. The water on the protective covers freezes and the latent heat released protects the plants from any dangerous lowering of the air temperature.

Many of the workers pointed to the following advantages of sprinkler systems to protect plants against frost: \(a\) sprinkling can be used during both advection and radiation frosts; \(b\) with present technology, sprinkling systems can be fully automated, thereby releasing a great deal of manpower; \(c\) the degree of protection provided is very high, and can be guaranteed even against frosts as severe as \(-6\) or \(-8^\circ C\); \(d\) the cost of setting up sprinkling equipment can be reduced by using it for summer-time watering; moreover, by fitting different accessories equipment can be used to combat plant pests and diseases, by spraying with insecticides and fungicides, weed killers, fertilizer solutions, etc.

Like every method of frost-fighting, sprinkling has its shortcomings. Uninterrupted sprinkling of plants can produce an ice layer which can cause branches and young trees to break (Reference 628, 669, 765, 808). A breakdown in the sprinkling system, causing an interruption of even 10 to 15 minutes, is enough for the year's yield to be lost through destruction of the plants by frost. Excessive moistening of the soil in spring-time can lead to overcooling which stunts the growth and development of warmth-loving farm crops (References 29, 653, 669). Uninterrupted sprinkling, particularly in hilly country, can lead to the erosion and washing away of soil (References 594, 653). Excess moisture in heavy soils can foster plant disease and can hamper methods to work the soil; therefore it is not to be recommended for flat country with these soils (References 49, 628, 808).
3.5 Air mixing

During radiation frost when a clearly marked inversion layer is present, the difference between air temperature at the surface of the soil and at a height of 2 m can be 4-6°C, and even as much as 10-11°C (Reference 79). This fact was used in proposing a frost-fighting technique for fruit plantations where propeller systems designed to mix the air were employed. Systems of this kind were first used in the United States, and later in other countries including the Federal Republic of Germany, the Soviet Union, Italy, and France (References 79, 85, 182, 285, 433, 523, 587, 599, 628, 644, 649, 652, 659, 669, 679, 808, 836). Mixing the lower cold-air layers with the warmer ones above can raise the temperature in the surface layers by 3-4°C. If air temperature is to be kept at a certain level, mixing must be continued without interruption right up until the end of the frost period, otherwise the temperature can fall to its initial value within 2-4 minutes (Reference 285). On sizeable areas, it is essential to establish a large number of fixed installations which require heavy capital investment. Experiments with propeller systems in Italy during 1965 showed that citrus on more than 100 hectares could be protected from frost at severe as 6°C. At the same time up to 30 to 40 per cent damage was caused on unprotected plots (Reference 652); this shows that the heavy capital investment for propeller systems is a paying proposition.

Giocomelli (Reference 652) described a typical wind system consisting of a supporting tower, a propeller rotor, attachment heads, an engine, horizontal and vertical transmission shafts, with a gearbox for transmitting motion from the vertical to the horizontal shaft. This system was equipped with frost warning apparatus consisting of a thermometer linked to an electric bell pre-set for a given temperature (Figure 13).

The supporting tower can be either a pipe or an open structure. The propeller shaft is normally mounted on the supporting tower at a height of 9 to 10 m, the optimum height which has been accepted as a standard by designers, after taking into account the height above ground of the inversion layer, the cost of the installation, the radius of effect, etc. Propellers range from 3 to 5 m in length and develop 600-800 revolutions per minute. It is proposed for the propeller a changing angle of incidence. However, for economic reasons, most firms prefer propellers with fixed angle of incidence. One system rotates about its vertical axis with a period of 4-5 minutes. Current wind-machines have a single propeller; systems with twin propellers mounted side by side or back to back have been tested, but in spite of expectations, they did not increase mixing of the air significantly.

The propeller blades are driven by an internal combustion engine or an electric motor which is located either on the ground or is mounted at the top of the tower together with the rotor. Engine power is normally 60-150 horse-power (in the U.S.A. engines up to 200 h.p. are used). Less powerful engines would not be capable of creating an air stream sufficient to raise the air temperature in the surface layer as far as required. On the other hand, excessive engine power is not economical. The proper type of frost protection is the one where intense mixing is obtained not by increasing the engine power, but rather by the proper distribution of wind equipment in the plot. The effective radius of the air stream ranges from 80 to 100 m, but sometimes reaches 120 m, so that the area to be protected can range from a minimum of two hectares to a maximum of five. Diesel engines are used in Italy since they are much more economical than electric motors if operated for less than 300 hours per year. Trials have shown that engines with a capacity of 60-200 horse-power are the most suitable for frost-fighting. A 60 horse-power propeller uses about 12 litres of fuel oil per hour. A single machine costs about 3-6 million lire in Italy and some 4000 marks in the German Democratic Republic. It is essential for propeller systems to be distributed over the area to be protected so that the whole plot is evenly affected by the air streams.

