SECTION II.—GENERAL METEOROLOGY.

I.

FROST PROTECTION.

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INTRODUCTION.

The purpose of this paper is to point out the fundamental principles that make frost protection a practicable branch of atmospheric physics. The natural laws that should guide the design and use of apparatus in this connection will be emphasized, but the relative merits of the heaters and other equipment already put out by different manufacturers will not be discussed, nor will any effort be made, at least not in this paper, to describe anything new in equipment or method of frost protection, though clearly there still is plenty of room for improvement in both particulars.

GENERAL CONSIDERATIONS.

As every one knows, an object may exchange heat with the things that surround it in either of two ways: (*a*) By conduction in case of actual contact, facilitated by convection when immersed in a fluid, and (*b*) by radiation when separated by a diathermanous region. However, it is not always easy to determine *a priori* whether a given object under an observed set of conditions must lose or gain in temperature, for this obviously is a complex problem of area exposed, thermal conductivities, and coefficients of radiation and absorption. But whenever only two objects are concerned the result is never in doubt; whatever the ultimate mechanism or process of heat conduction and whatever the ultimate nature of radiation and of absorption, it appears to be universally true that the balance of heat exchange between them (and there always is such exchange), whether by the one process or by the other, is ever in favor of the coldest body. In other words, where there is only a thermal exchange it is always the cold object that gets warmer and the warm object that gets colder, and never the reverse; a warm object never gets warmer at the expense of the remaining heat in one that is already colder. To the physicist this is familiarly known as the second law of thermodynamics.

Now, the surface of the earth, whether soil, rock, water, or vegetation, is constantly exposed to both the above processes of heat exchange, one of which, conduction, is greatly facilitated by atmospheric circulation. Hence, normally, the lower atmosphere and the covering of the earth, whatever that may be, begin to grow warmer about sunup, continue to gain in temperature till sometime in the afternoon, when loss and gain are equal, and then gradually to get colder and colder till the following sunrise, when the whole cycle is repeated. As a matter of fact, there are numerous temporary conditions due to clouds, winds, rain, and the like, that more or less disturb the ideal regular sequence of thermal events, but nevertheless the average normal sequence is substantially as given, and the clearer the atmosphere and the stiller the winds the more nearly is this sequence followed.

By virtue of this alternate heating and cooling, and especially because the temperature of the surface layer of the atmosphere is chiefly controlled by the temperature of the greedily absorbing and freely radiating surface of the earth, it happens that in the lower atmosphere the change of temperature per given change in altitude greatly varies, particularly from day to night. Thus, when the weather is calm and clear the temperature up to some hundreds of feet, at least, during the day and especially of early afternoons, when vertical convection is active, may decrease almost at the adiabatic rate of approximately 1.6°F. per 300 feet. On the other hand, under the same conditions of clear skies and no wind, the air close to the ground at and before daybreak frequently is several, even many, degrees colder than the air at very moderate elevations. In extreme cases the atmosphere at an elevation of only 5 to 10 feet is as much as 5 to 10, or even more, degrees warmer than that on the surface. This surface temperature inversion, as it is called—that is, the increase instead of the decrease of temperature with increase of elevation—becomes less pronounced with increase of height, and while it may extend to an elevation of several hundred feet it seldom reaches any great altitude.

From the above it is obvious that the tops of open and sparsely foliaged trees, especially if rather tall, often are less subject to frost and more easily protected than are the lower limbs. On the other hand, when the tree is low and its outer foliage sufficiently dense to produce a protecting canopy over the under and inner branches, as is generally the case with orange trees, the difference between the free radiation from the exposed fruit and the restricted radiation from that which is covered may usually be sufficient, even when there is a marked temperature inversion, to subject the former and not the latter to the greatest danger from frost and freeze.

But how, returning to the main discussion, it properly may be asked, can any object—to be specific, the surface covering of the earth—become colder than either the soil beneath or the atmosphere a short distance above? As a matter of fact, this could not be a permanent condition, but it frequently is a temporary one, brought about as follows: When the air is still and clear, the surface of the earth, which is a good radiator, rapidly loses heat by radiation to and probably to some extent even through the atmosphere, and at the same time receives heat by radiation from the atmosphere, and to some extent also by conduction from the atmosphere, though mainly by conduction from the warmer soil beneath. But as the thermal conductivity of the soil is poor and that of the atmosphere many times worse, it follows, under the assumed conditions of clear skies and still air, that the surface temperature is largely determined by the tendency toward an equilibrium between the amount of radiation given out by the surface covering itself and the amount of radiation it receives and absorbs. But since the atmosphere is more or less diathermanous or transparent to heat radiation it follows that the interchange of heat by radiation between the surface covering and the atmosphere extends in some measure to great altitudes, where, of course, the temperature is very low, and also that some of the surface radiation may even escape directly to space whose effective temperature, as a black body, or full radiator, is only a few degrees at most above the absolute zero. Hence the radiation *received* by the surface of the earth is only the little that would come from a full radiator at a very low temperature, and therefore, under the given conditions, the surface must lose more heat than it gains, and thus cool to a temperature considerably below that of the nearly adjacent atmosphere; it radiates to a great extent *through* and not *to* the adjacent atmosphere, and thereby temporarily cools to a lower degree.

