BASIC PRINCIPLES OF FREEZE OCCURRENCE AND THE PREVENTION OF FREEZE DAMAGE TO CROPS

V. J. VALLI

Advisory Agricultural Meteorologist
ESSA Weather Bureau
West Virginia University Experiment Station
Kearneysville, West Virginia

INTRODUCTION

Of all of man's attempts to control or modify the weather, the prevention of damage to agricultural crops from low temperatures is probably the oldest, dating back to Pliny the Elder, the Roman naturalist who lived in the first century A.D. Methods of modifying temperatures have taken four basic approaches: 1. Covering, 2. Sprinkling with water, 3. Mixing the air in the low levels, and 4. The addition of heat. Using one of these or a combination of two of the methods the prevention of cold or freeze damage is always possible but not always economically practical. Cold or freeze damaging temperatures range from the 53F. temperature that causes damage to bananas down to temperatures in the 20's necessary to damage mature cabbages. Selection of the method to be used depends upon the crop as well as other factors. This presentation is designed to cover the basic principles of freeze occurrence and the prevention of freeze damage. Although prevention of freeze damage is approached from a tree fruit standpoint, the basic principles also apply to small fruits and vegetables. The prevention of freeze or freeze damage has become an accepted practice in the production of tree fruits and nuts as well as other crops in those areas where the threat of damaging temperatures exists.

Before discussing the subject, it would be desirable to define the terms “FROST” and “FREEZE”. Frost is defined as the process by which ice crystals are deposited on an exposed surface. This is the result of the temperature of the exposed surface falling to the “DEW POINT” temperature of the air. This is simply the temperature at which condensation occurs in that particular air mass or the temperature that a surface would have to reach to form dew. In fact, frost is simply frozen dew. Instead of the moisture (water vapor) in the air condensing out of the air as a liquid, it sublimates out directly from the water vapor state to solid ice crystals. In many sections of the world the term “FROST” has been given various meanings when pertaining to the effect of the temperature on plants. “FROST DAMAGE” can result from a temperature as high as 32 degrees in some plants while with other tree fruits, “FROST DAMAGE” does not occur until temperatures fall into the low 20's. Modern agricultural meteorologists prefer to use the terms “FREEZE” and “FREEZE DAMAGE” when referring to low temperature damage to plants. “FROST DAMAGE” can result from a temperature as high as 32 degrees in some plants while with other tree fruits, “FROST DAMAGE” does not occur until temperatures fall into the low 20's. Modern agricultural meteorologists prefer to use the terms “FREEZE” and “FREEZE DAMAGE” when referring to low temperature damage to crops. These terms have but a single meaning. The temperature, at the level where it was taken, fell to 32 degrees F. or lower and damage resulted. It is possible to have freezing tempera-
tures at ground level while temperatures in an instrument shelter at the five foot level are as high as 40 degrees F. The variation in temperature that occurs with very little change in height is an extremely important fact to consider in freeze prevention. In this discussion the terms "FREEZE" and "FREEZE DAMAGE" will be used without regard to the presence or absence of ice crystal formation.

**TYPES OF FREEZES**

In planning to protect crops from freeze damage it is important to consider the two types of weather conditions under which freezing temperatures occur. The most frequent cause of freezing temperatures in most of the Northern United States and occasionally in the southern areas is the transport of cold air masses south-eastward from Canada over the U.S. These air masses have originated over the snow covered polar and arctic regions in Canada where by the process of radiation during the long nights and very little daytime sunshine, the air becomes progressively colder. The air mass then migrates southeastward into the U.S. It's temperatures at the surface are below freezing and become colder with elevation. This type is called an "ADVECTIVE FREEZE".

The temperature advects or moves into the area. A gradual modification of this cold air takes place as it moves into more southern latitudes, but on occasion temperatures at the surface will remain below freezing during the day until the air mass penetrates deep into the southern part of the country. This type of freeze occurs mostly in the winter in northern areas, is normally expected, and crops are not planted or actively growing during the normal season of advective freezes. However, the arrival of an early fall or late spring advective freeze in the northern areas, or in midwinter in the extreme southern areas of the country can be devastating. In most cases there is little in the way of advective freeze prevention that can be done on a large scale at the present time. The most usual type of protection in these cases is to cover the crop if feasible. Heating or other methods are in most cases not economically practical.