Wind machines are only effective during radiation frosts with a severity of not more than −5 to −6°C (References 79, 652). In winds greater than 5 m s⁻¹, the system is not recommended. In some countries, they are used in conjunction with heaters to protect plants from more severe frosts (References 182, 523, 649, 652, 836), and sometimes they are used in combination with smoke-generation equipment (Reference 285). In the latter case the heaters are arranged up-wind, at each tree in the first row, at every other tree in the second row, and at every third tree in the third row. Near the rotor (at about 30 m distance) they form a square. But because of its high cost, the
system has not met with much favour, and can be used only in countries where prices of fuel are low, since 150-200 heaters are needed per hectare, consuming some 250 kg of fuel per hour. Litvin (Reference 285) describes a rotor plus-generation system which had an insufficient effect, since the difference in temperature between protected and unprotected plots did not exceed 2°C.
CHAPTER 4

INDIRECT METHODS OF PROTECTING PLANTS FROM FROST

4.1 Biological methods

4.1.1 Hardening

From the earliest times it was established by many investigators, biologists, physiologists, plant-improvement experts and the like, that methods of increasing the frost-hardiness of plants could be found. Tjurina (Reference 470) states that these methods can be of various kinds. It can be done by binding the water in plants by sugars or hydrophil colloids which reduce the ice content in the fibres and dehydation of the cells, or by raising the resistance of their protoplasm to dehydation and ice content. Photosynthesis is important in this process, since it causes the production and accumulation of soluble sugar which has a "defensive role" at the onset of low temperatures (References 54, 176, 467). Hardening is one of the most effective existing techniques for increasing plant resistance to frost (Reference 465) and based on the prolonged effect of low temperatures on plant organisms, whenever these temperatures do not cause noticeable plant damage. The sugar content in the cells and fibres is increased through hardening and this makes them more resistant to low temperatures (Reference 77). The seed-hardening method proposed by Voronova (References 111, 112, 113) for heat-loving varieties using varying temperatures is noteworthy. The technique consists in subjecting the growing seeds to varying temperatures from the moment their nuclei are alive; they are stored in a warm place for a period of time as the cells slowly grow, and also during the emergent phase of the seedling. They are later placed in the cold at sub-zero temperatures to harden them. In this way, all developing cells of the seed and the seedling are gradually hardened. Hardening makes plants resistant to frost, and capable of withstanding air temperatures as low as −6°C. Hardened plants have greater osmotic pressure, contain more sugar, and have a higher albumen coagulation threshold, that is, a whole series of properties that increase the hardness (Reference 119). This seed-processing technique prior to sowing also raises the chlorophyll and ascorbic acid content in the leaf, which prevent any harmful effect of adverse temperatures (Reference 365).

Voronova’s technique was based on a series of field trials using tomato and water-melon seeds. It is particularly important that such hardened seedlings be placed in the open early in the year, so as to make room for the cultivation of other vegetables in forcing-beds (Reference 356). Seeds sown early in the year acquire the ability to bud at lower mean daily air and soil temperatures. This tomato-seed hardening technique has been successfully used by other workers (References 42, 43, 44, 61, 102, 113, 120, 177, 241, 287, 290, 302, 310, 327, 353, 366, 385, 449, 477, 496, 570, 622). However, seed-hardening experiments with varying temperatures do not always yield good results, for example, in the variable-temperature processing of water-melon seeds (References 178, 179). Evidently, water-melons, because of their thermal adaptability, are among the plants that counter the effects of lower temperature by a slow-down in growth and development. Some workers have succeeded in obtaining a good crop of cucumbers by variable-temperature seed-processing (References 120, 275), but others (References 127, 207, 366, 452, 520) prefer to use the constant deep-freezing of intergrown cucumber seeds, a technique that speeds up their growth and fruiting, and increases their frost-hardiness considerably; many have reported the beneficial effect of varying temperatures on maize seeds (References 120, 121, 148, 166, 216, 363, 437, 438), to increase cold resistance. It is considered that the kind of soil in which the seed is sown is an important factor. Where soils are subject to temporary cooling, seeds treated with the varying temperature process show a sharp decrease in germination, and therefore in the north, this technique is not recommended. Efforts are being made to develop hardening techniques for processing cotton-seed (References 2, 94), buckwheat (Reference 306) and spring-wheat (Reference 484), but this work is still in the experimental stage.
Attempts to harden seedlings of heat-loving crops, by varying the temperature, have so far not met with much success. Even the most cold-resistant varieties are poor at withstanding the hardening process (References 465, 466). An added shortcoming of this technique is the slow-down of the subsequent growth rate, which produces a smaller yield. It has been reported that resistance to frost can be increased by cold-rearing in sheltered ground at temperatures from 1 to 2°C, using the appropriate mineral fertilizers (References 114, 308, 359, 472). The essence of this method is that before sowing in the open, the seedlings are systematically hardened over a period of 10 to 15 days, by being gradually subjected to colder temperatures through the creation of draughts.