It is this diathermanous property of the atmosphere that, in great measure, is responsible for the production of frost: and the resulting strong inversion of the vertical temperature gradient, perhaps more than anything else, renders frost protection through ordinary heating both an experimental and a commercial success. The inversion prevents the air, if but slightly warmed by a protection method, from rising to any considerable height quite as effectually as would a solid ceiling, and thereby limits to a comparatively small amount the mass of air actually so heated. In other words, the inversion of temperature makes it possible and apparently practicable to restrict the actual heating to as little as 1 or 2 per cent of the total atmosphere overhead, and that little the very part that it is necessary to heat in order to prevent frost.

Of course the ideal condition above assumed, of absolutely still air, never obtains in nature, and therefore when the lowest air is chilled through contact with the radiation-cooled surface it becomes more or less mixed, through movements of one kind or another (over valleys largely by air drainage from the sides), with the atmosphere of greater elevations, and thus the temperature inversion spoken of above always extends to higher levels than it would if there was no air movement and no air mixing.

Figure 1, representing a somewhat idealized typical case, will help to make some of these points clear. Here the usual temperature decrease with increase of altitude is supposed to obtain only above the 500-foot level, while below that level the temperature is supposed to decrease with decrease of elevation more and more rapidly quite to the surface of the earth. Obviously if, under these conditions, a wind of only one or two miles per hour should start up, the dense, freezingly cold air at the bottom would become mixed with the much warmer atmosphere a little way above, and the surface temperature would quickly rise to a degree safe from frost. Similarly, any artificial stirring up of the lower atmosphere, if of sufficient magnitude, would have the same effect of raising the surface temperature.

Figure 1 shows how it is that ordinary heating can protect from outdoor frost, and also indicates how this heat can most economically be applied. Let the temperature distribution be as indicated in the figure, and suppose the object is to keep the temperature of the lower atmosphere just safely above the freezing point. Clearly the most economical way to do this, so far as the consumption of heat energy alone is concerned, would be to have the entire surface warmed to the particular temperature in question.

Thus any portion of the surface air artificially or otherwise warmed—say to 34°F., that is, 2° warmer than the surrounding air—would rise, under the given conditions, to only about 30 feet, while a portion of air heated to 40°F. would tend to rise more than 250 feet, and thus produce a great deal of useless heating, since the atmosphere at such elevations could have but little influence on the surface temperatures. Artificial heating of the air to still higher temperatures, by large fires and the like, clearly is even much more wasteful of heat energy, and therefore the fuel or whatever is used to produce the heat. To be sure, the column of rising air over a big fire has no such high temperature as has the fire itself, and, besides, the turbulence it produces rapidly entangles it with much of the surrounding unheated air, but for all that its temperature is quite too great and the elevation to which it rises entirely too high for economical heating. Besides, the hot air from large fires would be ruinous to any vegetation it should touch and thus itself destructive of the very thing it was designed to protect. There is then every reason for having the heat well distributed and liberated at a comparatively low temperature.

But one properly asks, What is the minimum amount of heat energy, or of fuel to produce it, necessary under

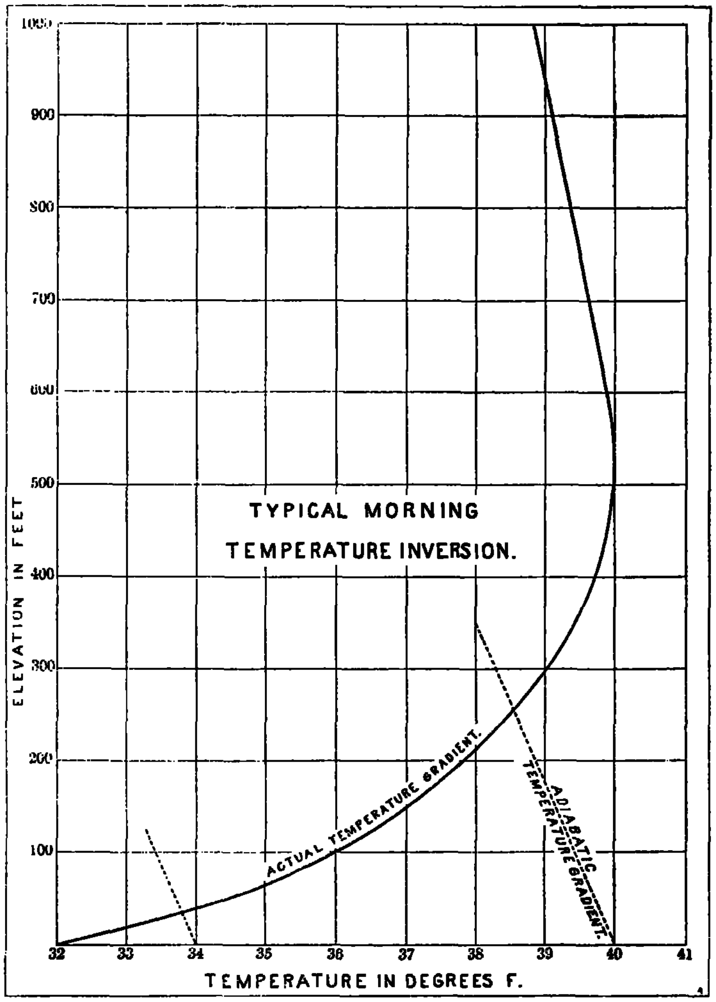

FIG. 1.—Illustrating the physical possibility of protecting outdoors from frost by artificial heating.

normal conditions, to prevent frost injury? This important question cannot be answered in terms of unqualified numerical values, because the actual conditions vary from time to time and from place to place. Still it seems worth while to assume certain more or less limiting conditions and to compute the corresponding thermal values.

Problem 1.—Let the sky be clear, the dewpoint below 32°F., the air calm, the time night, the surface of the ground horizontal and at the temperature 32°F. Find the rate of heat supply per unit area to prevent the temperature from falling lower.

