

PREDICTING FROST-A COOL SUBJECT

Jeff Andresen

Department of Agricultural Meteorology
Michigan State University

What is Frost?

Pedestrian or vehicular traffic across a frosted surface can result in serious damage to turf, and by preventing or delaying play on a course, in economic losses for course management. In meteorological terms, the term >frost= refers to any condition in which the ground surface (including any vegetation or the bare soil surface) has fallen below 32°F. This can be associated with a large scale incursion of cold air into the region of interest, so-called advection frost, or by the radiative cooling of a surface under relatively clear, calm conditions, which is referred to as a radiation-type frost. In addition, the formation of ice crystals on the ground surface can be the result of either the freezing of supercooled water droplets, referred to as rime frost, or by direct sublimation of ice on a surface, called whitefrost or hoarfrost. When the ground surface reaches freezing temperatures with no formation of any ice, the condition is called blackfrost. Of all these types, whitefrost, the typical whitening of the ground as the result of radiational cooling from the surface, is by far the most common in Michigan and the primary topic of our discussion.

To understand the formation of whitefrost (referred to hereafter as frost for brevity) near the ground surface, one must have an appreciation for the dynamics of atmospheric moisture. The ability of the air to hold water in vapor form is dependent upon its temperature. The higher the air temperature, the greater the amount of water vapor that the air can potentially hold. The dewpoint temperature is defined as the temperature at which water vapor in the air will condense (into dew, fog, or clouds) if cooled at constant pressure (a directly-related term, relative humidity is determined by the amount of water vapor that is actually in the air divided by the amount that could be potentially held by the air at that temperature level). When the air temperature falls to the dewpoint, the air is said to be saturated, as it cannot hold any more water vapor. Any excess moisture is condensed out into liquid (dew) or ice (frost).

Among the most important concepts in predicting frost is an understanding of meteorological factors leading to its formation. The overwhelming majority of frosts are accompanied by relatively calm, cloudless weather conditions during evening and early morning hours. During daytime conditions, when the presence of solar radiation and/or wind acts to mix up the lowest levels of the boundary layer near the ground, the temperature of a given location is relatively dependent on meteorological conditions within the surrounding region. In contrast, on clear, calm nights, there is no incoming solar energy to create thermal turbulence and the ground surface radiatively loses energy out to space, which are usually a function of the site's microclimate. Both of these factors combine to allow the ground surface to cool at a steady rate, and because air itself is an effective thermal insulator, the surface (and any vegetation on it) quickly become cooler than the air above it. In meteorological terms, this is termed a boundary-layer inversion. When the cooling surface reaches the dew point of the air above, the result is formation of dew, or if the surface is at or below freezing, frost. In such inversions, it is not uncommon to see temperatures several degrees F. cooler at the ground surface vs. 5 or 6 feet above the surface. This is the reason we frequently observe frost on the ground level when the >official= temperature, taken at 5 feet above the ground surface is in the mid- or even upper 30's F.

Other Factors Which Influence Frost Formation

There are several major factors which strongly influence the risk of frost and its formation:

Topography. As the ground surface cools and an inversion layer develops, some of the air near the surface cools to a temperature below that of layers above. Since cool air is denser than warm air, the air cooled near the surface begins to flow >downhill= like a liquid due to the force of gravity. This movement of air, which rarely exceeds velocities of more than 1-2 miles/hour, is referred to as >cold air drainage= and is one of the primary reasons that fruit crops can be successfully grown in Michigan (mainly on hilltops where cooler air drains away). Because of this, hilltops, ridges, hillsides, and other topographical features in which relatively cooler air can drain away are relatively less likely to experience frost formation. In contrast, low-lying areas, especially depressions where cold air can literally collect or pond, are significantly more likely to experience a greater frequency and length of frost. The rule of thumb here is that concave topographical features (relative to the sky) are cooler than convex features.

Soil Type, Moisture. One factor influencing the rate at which the ground surface cools is the movement of heat energy upwards out of the soil profile, called ground heat flux. The greater this upwards flux at night, the less the rate of surface cooling. Therefore, any modification of the soil or ground surface to increase or lessen this flux can have a significant impact on the surface temperature. The most common way of modifying the surface layer to trap some of the ground flux and move the radiative thermal boundary to a level above the surface is a mulch of some kind, preferably one which contains quantities of insulating air. Since this is not practical for turf management in most cases, we shift our attention to modification of the thermal properties of the soil itself. All else being equal, a soil with greater water content will have greater thermal conductivity than the same soil at lesser water content, and will allow more of the ground heat flux out of the ground towards the surface. Thus, keeping a soil well-watered can offer some limited protection against frost formation. On a longer term basis, this also means that coarse-textured soils with lesser water holding capacities will generally experience more frost than sites with fine-textured soils of greater water-holding capacities.