4.1.2 Treatment of seed with trace-elements and other chemicals

A large number of experiments have shown that treatment of seeds and plants with trace-elements or other chemicals increases their frost-hardiness (References 1, 3, 25, 26, 78, 104, 106, 108, 110, 152, 161, 169, 265, 281, 370, 453, 454, 603). In field trials identical trace-elements affect the resistance in various ways, depending on the variety (Reference 104). The resistance of maize increases if seeds are treated with solutions containing chemicals in the following ratio: boracic acid 200 mg/l ammonium molybdate, 500 mg/l manganese sulphate, 40 mg/l copper sulphate and 200 mg/l zinc sulphate (References 3, 307, 368). Pankratova (Reference 356) described experiments which show that the resistance of maize increases noticeably by soaking seeds in a 0.05 per cent solution of ZnSO₄. Lebedeva (Reference 281) reports that of all the trace elements, copper and zinc had the greatest effect on cucumber seed hardiness after the seed was soaked in 0.02 per cent solutions. Zinc, copper, manganese, and to a lesser extent, boron, increased the frost resistance of citrus (Reference 512). In studying the effects of copper, aluminium and manganese on the hardiness of the Uzbek variety of cucumber (Reference 740), it was noted that the first two metals had a beneficial effect at low temperatures. It is therefore possible to treat seeds in solutions of CuSO₄, at 0.01 per cent, MnSO₄ at 0.1 per cent and Al₂(SO₄)₃ at 0.1 per cent concentrations to increase the cucumber hardiness during early stages of their development (Reference 1). According to other studies (References 78, 110, 237, 238), molybdenum helps to increase the hardiness of annuals, although only where there are large amounts of nitrogen in the soil since the effect decreases sharply for smaller amounts.

The different salts present in mineral fertilizers can improve the frost-hardiness of farm crops. Pre-sowing treatment of potato tubers with a 0.25 per cent solution of ammonium nitrate and a 0.03 per cent solution of manganese sulphate, wherever the soil has a weakly acidic reaction, can increase for hardness of the leaves by 1 to 1.5°C (References 25, 26). By treating cotton seed with solutions of ammonium salts, ammonium nitrate, aluminium sulphate, and manganese sulphate, plant damage can be reduced, and the temperature damage threshold of the cotton plant to frost during the initial period of growth can be increased (References 169, 370, 441). Treatment of some heat-loving varieties (cucumbers, tomatoes, maize, cotton) with fungicide preparations has been proposed to increase seed resistance to cold (References 108, 166, 331, 332, 334, 392, 720).

4.1.3 Selection and grading of frost-hardy strains

The effect of low temperatures on plants during their vegetative period depends on their type and variety (Reference 282), for example, the shoots of radish, lettuce, turnip, carrot, spinach, parsley, and fennel are not very sensitive to frost, while the parts of potatoes above the ground are somewhat more sensitive. Potato leaf is killed at temperatures of -2°C, and the stalk dies at -3°C (References 435, 436). It has been proved that agricultural plants have higher frost-resistance in their initial stages of development, when the seed is growing and vegetative organs are taking shape, but this resistance decreases on further development. Therefore in northern areas, where frosts begin in the early autumn and can occur even in summertime, it is very important to select the more frost-resistant and early- and even medium- ripening varieties of potato (References 76, 79, 362).

Regions where heat-loving vegetables can be grown in the open are limited, since comparatively high temperatures are required for seed growth and for subsequent plant growth and development. Varieties do not all have the same ability to withstand low temperatures, for example, tomatoes are more resistant than melons and cucumbers.
Even separate parts of plants react to low temperatures differently; the parts of water-melons and melons above-the-ground are more resistant than the roots.

The duration of the frost as well as the severity of the freeze affects the degree of frost-hardiness of plants. Cucumbers, maize, and eggplants can be killed if subjected to low temperatures for periods of 3 to 10 days. Tomatoes and early french beans can withstand low temperatures for 5 to 10 days with only minor damage (Reference 79). The amount of frost damage depends on the plant variety and type. Plants with high stems, or with a well-developed formation of leaves, in particular the very bushy varieties of maize are less affected (Reference 215). The selection of varieties appropriate to different climatic areas is therefore very important for most agricultural crops (References 160, 315, 409, 434, 504, 640, 796), and especially for fruit and berries, since the latter are most sensitive to frost when their buds are developing and the ovaries are forming (References 7, 23, 24, 60, 157, 188, 214, 248, 252, 260, 274, 282, 301, 317, 374, 381, 423, 436, 513, 544, 592, 646, 681, 736-739, 743, 781, 801). In the early vegetative period the hardness of buds decreases rapidly so that even weak frosts can cause great damage. A knowledge of the critical temperatures which are fatal for the growing buds, blossoms, or ovaries of different fruits and berries therefore assumes great importance. According to Procenko (Reference 381) these critical temperatures vary little with species and variety but depend on duration as much as on temperature. For example, developing buds are completely killed at temperatures of −8°C for six hours. A fall in temperature to −2°C causes insignificant bud damage but only if this lasts for 24 hours or more. Bud mortality of varieties of apple, pear and cherry has been observed after they had been subjected to temperatures of −6°C for four hours, or −8°C for two hours. Damage to ovaries of most varieties is slight at temperatures down to −2°C for four hours. At −3°C pear ovaries die after four hours, but those of other fruits, after much longer periods. Table 5 shows the sensitivity of different kinds of fruit trees to frost at various phases of development (Reference 645).