These conditions are, of course, ideal and seldom very closely realized in nature, but they are definite and the problem therefore capable of approximate solution.

If, now, we assume no heat conduction from the soil beneath, an inaccurate but limiting condition, the essential thing necessary to the solution of this problem is the value of the "effective radiation" of the actual surface, or the difference between the thermal emission of the surface to and through the atmosphere and its absorption of incident radiation from the atmosphere and from the stars. For a black body or perfect radiator this is approximately known [1] and under the conditions assumed is roughly fifteen one-hundredths of a calory per square centimeter per minute.

It is unnecessary, presumably, to convert these values into their English equivalents, since the final answer will be given in both systems, metric and English.

The actual surface, however, is not a full radiator, but when it consists of green vegetation or of dark rich soil, it radiates something like two-thirds as much as does a black body at the same temperature, or, say, one-tenth of a calory per square centimeter per minute.

Now let there be one tree per each plot of 10 meters (approximately 33 feet) square—ample room for most apple trees, and more than necessary for peaches, pears, plums, etc. Then each such plot, or each apple tree, will require per hour 6 million calories. But the burning of a gram of petroleum oil averages about 8,500 calories. Hence, the required amount of heat per 10 meters square, or per tree, say, could be furnished by the burning of about 860 cubic centimeters, or approximately a pint and a half of oil per hour.

Problem 2.—As in problem 1, let the sky be clear, the dewpoint below 32°F., the time night, the surface of the ground horizontal and at the temperature 32°F., and a wind of two and a quarter miles per hour or approximately one meter per second. Find the rate of heat supply per unit area to prevent the temperature from falling lower.

Under the given conditions, in addition to the heat necessary to counteract radiation loss, as explained in problem 1, the air, as it enters the boundary to be warmed, must be heated up to the required temperature, in this case 0°C. To be liberal suppose the air to have sea-level density, or to weigh, at the given temperature, 1,290 grams per cubic meter, roughly $1\frac{1}{4}$ ounces per cubic foot, and let it, as it enters the protected area, be heated on the average 2°C. (3.6°F.) to an elevation of 12 meters (nearly 40 feet). Now the specific heat of the atmosphere is very approximately 0.24. Hence to warm 1 cubic meter of the given air 1°C. requires about 310 calories. Hence to warm the air 2°C. to an elevation of 12 meters, as it enters the given area with the given velocity of one meter per second, will require, per linear meter at right angles to its direction, approximately $2\times12\times310\times7{,}440$ calories per second, or the consumption of, roughly, 3.7 liters or 6.5 pints of oil per hour.

Let there be one tree to each 10 meters (nearly 33 feet) square, as before, and suppose the orchard to be 1 kilometer (a little more than three-fifths of a mile) square, and therefore to cover 247 acres, and the wind to be normal to one of the sides. Under all these conditions the necessary hourly consumption of oil to produce the required number of heat units to protect the entire orchard would be:

	Liters.
To counteract radiation	8,600
To warm the entering air	3,700
Total	11,300
Or 2,487 gallons.	

[1] A. Ångström, Astrophys. Jr. 37, p. 305, 1913.

Or, finally, assuming as before one tree per each 10 meters square, about 1.13 liters, or, very approximately, 1 quart per tree per hour.

Obviously the larger the area to be protected, provided it is compact, say approximately square, or else with its greatest length in the direction of the prevailing winds, the less important, relatively, is the initial heating of the entering air and the less the total fuel required per tree. Obviously, too, anything that checks the wind movement in the orchard makes it easier to heat. Hence small, scattered trees are harder to protect from frost than are large and spreading ones.

Of course a greater wind velocity than two and a quarter miles per hour, the velocity above assumed, would appear to necessitate a correspondingly larger consumption of fuel for the border or entrance heating. But this, presumably, is not true in practice, since probably even this velocity, certainly a greater one, would considerably mix the surface-cooled air with the warmer air above, and thereby decrease the amount of necessary heating. During a perfect calm the required border heating is zero; it is also zero when there is a fairly good breeze, and hence has a maximum value at some quite moderate intermediate velocity.

From the above considerations it appears that, under ordinary conditions, open-air protection from frost is not only possible but may even be economically practicable, and therefore, in what follows, the problem will be considered from the economic standpoint, and, for convenience, briefly under several distinct heads.

CONDITIONS FAVORABLE TO FROST.

In order successfully and profitably to protect an orchard against frost by means of artificial heating, whether a pit or pomaceous orchard in bloom, or a citrus orchard in fruit, it is necessary to know fairly accurately just when the heating is needed and when it is unnecessary, so that on the one hand no injury from frost shall be permitted, and on the other no useless expense incurred through response to false alarms. Hence it is urgently advisable to be in close touch with the Weather Bureau which systematically furnishes frost warnings to orchardists and to many others engaged in agricultural pursuits, especially to those who provide themselves with artificial means for heating their orchards, or otherwise mitigating or preventing frost injuries. Parties desiring to avail themselves of this service should make application to the Chief of the Weather Bureau or to the nearest Weather Bureau station, fully explaining their case and stating how they may promptly be reached by telegraph or telephone. Messages will be sent at the expense of the Government to local organizations and communities, provided arrangements are made for posting or otherwise effecting the general dissemination of the information. Messages to individuals at their expense can also sometimes be provided for under suitable conditions. Orchardists who cannot avail themselves of this service will find it to their advantage to inform themselves as fully as possible of the meteorological conditions that usually precede frost and thus be guided by their own knowledge of the subject. One or more alarm thermometers may, and indeed should, be placed in the orchard and set to any desired temperature; but it is well to have not only the immediate call of the alarm but also, for the purpose of making any small preparations that may be necessary, the timely recognition of well-known frost indications. The most important and reliable of these are:

1. An evening orchard temperature of 40° F., or thereabouts.

2. Clear skies, to permit rapid radiation from the surface covering.

3. No wind, or very light, to avoid mixing the warm atmosphere above with the cold surface air.

4. Wind movement, so far as there is any, from a northwesterly direction.

5. Dewpoint below 32°F., to avoid the formation of a fog blanket, or the liberation of heat of condensation at temperatures above the freezing point.