Vegetation. The type and amount of vegetation on a surface can have a significant influence on frost formation. Overhanging vegetation can directly interfere with radiative heat loss of the surface, preventing frost formation on the surface. Dense vegetation near the surface (such as dense, unmowed turf) can trap large quantities of air which can in turn can insulate the ground surface similar to a mulch.

Frost Dissipation

In most frost situations, the length of the event is directly dependent on daylength and the time of sunrise. As the sun reappears in the morning, it begins to radiatively heat the ground, which may melt the frost directly by heating the surface on which the frost has formed, or indirectly by causing thermal turbulence which mixes warmer air from above the ground surface layer down to the surface. Normally, the last areas to lose the frost will be those shaded by vegetation or by northern or western facing slopes. The rate at which the resulting liquid water evaporates from the surface will be dependent on the amount of solar energy available and the amount of water vapor already in the air above the surface (i.e. the sunnier and drier the air, the more rapid the rate of evaporation and drying of the surface).

Predicting Frost

From the discussion above, it is probably obvious that the key to predicting frost formation is the prediction of clear, calm conditions that are necessary for its formation. On a large scale meteorologically, clear, calm conditions are most likely associated with areas of surface high pressure (as opposed to areas of low pressure, which are generally associated with clouds and wind), so any prediction should be heavily based on surface weather maps where these features can be found. On the short term, consult your local TV weather prognosticator or the National Weather Service (NWS) short term (12-24 hour in the future) forecast. For all the reasons above, pay particular attention to the forecast cloud, wind, and temperature conditions for the period of interest. Also note the dew point temperature and compare with the forecast minimum temperature for a guess of the likelihood of dew or frost formation (the closer the dewpoint temperature to the air temperature, the greater the likelihood of dew/frost). For those who surf the world-wide web, one can obtain this information At MSU's Agricultural Weather Office www site. Once here, consult: a) the latest NWS forecasts, b) the MSU specific minimum temperature forecast for many agricultural locations around the state, and c) detailed computer-generated forecast guidance information for 16 sites across the state which include forecasts of all relevant variables (clouds, wind speed, etc.) at 3 hour time increments out to 60 hours in the future. The url of the site is www.agweather.geo.msu.edu.

And how low might the minimum temperature go if you don't have access to any forecast information? Here is a rule of thumb that works fairly well for most humid climates like Michigan. Many of you may have a sensor that gives wet bulb temperature, which is not the same as dewpoint temperature. The wet bulb temperature is the temperature to which air can be cooled by liquid water evaporation (the rate of cooling is dependent upon how much water vapor is already in the air). This is normally measured by moving air across a temperature sensor covered with a wetted wick (usually with either a fan or by a hand-held sling). Given the wet bulb temperature, one can also obtain the dewpoint temperature and relative humidity. For reference, the dewpoint temperatures will always be less than or equal to the wet bulb temperature, which will always be less than or equal to the air temperature. The only time all three of these temperatures can be equal is at 100% relative humidity.

The rule of thumb in here is that the minimum temperature on a given morning will approach the dewpoint temperature taken the prior evening. This "rule" has some scientific merit for the most common

frost scenarios; clear, calm conditions with cold air drainage and vertical temperature stratification. In this situation, there may be little transport of moisture in the air in or out of a general area, so the dewpoint temperature taken the prior evening will be indicative of the moisture in the air during the following several hours. When the air temperature does fall to the dewpoint temperature, two things happen. First, water vapor condenses out of the air and gives off heat (from the phase change of water vapor to liquid water). Secondly, some of the vapor may condense in the air itself, forming fog. This in turn drastically reduces the amount of heat lost by the ground to space. Both of these combine to prevent the air temperature from falling much further. From past experience, you may have noticed that the minimum temperature during one of these events commonly remains a few degrees above the dewpoint temperature. This is probably because the air temperature is taken at 5 feet above the surface, and under these calm, clear conditions, it is warmer than the temperature at or near the surface, which is relatively cooler and has reached the dewpoint.

Some important notes of caution with this rule of thumb. First, it is only helpful under the circumstances described above (relatively clear, calm conditions.). Freezing temperatures experienced under cloudy, windy conditions would be much more complicated to determine (based on the temperature of airmass upstream, etc.). Secondly, with the clear, calm frost scenario, it is not uncommon for the dewpoint temperature to drop a few degrees during the nighttime hours, as moisture is condensed out of the air and into dew or frost, resulting in minimum temperatures somewhat lower than those estimated the evening before. The best strategy is still to closely monitor conditions throughout the event, by occasional reading of thermometers and/or dewpoint/wet bulb sensors in the field.