It may be seen that the fruit and berry varieties which have a later blossoming period, as well as high crop-yields and good hardiness, should be selected from the available species if major frost-losses are to be averted. This is particularly important for different types of citrus, and to some extent for almonds (Reference 737). Potapenko has recommended that grapevine varieties should be selected having late-developing eyes capable of producing grape bunches from the ancillary buds (Reference 374).

4.1.4 Development of new frost-hardy varieties

The development of less temperature-sensitive and earlier-ripening varieties of crops is very important in order to obtain high yields. The length of time required to grow different crops in the open is extremely variable, and depends on their ability to withstand low temperatures. By increasing plant resistance to low temperatures by 5°C, the vegetation period can be increased by almost 50 per cent (Reference 79). The efforts of plant-improvement experts are therefore aimed at increasing the frost-hardiness of plants and at developing early-ripening, late-flowering and early-maturing strains (References 4, 40, 52, 67, 72, 94, 97, 98, 147, 149, 168, 173, 212, 219, 225, 233, 266, 289, 347, 349, 350, 352, 372, 381, 382, 394, 410, 430, 465, 475, 500, 501, 503, 504, 507, 513, 518, 519, 660, 697, 715). Cold-resistance is improved by grafting new growth from heat-loving plants onto more cold-resistant forms. Grafting is particularly important in extending the cultivation limits of warmth-loving plants northwards. Good results have been obtained in grafting water-melons and melons onto marrows (References 72, 465), and cucumbers onto melons or water-melons (Reference 4). The combined influence of the root system and leaves of the stock alters the metabolism of the scion and thereby improves its hardiness. Thus crossing can produce high-grade hybrids of potato, maize and other plants (References 67, 97, 98, 225, 372, 382, 430, 504, 507, 518). The grafting and crossing methods has been used with particular success in fruit growing, where less frost-resistant varieties and strains are crossed with harder ones (References 168, 218, 349, 381, 394, 475, 501, 513, 660). In recent years, grafting via intermediate stock has met with growing success in some countries (Reference 715), and increases hardiness and improves fruit yield. The long process of selection and crossing is of practical significance for developing new varieties and hybrids which possess greater hardiness and blossom later and ripen earlier (References 40, 52, 94, 149, 173, 215, 266, 289, 347, 350, 410, 427, 519, 697).
4.1.5 Regulation of bud development

Secondary shoot-growth in citrus species is often delayed to the autumn period, when it is very dangerous especially for lemons whose frost resistance is sharply reduced in such an active state. Even weak frosts of no more than 

\[-2 \text{ or } -3^\circ C\] can cause damage, while death occurs at \[4^\circ C\].

Spraying citrus trees with a solution of alpha-naphthyl acetic acid has been recommended (References 255, 412) to reduce activity in secondary shoots. The best time for spraying is the period when summer-shoots cease to grow. Spraying halts the autumn growth, accelerates the transition of plants to a state of growth quiescence and thereby increases their resistance. Some workers consider that tree-spraying by alpha-naphthyl acetic acid can slow down the development of buds in fruit-bearing species. Study of the effect of this compound on three types of pear (the Moscow Grusovka, the brown-striped and Antonovka varieties) has shown that bud development is noticeably retarded, and that blossoming begins later (Reference 393); if the concentration of the acid is increased bud development is arrested more. A slackening in the breathing process and a reduction in the activity of oxidizing ferments are among the effects induced by the compound. Nigond (Reference 728) reports results of experiments in using alpha-naphthyl acetic acid in vineyards (Table 6). Since the less developed buds are more frost-resistant, treatment by chemicals can be an effective method of fighting frost.

To mitigate the effect of spring frosts in orchards, Ambaramjan (References 22, 23) recommended using a solution of potassium bromide, calcium chloride, potassium nitrate and potassium chloride in water; this increases frost resistance in the generative organs of citrus species, for example, by 40 to 50 per cent in peach. Booth (Reference 539) reports the successful use of gibberellic acid in treating pears. Proehsting and Mills (Reference 751) propose treating fruit trees two months before the leaves fall with a solution of ethephon at 250-500 mg per litre concentrations; this can delay blossoms by three to five days.