But all these "signs" are only so many admonitions to be on one's guard in a matter where the price of success is eternal vigilance; they may be ever so helpful, but they are not infallible.

The moisture in the air is of special significance in this connection, and therefore it seems worth while to give some account of why it is so and of how it operates.

In the first place, an atmosphere containing a great deal of moisture does not let radiation from the earth pass through it nearly so well as does a dry one—it is not diathermanous, and therefore low humidity is essential to rapid surface cooling. Secondly, so long as the dewpoint remains above 32° F. frost can hardly form, since, as soon as the temperature of an exposed object falls below that of the dewpoint, vapor from the atmosphere condenses on it and in so doing converts its latent heat of vaporization into sensible heat and thereby prevents a greater temperature decrease. This relation of dew point to minimum temperature is not only obvious from elementary principles, but is also supported by the observational fact that at most places *frozen dew* is a thing of unusual occurrence.

To explain further: Since radiation is a surface phenomenon and therefore in amount is directly proportional to the area involved, while heat content, in the case of a uniform or homogeneous substance, is a volume phenomenon, it follows, in the case of cooling by radiation, that the coldest portion of an object is that portion whose exposed surface bears the greatest ratio to the mass it covers. Hence a sharp point or spine is the coldest portion of a body cooling as the result of its own radiation while the corners, edges, and flat surfaces follow in the order of increasing temperature. Hence both dew and frost collect most abundantly on exposed points, corners, and edges in the order named In the case of dew the surface tension of the water forces it to assume the shape of least area—that is, the sphere. Frost on the other hand, resulting as it does from the direct conversion of water vapor into ice, is a solid from the beginning, and therefore develops in the form of spicular crystals.

Now, if the temperature could fall considerably below the dewpoint, it necessarily often would happen that the droplets of dew formed in the earlier portion of the night would later be congealed into so many little balls of ice, on which a subsequent coating of hoar or white frost might or might not accumulate. But this phenomenon, which a sufficient drop in the humidity *after* the deposition of the dew may cause to happen, apparently does not otherwise occur. Hence it seems fair, both from elementary reasoning and from ordinary observation, to assume that the temperature of even exposed leaves and flowers will not fall appreciably below the coincident dewpoint. Hence a knowledge of the exact value of the current dewpoint is indispensable to successful frost prediction, and especially so since during "frosty" weather—that is to say, when the skies are clear and the atmosphere calm, the dewpoint usually remains nearly constant for several hours, and often much longer.

It must be remembered, however, that occasionally the dewpoint does change decidedly in the course of only an hour or two, and therefore that a high humidity in the early evening is not always a guaranty against a frost later in the night. Such changes naturally are most frequent, and hence the dewpoint indication least reliable, in regions that lie between the ocean on one side and arid mountains or plains on the other.

The simplest and most practical instrument for determining the dewpoint is the sling psychrometer. This consists of two thermometers fastened on a common frame and the frame in turn connected by a short flexible cord, link, or chain to a handle by which the whole may easily be whirled about at will. The bulb of one of the thermometers is bare and dry; the other is covered with a piece of clean unsized muslin which, when an observation is to be made, is saturated with clean water. As the psychrometer is whirled the water in the muslin covering evaporates, and thereby, if the covering is kept wet, cools to a certain temperature below which further whirling will not force it. When this minimum temperature is reached, and it usually takes but two or three minutes to obtain it, both thermometers are read; the temperature of the dry thermometer gives the temperature of the air; with this and the difference in the readings of the two thermometers, the dewpoint is easily found. [See the suitable tables, given in the Weather Bureau publication, No. 235, edition of 1900, entitled "Psychrometric Tables."]

For a given air temperature and a given dewpoint the difference in temperature between the dry and the wet thermometers of the psychrometer varies slightly with the barometric height in the sense that the greater the actual atmospheric pressure the less this temperature difference. However, as the variation in question is small, it will be sufficient for most practical purposes to use a psychrometric table adapted to a barometric height of 29 inches; and besides, for ordinary frost prediction only a small range in air temperatures will be needed.

Now that we have seen the conditions under which frost is most likely to occur it will be convenient to list and briefly to discuss a number of methods by which frost injury may be prevented.

SELECTION OF FRUIT AND OF REGION.

It has wisely been said that the best time to work corn is before it is planted, meaning of course that the most important factor in the production of a good corn crop is the preliminary preparation of the soil. In the same general sense it can truthfully be said that the best time to protect fruit from frost injury is before the orchard is set out; obviously by carefully considering what kind, or even variety, to grow and where to grow it.