The second type of weather situation that causes freezing temperatures is called a "RADIATIONAL FREEZE." This type of freeze occurs when a relatively cool but very dry air mass moves into an area. This air also originates over Canada where it's surface temperatures were below freezing. However, as it moves southward it becomes modified and the afternoon temperature in this type of modified air mass can often reach as high as 60 degrees F. In this air mass temperatures at the surface during the day are above freezing for several hundred feet aloft. The daytime temperatures in this dry air, generally with considerable sunshine, reach afternoon values in the 50's and even the lower 60's. After sunset radiational cooling from the earth's surface causes temperatures in the very lowest layers of the atmosphere to fall below freezing. While temperatures at the surface fall 30 degrees or more below the afternoon high, temperatures just a few hundred feet above the ground remain fairly constant thus forming what is called an "INVERSION". This is a situation in which the temperatures increase with elevation instead of falling with elevation and the lowest temperatures occur in the lowest places.

**THE COOLING PROCESS**

To understand the formation of an inversion, it is necessary to first review the ways in which heat can be transferred. The cooling process is in fact the loss of heat energy. Heat energy represents molecular motion. The higher the temperatures (vibration) of a surface, the more rapid the motion of the molecules and the shorter the wave length (Higher frequency) of the transmitted radiation. In the atmosphere, heat can be lost by three processes, conduction, convection, and radiation. (Figure 1) CONDUCTION: is the process of heat energy moving from one molecule to another. The higher the temperature the faster the vibration of the molecules. The higher temperatures (vibration) moving in the direction of the lower temperatures (vibration). The closer together (denser) the molecules of the material, the more readily the transfer of heat by the process of conduction. Metals are more dense (heavier) than wood and therefore better conductors. Because of the very low relative density of air it is a poor conductor, an important factor in the formation of an inversion.

CONVECTION: is the process of mass motion in fluids caused by a density differential and convection heat loss results when the heated mass moves away from the heat source. Air in
contact with the ground is heated by conduction. As it becomes warmer it expands and becomes lighter, (less dense) and rises, to be replaced by cooler (denser) air. This develops "CONVECTIVE MIXING", where by the heated air is moved from the lowest layer of the atmosphere and mixed up to several thousand feet. This convective mixing prevents the lowest layer of the atmosphere from becoming extremely hot during the day by mixing the heat thru the first 5 or 10 thousand feet of the atmosphere.

RADIATION: is the process of heat transfer by electromagnetic radiation from one object to another, without need for a connecting medium. Radio waves are a form of radiation by which sound is transferred from one antenna thru the air or space to another antenna. Radiant heat is transmitted from the extremely hot surface of the sun. High temperatures give high molecular vibration and high frequency, which results in short wave lengths. Radiation has two characteristics, wave length or the distance between peaks of the wave, and frequency, the number of waves passing a point per unit time. Therefore the higher the frequency the closer (shorter) the distance between waves. Radiant heat is transmitted as short wave radiation from the sun as shown in Figure 2. On reaching the outer edge of the atmosphere 9% is reflected back into space. Passing thru the atmosphere another 23% is reflected back to space by clouds and suspended particles, while 19% is absorbed by the atmosphere. On reaching the earth's surface another 2% is reflected back and the remaining 24% is absorbed by the earth. Thus of the total energy reaching the outer edge of the atmosphere, 34% is lost. This distribution is shown in Figure 3.

BASIC ENERGY EXCHANGE

Figure 4 shows the basic exchange of energy between the earth and the sun and space. That portion of the sun's radiant energy reaching the earth's surface causes heat energy to enter the soil. Some of this energy is then radiated outward by the earth. The energy remaining causes the soil temperatures to rise. As the soil temperature becomes warmer than the air in contact with the soil, the heat energy flows from the
Figure 2.—Energy source.