Flowering can be delayed not only by agrobiological or agrochemical action on plants, but also by simpler agricultural techniques. Good results can be obtained by completely whitewashing fruit trees during autumn, winter and spring (References 86, 87, 267, 492, 824). Buds on whitewashed trees open up five to seven days later than normal in the springtime. Some delay can also be obtained by using snow, compacted around the tree boles. Grapevines should be uncovered later in the season to hold back the opening of buds and flowering (References 28, 374, 375). Late pruning is important for delaying vine and citrus growth (References 7, 167, 221, 255, 652, 661); in combination with covering, this technique can delay grapevine development by approximately six to eight days.

4.2 Ecological methods

4.2.1 Mineral nutrient control

Both mineral and organic fertilizers are very important for increasing frost-hardiness (References 19, 22, 139). However, no consensus has emerged on the part played by individual mineral nutrient components in increasing frost resistance. For example, it has been assumed (References 7, 19, 126, 161, 435) that the plant resistance is increased when potassium nutrient is added; but several workers (References 105, 311) deny that potassium has a beneficial effect. Others (References 34, 109, 237, 431) claim that nitrogen is the most necessary chemical for plants in the early part of their vegetative phase, since it promotes better development and thereby assists them to withstand frost better, a fact which is more obvious at low temperatures. This has been confirmed by other studies (References 126, 127, 161, 162, 230, 444) which report that nitrogen (via ammonia) has the greatest effect, even though Badanova (Reference 34) discounts its beneficial effect as based on experience in tobacco cultivation.

Many workers have dealt with the part played by phosphorous and sulphur in increasing plant frost-resistance. Phosphorus fertilizers mitigate or completely neutralize the harmful effect of brief cold snaps on the growth and
development of plants (References 140, 141, 189, 228, 229, 232, 234, 235, 409, 516). The work of Korovin and his colleagues in the northern Soviet Union is worthy of note. They showed that one and the same mineral nutrient component can reduce frost-hardiness in some species and increase it in others. For example, large amounts of nitrate fertilizer reduce the resistance of most species but increase that of beans (References 235, 237, 343). Phosphorus and calcium fertilizers (in large amounts) increase the hardness of buckwheat and potatoes, but calcium nutrients, soya and maize (References 227, 232, 235, 240, 343). Increased amounts of phosphorus improve hardness but can also intensity plant-growth at above-zero temperatures which reduces the ability of beans to withstand frost. On the other hand phosphorus assists damaged plant organs to recuperate and develop new growth swiftly. In heavy frost, the beneficial effect of super-phosphates containing sulphur (as CaSO₄) is great (References 140, 141, 162, 189, 234, 235, 241, 343). Korovin found that resistance is increased by the nutrient which a species specifically requires. In the northern areas of the U.S.S.R., the most suitable form for complete fertilization has 2 to 3 parts of phosphorous, 1.5 of potassium and 1 of nitrogen. This ratio is called the “northern dose” (References 7, 226, 227-229, 231, 232, 235, 236, 239, 241, 343). It thus becomes obvious that regulation of the level and type of nutrient allows the frost-hardiness of plants to be raised considerably.

4.2.2 Crop-site selection, taking relief into account

A proper selection of site and distribution of fruit and other warmth-loving crops, taking into account the relief of the terrain, is very important for protecting them from frost on open ground (References 15, 33, 76, 79, 130, 149, 174, 210, 213, 227, 229, 233, 242, 261, 278, 312, 322, 340, 353, 405, 428, 487, 528, 537, 630, 655, 668, 679, 685, 714, 723, 749, 783). In very broken country special conditions may arise. Goldberg (Reference 130) reports that when a cold wave accompanied by strong wind passes over such country the greatest risk of frost occurs on the open slopes, particularly the upper parts. Depressions in the terrain and down-wind slopes remain relatively warm for a quite a long time. During radiational cooling, the cold air flows down the slopes, while in the depressions the stagnant air becomes colder than elsewhere. Clearly defined summits and the upper and middle portions of steep slopes run the least risk of frost, since in these areas there is an intensive runoff of cold air which is replaced by warmer air from the free atmosphere. Low hills and hillocks with relatively low altitudes and gentle slopes have a reduced risk of frost, provided that they are above the “cold pools” and that cold air can easily flow off them.