Of course many things besides frost must be considered in establishing a commercial, or financially profitable, orchard, such as convenience to markets, kind of soil, shipping, keeping, and other qualities of the fruit and the like, but for all that in many cases climate is paramount and in every case important. An attempt to grow oranges in Ohio, for instance, or pears at Panama, would mean certain disappointment because of climatic conditions, regardless of proximity to market or any other local advantage there might be. Again, to illustrate with a less extreme and obvious case, it would be a commercial blunder, which fortunately no one makes, to attempt the production of prunes anywhere in the Eastern

United States, the region, perhaps, of their greatest market, simply because the climate does not suit them. To a less, though still important, degree this principle of climatic adaptation extends even to varieties of the same kind of fruit, and therefore if the variety is already selected, then the proper place in respect to climate, as well as soil and other factors, must be determined accordingly; or, if the place is already determined, the fruit and its variety best adapted to the climate and other conditions of the given locality should receive most careful consideration. Thus an early blooming and tender fruit should not be planted in a region where frosts are likely to occur late. In such a region there should be grown, if any, only hardy and late blooming varieties. This rule, everyone will admit, is perfectly obvious, but nevertheless it appears not always to be obeyed, and to its violation may well be attributed a goodly number of failures that need never have happened.

SELECTION OF LOCATION.

From the standpoint of frost protection the exact location is so vitally important that the difference of but a few hundred yards often determines between failure and success. The location should be such that:

1. The time of flowering shall be late.
2. The rate of morning heating shall be slow.
3. The air drainage shall be free and rapid.

The cold and therefore dense surface air formed on frosty nights drains away, under the influence of gravity, somewhat as water does to lower levels. Hence the expression "air drainage" in anology with water drainage. The importance of this last condition, air drainage, is so great as to justify, if it does not even demand, some account of exactly what it is and how it takes place.[2]

As already explained, during clear calm weather when the surface of the earth is warmed by sunshine and the lower air in turn by the earth the atmosphere up to from 2,000 to 3,000 feet at least is likely to decrease in temperature with increase of elevation very nearly at the adiabatic rate of approximately 1.6°F. per 300 feet. Above this level the rate of decrease is less. Under the given condition a quantity of air anywhere within the adiabatic layer, if slightly heated, would rise quite through this layer to and beyond its highest level before coming to a state of equilibrium, because although as it rose it would cool at the adiabatic rate, neglecting the always small loss of heat to the surrounding cooler air, this would be only the same rate of cooling as that of the atmosphere through which it was passing, and therefore if it started warmer than the adjacent atmosphere it would remain to the same extent warmer at every level than the newly adjacent atmosphere so long as the adiabatic of other equal rate of cooling applied to both. Similarly, a mass of air anywhere within the adiabatic layer, if slightly cooled, would continue to sink, remaining at every level colder than the surrounding air, until it reached the surface of the earth. If, however, the temperature gradient of the free atmosphere should be less than the adiabatic, say 1°F. instead of 1.6°F. per 300 feet, then a restricted volume of this air cooled to 1°F. below the temperature of the surrounding air would fall as before, but in falling 300 feet it would warm up roughly 1.6°F. while the temperature of the newly surrounding air would be but 1°F. warmer than that of the old, thus leaving still a difference of 0.4°F.; that is to say, the temperature of the falling mass would gain on that of the atmosphere through which it passed at the rate of only 0.2°F. per 100 feet. Hence, as it started 1°F. cooler than the adjacent atmosphere, to reach a level whose temperature is the same as its own, and therefore to come to equilibrium, it would have to fall 500 feet. In short, to small changes in temperature in the free atmosphere there usually correspond large changes in elevation.

Now the surface of the earth, and especially its covering of vegetation, loses heat by radiation much faster than does the atmosphere itself. Hence, after sundown, as Hann[3] and many others have explained, the surface layer of the atmosphere, rapidly grows colder and denser than the air somewhat above the earth and therefore tends to flow away to lower levels. This, too, in general, is the condition of the surface air at the next lower level, downhill say, and at the next and the next to the bottom of the slope. But, as water drainage tells us, there is everywhere among hills and mountains, except in occasional and restricted basins, a continuous more or less precipitous "downhill" all the way to a gently sloping valley or open plain; and hence in such regions surface cooled air must drain away or run downhill (the steeper the slope the more rapid the flow), substantially as does water, nowhere completely damming up, though often becoming sluggish, and nowhere forming frigid stagnant lakes save where water itself would form lakes.

As the cool, dense air flows downhill it of course slowly gains heat by compression but this does not necessarily mean that its temperature increases, for this dynamical heating may be, and on gentle slopes doubtless usually is, less than the simultaneous cooling it suffers through contact with the cold surface of the earth. But suppose, for instance, that the descending air has reached a place where it is at the temperature of the free atmosphere of the same level and therefore for the moment in equilibrium with it; even so it must continue to cool, through contact with the surface, more rapidly than the open air, because the earth and the plants that cover it are better radiators than is the atmosphere, and hence must continue its downward course toward a new place of equilibrium that is ever farther on.

In the special case, however, of a steep-walled basin in which water would form a lake, and, to a less extent, even in gently sloping valleys with steep sides, the drainage air from higher levels may and doubtless often does more or less overflow that of the lowest reaches, but this does not materially affect the general drift of air drainage nor greatly decrease its importance in relation either to frost formation or to frost protection. Whatever the details of this air drainage or however it may differ from time to time and from place to place, the lake of frigid air, if in a basin, or sluggish river, if a gently sloping valley is concerned, always has its surface or flood crest, so to speak, at the limit of the temperature inversion, or at that level both above which and below which the temperature decreases. Hence this level, more or less up on the adjacent slopes, necessarily is the warmest level, and therefore the one least subject to frost, or the one that marks the well-known and much-sought-after "thermal belt."