Figure 3.—Distribution of incoming radiation.
warmer soil to the relatively cooler air by conduction. This air in contact with the soil becomes warmer and lighter than the air and rises to be replaced by cooler air which in turn is warmed. This develops convective circulation. Thus the daytime energy flow is from the sun’s radiation into the soil, from the soil into the air by conduction where it is mixed through the lower layer of the atmosphere by convection. At night this energy flow is reversed. After sunset incoming radiation from the sun ceases, but the outgoing radiation from the earth continues. As the heat energy from the soil is lost by outgoing radiation the soil surfaces cool and become relatively cooler than the air in contact with it. This starts a flow of heat energy from the warmer air to the relatively cooler soil by conduction. This heat energy is then lost by outgoing radiation into space. As the outgoing radiation continues, more and more heat energy is withdrawn from the air. However, because the air is such a poor conductor of heat energy, the soil is able to withdraw heat energy from only the first hundred feet or so of the atmosphere. This leads to the development of what is called an “INVERSION.”

**The Greenhouse Effect**

Before discussing the formation of an inversion, it would be well to discuss what is called the “Greenhouse Effect” shown in Figure 5. This effect is the process by which heat energy from the sun is trapped in the atmosphere in the manner of a greenhouse which allows the heat from the sun in through the glass, but retards the heat loss. Certain components of the atmosphere, mainly carbon dioxide and water vapor are highly selective with regard to the passage of differing wave lengths of radiation. The short wave radiation from the sun passes quite readily through them. But when this energy is absorbed by the earth’s surface and radiated out it’s wave length is changed. Remember that the temperature of the radiating surface (the speed of vibration of it’s molecules) determines the frequency and wave length of the radiation. Thus the radiation from the much colder earth’s surface is in
the form of lower frequency (slower vibration) and longer wave lengths. The carbon dioxide and water vapor in the atmosphere block most of this longer wave radiation, absorbing and reflecting this heat energy back to earth, trapping the heat energy in the atmosphere. The amount of water vapor (humidity) in the atmosphere exercises considerable control on radiational heat loss. The lower the humidity, the greater the loss.

**The Formation of Inversion**

Figure 6 shows the formation of an inversion. During the day, radiation from the sun heats the earth's surface. The soil becomes warmer than the air in contact with it, and, by conduction, air in contact with the ground is heated. As it is heated it becomes lighter and rises, being replaced by cooler air which in turn is heated and rises. This leads to convective mixing of the heat through the lower several thousand feet of the atmosphere. The heat is distributed through the atmosphere so that the warmest temperatures during the hottest part of the day are at the surface, with a decrease in the temperatures with height. After sunset, when the incoming radiation ceases, the ground loses heat by radiation and becomes colder than the air in contact with it. Then the heat flow moves from the warmer air, by conduction into the soil, which radiates the heat energy out. The soil acts as a sponge, soaking the heat energy out of the air in contact with it. Because the air is a poor conductor, the heat removal by conduction is limited to the lowest few hundred feet of the atmosphere, with the air in contact with the ground becoming the coldest, so that temperatures will increase from the ground level up 200 to 300 feet. This increase in temperature with height is called an “Inversion”, the temperature change is inverse to the normal. This inversion is what makes the prevention of freeze damage possible through heating or mixing of this lowest layer of air.

**Methods of Prevention of Freeze Damage**

There are many methods used to prevent low temperature damage to crops. They range from
covering, sprinkling, and creation of fog covers to prevent radiational heat losses through heating and mixing of the lowest level of the atmosphere. The most commonly used, and at the present time the most economically practical on a large scale, are heating and mixing. The use of many heaters or small fires is in widespread use throughout the world. These methods and the, physical principles are simple and effective. The objective is to add enough heat to the lowest layer beneath the inversion to prevent the occurrence of a critical temperature. This is illustrated in Figure 7. This critical temperature can range from the 32 degree F temperature shown, on down, depending upon the crop and it's stage of development. Heating is most effective under conditions of a relatively strong inversion and little or no wind drift. The heaters can burn oil and/or gas individually or can be centrally supplied. Petroleum or other based blocks have also been used. Whatever the method, it is important to emphasize that a large number of small fires are much more effective than a few large fires. In fact, a fire that is too large or hot can cause a powerful jet of hot air to rise through the inversion, causing a chimney effect, which punctures the inversion, as shown in Figure 8, causing the heat to be lost and the drawing colder air into the area. In practice, the number of heat sources is increased to provide more heat where necessary, such as in low areas, where cold air has collected. Cold air drainage as shown in Figure 9 is the result of the fact that cold air is denser than warmer air and will in a general way, flow and collect in pockets as will water. So called “FROST POCKETS” are simply low areas that do not allow the cold air to drain away. The important fact to remember in heating is that the purpose is not to heat all outdoors, but to heat that area under the inversion that is below your critical temperature, (see Figure 10.) Heaters are lit as the temperature falls to near the critical level and as the temperature continues to drop are either turned up or increased in numbers. Each heater convectively heats an area as shown by Figure 11. There are two important facts concerned with the output of the heaters. First is the fact that the smoke the heater may develop does not help to retain heat. The size of the
AREA UNDER INVERSION THAT MUST BE HEATED TO PREVENT CRITICAL TEMPERATURES