Areas most open to frost are the bottoms and lower portions of the slopes along broad, winding valleys, possessing relatively high (greater than 50 m) and steep slopes, narrow bottoms (less than 1 km) and gentle gradients. Where these valleys narrow down or twist sharply, there is a “closed” valley which greatly hampers the cold air from running down the valley, so that wide “pools of cold air” are formed. Closed valleys and hollows fill up to their rim with cold air, and are not recommended for orchards, vineyards or for growing warmth-loving crops (References 79, 210, 233, 312, 487, 587, 621, 668, 679). Woodland glades also constitute a great frost hazard, since at night cold air easily finds its way down from the higher standing trees surrounding them (Reference 655). Nocturnal air temperatures in these places can be several degrees lower than in the open fields. Therefore, for each farm it is extremely important to divide the land into sectors of differing frost-risk before laying out orchards or plantations for warmth-loving crops. The most suitable slopes for plantations and orchards in the southern areas of the U.S.S.R. are the northern, north-western and north-eastern faces, with gradients up to 10 to 12 degrees (References 174, 405). More snow accumulates on these slopes during winter and they are more moist in summer than the southern and south-eastern slopes where temperature variations are more sharply defined, and where trees are parched by the sun and lack of moisture. Fruit and berry crops can be damaged by frost on the lower portions of slopes, hence late-flowering shrubs (for example, raspberries) are recommended for cultivation wherever cold air tends to accumulate. The best sites for vineyards are the middle and upper portions of south- and west-facing slopes (References 116, 746). Gullies, rivers and lakes in the neighbourhood are beneficial for fruit plantations; the cold air tends to flow off into deep gullies so that gardens and orchards suffer less from frost during flowering (Reference 405).

In the cultivation of heat-loving crops, such as water-melons, melons, pumpkins, peppers, preference should
be given to the gentle southern and south-western slopes, well-protected from the cold north and north-east winds (References 15, 33, 76, 227, 229, 242, 278, 340, 428).

4.3 Other agricultural techniques

Numerous advantages in cultivating frost-hardy seedlings of early vegetables are obtained by growing them in peat compost pots or in nutrient blocks. In transferring these seedlings to the open almost the entire fodder system is retained, the plants are not damaged, and they do not fade and are more resistant to frost (References 20-27, 53, 69, 79, 114, 135, 207, 258, 273, 309, 439, 456, 459, 506, 515, 527, 731, 794, 798). The use of potted seedlings is a well-tried method for obtaining increased vegetable crop yields earlier in the season. A special lathe has been devised for manufacturing these pots (Reference 459).

On heavy, excessively moist cold soils, the ridge-technique for sowing vegetables and potatoes has produced good results (References 11, 63, 69, 76, 77, 79, 479, 547, 655). During the entire vegetative period temperatures on ridges are usually 1-2.5°C higher than on flat ground (Reference 79), which weakens the destructive effect of radiation frost. Heat exchange between air, soil and plants is also improved.

Appropriate soil cultivation techniques are very important, for example, nocturnal cooling can be reduced by compacting the soil (References 19, 147, 450, 628). Since this reduces the radiating surface area, increases the inflow of heat and moisture from below, increases the evaporation and consequently the humidity in the surface layer of air. However, this method is only beneficial for very weak frosts. During frost periods soil cultivation should be avoided, but removing weeds from orchards and market gardens is recommended.

It is well known that drained swamps and marshes have a high risk of frost. The moisture in the turf is drastically reduced during draining so that its thermal conductivity is lowered. To reduce frost risk on drained fields, some western European countries have, as a major task, introduced mineral soil into the ploughed levels of drained swamps and marshes. Air temperatures 2 cm above the surface of drained swamps or marshes, which have a mixture of slurry, are 3°C higher than that over pure turf (References 6, 372). Protective timber shelter-belts and corridors have been successfully used to protect orchards and heat-loving crops from cold winds (References 10, 15-17, 69, 72, 74, 77, 79, 87, 93, 138, 144, 145, 218, 325, 346, 358, 376, 418, 420-422, 435, 465, 476, 483, 490, 530, 556, 560, 604, 633, 636, 656, 685, 758, 772, 775, 780). Protective wind-breaks along slopes retard the downflow of cold air and reduce the risk of frost in lower lying depressions.
CHAPTER 5

CONCLUSIONS

From the foregoing discussion some conclusions can be drawn on the advisability of using different methods for protecting plants against frost:

(a) Depending on the intensity of the frost, the site of the plot to be protected and the kind of crop, plants can be protected from radiation frost by using the different direct and indirect methods described above. In the majority of cases the most effective methods would involve mixing the air and sprinkling, whereby a thermal effect of up to 6°C can be obtained;

(b) The most advisable method of protecting plants from advection frost is by covering them (preference should be given to high plastic tunnels, beneath which temperatures are 2 to 3°C higher than in the ambient air, even when unheated); the sprinkling technique is also often beneficial however, its effectiveness depending largely on wind speed;

(c) The temperature effect produced by different kinds of smoke-generation methods ranges between 2 and 3°C (Table 1), depending on wind speed and humidity. If judged by their smoke output, smoke-generating chemicals (red phosphorous, ammonium chlorate, ammonium sulphate, etc.) have distinct advantages; on burning these special apparatus, artificial fogs or smoke-screens can be formed over wide areas;