The above three conditions, late flowering, slow morning heating, and free air drainage, are, as a whole, best fulfilled on the northern or northwestern slope of a mountain or high hill, and therefore, so far as protection from frost alone is concerned this would be the ideal location. But then soil fertility and other conditions have to be considered, so that it can only be urged that the question of

[2] The reader's attention is invited to a different explanation of this so-called air drainage on p. 583.—[Editor.]

[3] Lehrbuch der Meteorologie, 3d edition, p. 446, Leipzig, 1914. [Hann does not discuss this species of air drainage critically. The above text simply conforms to the textbook versions, but the explanation is not satisfactory as it does not account for the inversion of temperature and the warming of the upper slopes.—Editor.]

frost immunity be given due—and that means very great—consideration.

Of the three conditions above mentioned, the third or free and rapid air drainage is by far the most important, and requires only that the orchard shall be located well up on the side of a mountain or hill. Even the top of a mountain or hill has distinct advantages as follows:

1. Low average temperature and consequent late flowering.

2. Complete air drainage and therefore comparative freedom from the effects of surface cooling.

3. The maximum of air movement and of air mixing.

There is, however, from the climatic standpoint, a limit, different for different regions, to the height at which orchards should be planted. The extreme and even the average temperature at points of greater and greater elevation soon becomes too low and the growing season too short for profitable fruit growing.

DELAY OF TIME OF FLOWERING.

The piling of ice and snow about the trees.—Obviously if the time of flowering could be delayed till after the latest killing frost, assuming there be left a sufficiently long growing season, the chance of having an abundant crop of fruit would be greatly increased. Indeed people have often sought to attain this end through the piling of snow or ice about the trees, but the results have never been equal to the expectations.

As a matter of fact the development of the bud, even to the opening of the flower, depends primarily on its own temperature and the temperature of the twig and the limb to which it is attached, and to only a very slight extent on the temperature of the roots. Now, since cold surface air remains close to the ground and even drains away wherever there is any appreciable slope, it follows that snow or ice piled about trees, however much it may chill the roots, can not greatly affect the average temperature of the twigs and the buds, nor therefore appreciably delay the time of flowering. It can not be said of course that no delay in the time of flowering can be produced in this way, for obviously the average temperature of the air that bathes even the topmost branches would be slightly decreased by any snow or ice piled about the trunk, and hence the time of flowering would certainly occur a little later. But it can be said that the probable delay is never sufficient to justify the necessary expense—that this method of preventing frost injury is commercially impracticable, and in all cases more of a delusion than a success.

Spraying with whitewash.—The object of this process is to cover the twigs and buds with a harmless white coating which, because it strongly reflects solar radiation instead of absorbing it, will keep down the average twig temperature and thereby delay the date of blossoming. Now a coating of lime whitewash besides being cheap and rather easily applied by means of a suitable spray seems to be harmless and certainly is a good reflector and therefore a poor absorber of solar radiation. Nevertheless the temperature of the twigs and of the buds can not greatly differ from the temperature of the air that surrounds them, and therefore it would seem that this particular method also of delaying the time of flowering does not promise much success. Just exactly what small effect it would have does not appear to have been definitely established, but it does not look promising from a commercial standpoint unless indeed the coating of whitewash should be beneficial for some other reason, such as the killing of insects, the prevention of fungus and the like.

FROST PREVENTION.

Material of ground covering.—Since the temperature of the atmosphere at and near the surface of the earth is largely determined and controlled by the temperature of this surface itself, it follows that where the ground covering is a good radiator the temperature of the air will fall lower, other things being equal, than it will where the covering is a poor radiator. Hence the probability of frost can be somewhat reduced by covering the ground with a poorly radiating material. Indeed it has already been the custom for a number of years to cover certain cranberry grounds with white sand as a means of reducing the danger from frost, and it is quite certain that part of its efficacy in this respect, though only a part, is due to its low power of radiation. However, to cover an entire orchard with this or any other poor radiator probably would seldom be practicable. Besides, such a ground covering at best can never be more than a slight and very imperfect protection from frost.

Condition of ground covering.—Obviously there never is any occasion to protect either fruit or flower from frost when the ground is frozen—either the trees have not yet come into bloom or else the fruit is already killed. Hence, whenever there is any need to protect from frost the earth is unfrozen, and contains more or less heat to spare. Clearly, then, this soil heat should be made available, and to this end the soil *bare* and *tightly rolled*. Bare because weeds and other trash not only are free radiators as a rule, but also to a great extent insulate or render unavailable the ground heat, and tightly rolled for the purpose of rendering the soil more compact and therefore a better conductor and better warmer of the air above.

In many cases, however, it is not practicable to utilize the ground heat to best advantage, owing to the necessity of covering the orchard (citrus) during the frost season with some good humus-producing crop. But this practical method of obtaining the necessary humus does not alter the general fact that ground heat is valuable in warding off frost, nor that this heat is best secured from a bare and tightly rolled surface.

Whether the soil should also be moist seems doubtful. The water would of course have much heat of its own, and besides it would increase the thermal conductivity and thus bring a larger amount of heat to the surface. But, on the other hand, there would also be an increased amount of evaporation with its attendant cooling, so that the net result presumably might be either a heating or a cooling depending upon the rate of evaporation directly, or indirectly upon the surface temperature, absolute humidity and wind velocity.

Deflection of air drainage.—Clearly if cold air drains into an orchard danger from frost is somewhat correspondingly increased. Hence in some localities it might be worth while to run a closely planted hedge, a tight plank fence, or even a stone wall along the upper side of the orchard in such manner as to deflect the maximum amount of cold air away from the trees. Of course this refinement may seldom be commercially practicable or even very effective, but the vital importance of air drainage justifies its inclusion among the possible means of preventing frost.