Figure 7.—Area under inversion to be heated.

Figure 8.—Heat loss thru inversion.
Figure 9.—Cold Air Drainage.

Figure 10.—Vertical temperatures in orchard.
smoke and the soot particles are such that the long wave radiation from the earth passes through. In fact smoke can be detrimental because it does block the short wave radiation from the sun which normally would have warmed the ground which in turn heats the air. Smoke can make it necessary to heat for several hours after sunset which increases heating costs. The second important fact is concerned with the convective-radiative heat output of the heaters. Radiation, in the form of infra-red rays from the heaters does not heat the air. These rays must strike a solid surface, such as a branch, leaf or fruit bud for a heat effect to be produced. But the most important fact about radiation is the way in which its heat effect is reduced with distance. Assuming a maximum tolerable radiant heating effect of 100 degrees F at a distance of one foot to prevent burning up the area surrounding the heater, let us examine how this heating effect is reduced, as is all radiation, with the square of the distance. If a heating effect of 100 degrees F is attained at a distance of one foot from the heater, the heating effect at two feet would be reduced to 25 degrees F and at three feet about 10 degrees F and at four feet only about 6 degrees F and finally at a distance of 10 feet to only one degree F. It has been demonstrated that the heating effect from the most effective type of oil or gas burning heater on these fruit buds that are fully exposed to the radiation from the heater, is less than one degree F at a distance of 16 feet, which allows a heater spacing of 32 feet. The fact is that only a small percentage of fruit buds are fully exposed to the radiative source and a system that has only a one degree heating effect is not economically practical. This leads to the truth that it is the conductive-convevtive output of a heater that is the best measure of its heating effect potential. The burning fuel heats a certain volume of air in the combustion process, the flame heats the metal of the container and this leads to a convective circulation as the heated air rises and is replaced by cooler air which in turn is heated. To prevent a "chimney-effect" from occurring, by which the heat is lost through the inversion to outerspace, as in Figure 12, the thermal velocity of the heated air should be such, that by adiabatic cooling, due to expansion as it rises, the temperature of the air parcels reach the temperature of the surrounding air which causes them to stop
Figure 12.—Breaking inversion.

Figure 13.—Heated and unheated areas in orchard.
rising before reaching the highest temperature in the inversion. The output of a single heater combines with other heaters to produce the desired heating effect shown in Figure 13.

**Wind Machines**

Wind machines are another commonly used method of freeze damage prevention. These systems place motor driven fans about 40 feet over the area to be protected. They operate on the principle of mixing enough of the warmer air up in the inversion with the colder air below the ground level so that the temperature in the protected layer is at or above the critical level. This is shown in Figure 14. Wind machines are effective only when warmer air exists in the inversion layer because they do not produce effective heat themselves. In some areas, under conditions of weak inversions, supplemental heat is used together with the wind machines to provide freeze prevention.

In summary, the prevention of freeze damage is possible under many situations, with several types of systems. However, under certain conditions of advective freezes, no system or combination of systems will prevent freeze damage. There are many types of systems, with varying costs of capital investment and operation. The individual grower must determine for himself, which system or combination of systems may best suit his particular needs, at a cost that is most economical in his particular circumstances.