(d) According to the severity of the frost, wind speed and local conditions in the area to be protected, the thermal effect of different kinds of heaters (100-250 units per hectare) averages out at about 3°C. Increasing the number of heaters or their heat output can produce an improved thermal effect; the best effect (3-4°C) is obtained with paraffin “candles”. To avoid atmospheric pollution however, preference should be given to gas or electricity for heating plants and the ambient air;

(e) The effectiveness of any method primarily depends on the depth of the inversion layer. When this is small (2-5 m) open-air heating can be successfully employed. With deeper inversion layers (5-10 m) heating becomes much less effective, so that it is advisable to mix the air with propellers. If the height of the inversion layer exceeds that of the propeller system (higher than 10 m) the desired results cannot be achieved. In this event, evidently, covering is preferred, supplemented by heating or sprinkling;

(f) The economic effectiveness of using different techniques for frost protection differs between countries and even between different areas of a given country, depending on the availability of the necessary raw materials in sufficient quantities, their cost and the country’s general level of economic development, etc. Where cheap fuel (oil, etc.) is available, all other things being equal, liquid-fuel heaters are bound to have the advantage; where natural gas or electricity is inexpensive, it will evidently be advisable to utilize them in the appropriate heating systems; where water is plentiful, sprinkling could well be the most economic method, etc;

(g) In selecting a given method of protecting plants from frosts, its repercussions on the environment must be considered along with its physical and economic effectiveness. Since at the present time atmospheric pollution is a world-wide problem methods involving smoke generation or open-air heating with liquid or solid fuels cannot be recommended for densely populated areas or countries. Excessive engine noise can also limit the use of propellers. Thus, covering or sprinkling provide better prospects;

(h) The length of time that covers are used has no practical effect on the protection efficiency. By prolonging the time for generating and for heating, the costs rise proportionately, thereby forming a natural limit
to their economic effectiveness (which differs for various methods of protecting crops). The length of time that sprinkling may be employed also has its natural limits, but these are of a different nature: uninterrupted ice formation on plants over a long period of time can cause branches and young trees to break; in hilly country it can cause erosion and washing away of soil; while excessive soaking of heavy soils in flat country can induce different kinds of disease.

(i) Accurate and early weather forecasting is essential, if the effectiveness of the different direct methods for protecting plants is to be increased;

(ii) In some circumstances it is better to employ indirect (biological and ecological) methods of protecting plants. Among these, the best are plant-toughening, treating plants with chemical preparations, proper selection of cultivation sites and regulation of mineral plant-nutrition. They can produce the same or even somewhat greater thermal effects than the direct methods. For example, variable-temperature toughening of tomato seed enables the plants to withstand air temperature down to as low as $-6^\circ$C. Depending on the date when vines are treated with various chemicals (alpha-naphthyl acetic or gibberellic acid, or ethephon), plant development can be held up from two to twenty days (Table 6). Resistance of farm crops to frost is increased by adding the mineral nutrient which they distinctly need;

(k) Finally, the most effective technique is bound to be a combination of the direct and indirect methods of frost-fighting.
## TABLES

### TABLE 1

**Effectiveness of different smoke-making devices in calm weather**

<table>
<thead>
<tr>
<th>Type of device</th>
<th>Combustion time</th>
<th>Maximum thermal effect ($^\circ$C)</th>
<th>Amount of material per hectare</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoke-piles</td>
<td>1 h</td>
<td>2</td>
<td>60-150</td>
<td>(49, 84, 85, 115, 129, 336, 628)</td>
</tr>
<tr>
<td>Smoke-pots</td>
<td>5-7 min</td>
<td>2-2.5</td>
<td>100</td>
<td>(48, 49, 84, 85, 196, 341, 354)</td>
</tr>
<tr>
<td>Briquettes in conjunction with waste heaps</td>
<td>15-20 min</td>
<td>2</td>
<td>10-50 briquettes, 2-25 waste heaps</td>
<td>(628)</td>
</tr>
</tbody>
</table>

### TABLE 2

**Heat content of different types of fuel**

<table>
<thead>
<tr>
<th>Type of fuel</th>
<th>Amount of heat released by combustion of 1 kg of fuel (k cal)</th>
<th>Minimum from</th>
<th>Maximum to</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal dung</td>
<td></td>
<td>500</td>
<td>2000</td>
<td>1250</td>
</tr>
<tr>
<td>Wood</td>
<td></td>
<td>2000</td>
<td>3000</td>
<td>2500</td>
</tr>
<tr>
<td>Oil</td>
<td></td>
<td>5000</td>
<td>–</td>
<td>10000</td>
</tr>
<tr>
<td>Coal</td>
<td></td>
<td>7000</td>
<td>7800</td>
<td>7400</td>
</tr>
<tr>
<td>Coal briquettes</td>
<td></td>
<td>2500</td>
<td>8000</td>
<td>7500</td>
</tr>
<tr>
<td>Peat</td>
<td></td>
<td>–</td>
<td>3500</td>
<td>3000</td>
</tr>
<tr>
<td>Petroleum waste</td>
<td></td>
<td>–</td>
<td>–</td>
<td>10500</td>
</tr>
</tbody>
</table>