Forced air drainage.—Since air drainage is so important as a means of preventing frost, it follows that where natural drainage is obstructed artificial or forced drainage, if sufficiently abundant, might be substituted with good effect. That is to say, with good effect so far as preventing the frost is concerned, but the cost of the plant necessary to produce this drainage, and the cost of operating it, obviously rule it out absolutely as a commercial process.

Mechanical mixing of the atmosphere.—As already explained, frost, at the time of year when it is likely to injure fruit, does not often occur when there is wind sufficient so to mix the lower atmosphere as to prevent excessive surface cooling and therefore a temperature inversion. Hence, on perfectly still nights, vigorous mechanical mixing of the air, if on a sufficiently large scale, would have results similar to a natural mixing by the winds.

But this process, too, like forced drainage just discussed, clearly is totally out of the question as a commercial proposition, and is mentioned here only further to emphasize the narrow limits within which the problem of commercial frost-prevention is restricted.

Spraying with water.—As already explained, when the amount of humidity in the atmosphere is sufficient to put the dew point above 32° F., frost can hardly occur. Hence it would seem that a number of spraying fountains scattered through an orchard might raise the dew point above the freezing stage and thus avoid the formation of frost.

However, the problem is not so simple as it looks, nor is the prevention of frost by this means an *a priori* certainty. In the first place the spray, to be effective in the manner explained, must evaporate, and that means cooling, or the conversion of just as much heat from the sensible to the latent stage as later can be set free by condensation. Again, if the spray falls directly on the trees when in bloom great injury may be done to the flowers by washing away the pollen. Of course no such objection applies after the fruit is formed. Spraying with water, therefore, apart from the expense and difficulty of putting it in operation, does not seem to promise well as a means of preventing frost. However, further experimentation in this line seems desirable.

Screening against loss of radiation.—Since the low night temperature that threatens or even brings frost, results from more or less free radiation from the surface covering of the earth to and through the atmosphere above, it follows that any intercepting screen, *if itself a poor radiator*, will more or less effectively prevent the formation of frost. This explains why frost seldom occurs on cloudy or foggy nights, and why a covering of papers or of cloth partially protects plants of any kind from freezing.

It must be distinctly remembered, as above implied, that it will not do to use just any sort of covering. A rusty tin can or bucket, for instance, turned over a plant increases its chance of freezing. In fact it occasionally happens that plants "protected" in this manner are entirely killed while the unprotected ones remain uninjured. The explanation of course is simple enough. The rusty tin can is a better radiator than is the soil and hence it, and the air within it, becomes even colder than the ground or the surface air round about.

There are, however, many substances, such as paper, cloth, and wood that are, in various degrees, poor radiators, and these may be used as screens to great advantage, particularly in the case of small fruit, beds of tender vegetables, and the like, where neither the cost of the screens nor the labor of handling them is prohibitive. Clearly though, the screening of an orchard, whether only tree by tree or the entire area, is quite another thing from screening a flower bed or berry patch, and obviously in nearly if not quite all cases is commercially impracticable, both because of the original cost of an efficient screen and because of the labor necessary hurriedly to put it in position. To be sure the screen might be a lattice covering permanently in position, but the obvious disadvantages of such a covering, original cost, cost of upkeep, interception of sunshine and doubtless still others, are so great that manifestly it can have but little practical use.

Smudging.—A pall or canopy of smoke, or smoke and steam, spread over an orchard by burning such stuff as damp leaves, stable manure, wet straw and the like, among the trees, especially on the windward side, constitutes a moderately effective screen against radiation losses. The process of securing this screen also supplies more or less heat to the surface air and still further protects the orchard from frost. Smudging, then, if properly carried out, seems to be not only scientifically sound but also economically practicable.

Dry heating.—As explained in the first portion of this paper and illustrated by the two numerical problems, large orchards usually can be protected from frost by a properly distributed dry heat, and that too at a small fuel cost per tree. What the fuel should be, whether wood, coal, oil, or even gas, must depend of course upon such things as cost, availability, convenience of use, and the like. In most places crude oil seems to have more advantages than does any other fuel, though, if burnt with a smoky flame, it has the very distinct disadvantage of smutting the fruit, an objection that applies essentially to citrus orchards in fruit and not to orchards in bloom. It also smuts houses and, in general is objectionally dirty.

Dry heating for the protection of an orchard against frost should be carried out in the largest practicable number of small units, however the heat is supplied, whether by direct combustion of some suitable fuel, by the circulation through pipes of warm water, by the delivery of warmed air to the individual trees, or by any other process. A few strongly heated centers both endanger the nearest trees and also, through the strong local convections set up, send most of the heat to levels where it will be of little or no service.

Just how the oil pots or other heaters should be constructed is another problem, and one which obviously may be more or less excellently solved in innumerable ways.

Irrigation.—Flooding of the ditches in a cranberry bog has long been practiced as one of the most effective means of warding off a threatened frost. The great heat supply of the water prevents the temperature of the surface air from decreasing nearly so rapidly and therefore from reaching so low a temperature as it otherwise would. Now, just as irrigation is effective as a means of preventing frost in a cranberry bog, so too it would be effective in warding off frost in an orchard. But then comparatively few orchards are so situated that they can be easily and cheaply irrigated whenever occasion may require. Besides, it must be remembered that a wet soil, whether wet from rain or from irrigation, warms but slowly by day, and even cools when the weather is windy and cloudy, so that if the supply of irrigation water is small, a single irrigation, even if it should prevent the frost of the first night, might render a later frost all the more likely. Irrigation, then, even in the few places where it could be used, is rather a dangerous weapon to employ in fighting frost, one liable to become a meteorological boomerang as it were. A further objection to irrigation is the fact that it is likely to interfere with other forms of artificial heating by rendering any necessary hauling of fuel difficult if not impracticable.

FROST CURE.

In a measure frost injury to flower as well as to fruit may be cured by slow thawing. Probably it would be much more accurate to say that frost injury, at least in many cases, is caused rather by rapid thawing than by the original freeze; though it must be admitted that just how fruits, flowers and plants actually are injured by low temperatures is not perfectly understood. At any rate when fruit or flower is very slowly thawed out it often appears to be uninjured. Hence even after frost has covered an orchard it sometimes is possible, especially by the use of a heavy smudge on the windward side, so to shut off the morning sunshine and thereby so greatly to decrease the rate of thawing that but little injury follows. Clearly, though, this is a risky practice. It is another case where the old adage, "an ounce of prevention is better than a pound of cure," applies with full force.

CONCLUSION.

The most important thing in relation to frost protection is the proper adaptation to each other, at the time of planting, of fruit, climate, and location, with reference especially to time of flowering, probable dates of latest and earliest killing frosts, and freedom of air drainage. In this way natural frost immunity may generally be secured.

In places not so favored artificial heating often may be used on a large scale and with commercial success to prevent frost, the strong temperature inversion of a frosty night serving as a ceiling that restricts the heating to a thin surface layer of the atmosphere, provided, of course, that the heating is diffuse and the temperature of the air raised only a few degrees.

The meteorological principles and the physical laws involved in the problem of frost protection seem reasonably clear, but the question of economy introduces so many and such uncertain factors that its commercial practice must be difficult if not impossible completely to standardize. The best practice at one place and under one set of conditions presumably will differ in detail and may even differ in method from that of some other place under other conditions. To each region, and even to each orchard, pertains its own problem, which rational or scientifically guided experimentation alone can approximately solve.

In closing I wish to thank Mr. J. W. Garthwaite, of Corona, Cal., for his kindness in reading the manuscript of this article and for his generosity in putting several valuable suggestions at my disposal.

II.

UTILIZATION OF FROST WARNINGS IN THE CITRUS REGION NEAR LOS ANGELES, CAL.

By FORD A. CARPENTER, Local Forecaster.

[Dated Weather Bureau, Los Angeles, Cal., Jan. 22, 1914.]

CONTENTS.

(a) *Introduction.*—For 20 years or more oranges and lemons have been successfully raised in southern California, but it is only within the past decade that strictly scientific and up-to-date methods have been used in raising and selling the citrus products.[1] This has brought about a standardization of both the fruit and the marketing. Improved and more expensive methods of preparing the land, irrigating it, and planting with high-grade stock, as well as constant vigilance in fumigating and spraying for fruit pests, have necessitated better facilities for packing, handling, and selling the product. The frost menace made its first appearance in 1896, when some regions escaped without serious damage. The orchardists in the frosted localities immediately began experimenting with various preventives, thus antedating the frost protective work of the deciduous fruit growers in Colorado, Washington, and Oregon. The frost of two years ago increased the number of heating appliances, and the severe freeze of last year brought the entire industry in all portions of California face to face with an added hazard. It has been said that the freeze of 1913 raised a new crop of prevaricators, which may be divided into two classes—those who claimed that their district was frostless and others who declared that their district suffered destruction. A year has passed, and it is not too optimistic to say that the truth is a little nearer the former than the latter. Those orchardists who, anticipating severe frosts, had provided themselves with artificial heating devices realized handsomely on their additional investment, for the short crop of oranges, lemons, and grapefruit brought excellent prices. Fruit growers in the citrus region of California now add to their fixed expense account a liberal allowance for oil or coal pots, storage of fuel, instrumental equipment, and quarters for emergency labor. One million approved oil pots are now scattered over the citrus region in southern California.

It is the object of this memorandum report to give a brief description of the character of the country, its elevation and configuration, the variation in the exposure to sunshine and wind, and the variations in temperature that are caused by local environment. It is proposed to treat very briefly the distribution of lemons and oranges in differing climatic areas. Weather conditions causing frost will be briefly discussed. The manner in which warnings are issued by the local office of the Weather Bureau at Los Angeles, and how they are utilized by the fruit growers in this district will be considered in detail,

[1] Citrus crops of California for 1913; annual estimate by the Riverside Daily Press, Jan. 20, 1914; reduced to percentage by F. A. Carpenter.

Counties.	Orange.	Lemon.
	Per cent.	*Per cent.*
Redlands district	12	0
Riverside	10	0
Pomona	12	6
Ontario	11	8
Azusa-Glendora	9	6
Orange	7	9
Highland	6	0
Covina	5	0
Placentia, Fullerton, Rialto	11	....
Rialto, San Fernando	....	6
Whittier, etc	6	11
Ventura	5	15
San Fernando, Pasadena	4	....
Rialto, San Fernando, etc	....	6
San Diego, etc	2	....
Pasadena, San Diego, etc	....	10
Corona	0	12
San Dimas	0	9
Santa Barbara	10	8
Totals	100	100
SUMMARY.		
Northern California	14	0
Southern California	86	100
Crops, respectively, by carloads	35,270	3,900

Total, 39,170 carloads, or about 80 per cent of normal.