### TABLE 3
Example of change in hourly fuel consumption by a single heater over a period of time

<table>
<thead>
<tr>
<th>Time period</th>
<th>Fuel consumption (kg)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max. open</td>
<td>Half open</td>
<td></td>
</tr>
<tr>
<td>First hour</td>
<td>4.5</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Second hour</td>
<td>3.0</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Third hour</td>
<td>2.3</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Fourth hour</td>
<td>1.6</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Fifth hour</td>
<td>–</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 4
Variations in sprinkling rate for frosts of varying severity

<table>
<thead>
<tr>
<th>Critical frosts (in °C) for nozzle rotation rates (in min)</th>
<th>Sprinkling rate (mm h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>−4.5</td>
<td>−4.0</td>
</tr>
<tr>
<td>−6.0</td>
<td>−5.5</td>
</tr>
<tr>
<td>−7.5</td>
<td>−6.5</td>
</tr>
<tr>
<td>−9.3</td>
<td>−8.6</td>
</tr>
</tbody>
</table>
### TABLE 5

Resistance of different types of fruit tree to frost at various phases of development

<table>
<thead>
<tr>
<th>Species</th>
<th>Critical temperature (in °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Closed buds</td>
</tr>
<tr>
<td>Apple</td>
<td>-4</td>
</tr>
<tr>
<td>Pear</td>
<td>-4</td>
</tr>
<tr>
<td>Cherry</td>
<td>-4.5</td>
</tr>
<tr>
<td>Peach</td>
<td>-4</td>
</tr>
<tr>
<td>Apricot</td>
<td>-4</td>
</tr>
<tr>
<td>Walnut</td>
<td>-1</td>
</tr>
<tr>
<td>Almond</td>
<td>-3</td>
</tr>
</tbody>
</table>

### TABLE 6

Effect of using alpha-naphthyl-acetic solution on the springtime development of “Aramon” grapevine buds

<table>
<thead>
<tr>
<th>Date of</th>
<th>Date of</th>
<th>Concentration</th>
<th>Stage of bud development (1955)</th>
<th>Three-leaf stage (1955)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Control vines</td>
<td>Treated vines</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1955</td>
<td>1954/1955</td>
<td>0.5¹</td>
<td>30.3</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.75²</td>
<td>5.4</td>
<td>14.4</td>
</tr>
<tr>
<td>14.3</td>
<td>14.3</td>
<td>1.0</td>
<td>21.4</td>
<td>16</td>
</tr>
<tr>
<td>1956</td>
<td>1957</td>
<td>0.88¹</td>
<td>12.3</td>
<td>16.3</td>
</tr>
<tr>
<td>20.11</td>
<td>20.11</td>
<td>0.88</td>
<td>13.3</td>
<td>25.3</td>
</tr>
<tr>
<td>8.1</td>
<td>8.1</td>
<td>0.88²</td>
<td>16.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

¹ 1 litre of solution per vine
² 0.2 litre of solution per vine
FIGURES

Figure 1 – Plant covering by machinery (Reference 778)

Figure 2 – General view of different types of tunnel covering (Reference 704)
Figure 3 - Comparison of minimum temperatures in tunnels using different types of cover. 1 - Mulching with PVC sheet tunnel covered by PVC sheet and matting (overnight); 2 - Tunnel covered with PVC sheet and matting (overnight); 3 - Tunnel covered with polythene sheeting and matting (overnight); 4 - Mulching using PVC sheeting, tunnel covered with PVC sheeting; 5 - Tunnel covered with polythene sheeting; 6 - Tunnel covered with PVC sheeting; 7 - External temperature. Temperature at which damage is caused.

Figure 4 - Section of rigid plastic high tunnel (Reference 704)
Figure 5 - Types of heater employed in the U.S.A. (Reference 649)

Figure 6 - Types of heater employed in New Zealand (Reference 669)
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Figure 8 – “Paraffin candle” (Reference 718)
Figure 9  Ice-formation from successful sprinkling technique (Reference 669)

Figure 10  Ice-formation from successful sprinkling technique (Reference 669)
Figure 11 – Sprinkler column in orchard (Reference 669)

Figure 12 – Costs of sprinkling compared with those for heating (Reference 669)
“\(A\)” Using specially designed water tank
“\(B\)” Using natural water supply

Figure 13 – Working apparatus for approaching frosts (Reference 652)
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