Real-Time Weather Monitoring for Frost-Protection Sprinkler Operations in Almond Orchards

Project No: **10-HORT10-Snyder**

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Objectives:

- Develop and test an automated computer-based model to monitor real-time weather conditions in orchards as a basis for managing sprinkler operations for frost protection.
- Develop guidelines for using the model to manage sprinkler operations on radiation frost nights.

This project was designed to assist growers in making prudent decisions about whether or not to use sprinklers and to help them predict when to start and stop the sprinklers during a radiation frost night (i.e., a night with calm winds and mostly clear skies). One goal was to develop a model to predict trends in air and dew point temperature during typical frost nights and to determine the corresponding wet-bulb temperature trend. The air and dew point temperature trends depend on the temperature at a starting point, i.e., just after sunset, and a forecast of the minimum temperature the morning following the frost night.

Interpretive Summary:

This project is nearly finished. The developed computer model provides an easily understandable methodology to help growers decide if and when to use under-tree sprinklers for frost protection. The methodology is based on the air and wet-bulb temperatures and how they relate to the critical damage temperature, which depends on the crop stage. Temperature measurements and forecasts from public or private weather services are input into the model to provide an initial trend for air, dew point, and wet-bulb temperatures. Remote data transfer from a weather station near the orchard is used to update during the night and improve accuracy. We are working with potential vendors to add the developed program to commercially available weather stations and to apply the real-time update model. Demonstration model(s) will be shown at the annual Almond Board conference.

Model Application

When water cools or freezes, the chemical process is exothermic meaning that it releases energy (or heat) to the environment. When water evaporates, the chemical process is endothermic meaning that energy (or heat) is removed from the environment. Therefore, cooling and freezing of water is beneficial and evaporation is detrimental for frost protection. The sprinkler application rate needed for frost protection depends on the evaporation rate, which in turn, depends mainly on the wind speed and dew point temperature. Higher wind speeds and lower dew points lead to more evaporation and more cooling, so more water must be applied for the cooling and freezing to compensate. The effectiveness of under-plant sprinklers for frost protection depends on the application rate with more protection afforded by higher application rates.

The wet-bulb temperature is the temperature that is reached when there is no external source of energy (e.g., sunlight) and the energy used to evaporate the water comes mainly from heat in the air. The temperature drops because the energy from the air is used to evaporate the water and the dew point rises because evaporation adds more water vapor to the air. Eventually, cooling the air and increasing the dew point will cause the air to reach saturation (i.e., 100% relative humidity) when the temperature equals the wet-bulb temperature and the vapor pressure equals the saturation vapor pressure at the wet-bulb temperature. The wet-bulb temperature is typically measured with a wet-bulb thermometer (i.e., a thermometer with a wetted cotton cloth over the thermometer bulb). The cotton cloth is wetted with distilled water, and the bulb is ventilated to cause evaporation until the temperature stabilizes at the wet-bulb temperature. Unfortunately, the wet-bulb temperature is not commonly measured by automated weather stations, and it is difficult to estimate the wet-bulb temperature from other humidity measurements.

When sprinklers are first started during a frost night, the air and plant temperature will initially drop to the wet-bulb temperature until the water begins to freeze and releases sufficient heat to compensate for the energy losses to evaporation. If the wet plant parts cool to below the critical damage temperature long enough for internal ice formation and cell dehydration, it can cause frost injury. Similarly, if sprinklers are stopped before the wet-bulb temperature measured upwind from the orchard is above the critical damage temperature, the plant parts can cool to the point where damage occurs. The key to proper management is to start and stop the sprinklers when the “wet-bulb” temperature measured upwind of an orchard is above the critical damage temperature, which is related to the crop development stage of the orchard.

Glossary

wet-bulb temperature (T_w)

critical damage temperature (T_c)

air temperature (T)

dew point temperature (T_d)

As noted above, almond growers are often faced with decisions about (1) whether to use sprinklers to protect against frost damage, (2) when to turn them on, and (3) when to turn them off. Proper management can often protect an orchard against losses, while making poor decisions can potentially increase crop losses. This project was designed to help growers with these decisions. The project is based on calculating trends in the ***wet-bulb temperature (T_w)*** and comparing with the orchards ***critical damage temperature (T_c)***, which depends on the crop development stage of the trees.

When sprinklers are first started, the ***air temperature (T)*** will generally drop to the wet-bulb temperature (T_w), and T will increase again as the water begins to freeze and release heat. If water is applied at an adequate rate, the soil surface temperature will quickly rise to near the melting point (0^oC or 32^oF), and it will stay there as long as the sprinkler application rate is high enough so that more heat is gained by freezing water than is lost by evaporating water from the wet-ice covered surface.

The decision about whether the sprinklers should be used depends on how far the air temperature will fall below T_c and how long it will stay below the T_c. Generally, frost damage is minimal if the air temperature measured between 1.5 and 2.0 m (5-6 feet) height falls within about 0.28^oC (0.5^oF) below the T_c for one hour or less, but the likelihood of more damage increases at lower temperatures or if the temperature is below T_c for longer periods of time.

Because the air temperature initially drops to the T_w when sprinklers are started, it is important to start them when the T_w is still above the T_c on the first night. If the sprinklers are used for more than one night and the temperatures remain near the melting point ($T=0^oC$ or 32^oF) during the day, then the sprinklers should be started before the T_w falls below 32^oF on the second and subsequent nights. This is needed to prevent the sprinkler heads from icing up and preventing sprinkler operation. After the sun has come up and is starting to warm the surface, it is possible to stop the sprinklers after the T_w exceeds the T_c. However, waiting until the T_w exceeds 32^oF is safer. To help growers make decisions about frost protection with sprinklers, we developed a computer program that generates a trend line of T_w and compares T_w with input T_c.

We use two approaches to determining the trend line of T_w. One approach is to input the measured air and ***dew point temperature (T_d)*** on the hour between 1 and 2 hours after sunset and on the hour between 0 and 1 hours following sunrise. For example, if sunset is at 5:41 p.m. and sunrise is at 6:15 a.m. standard time, then the starting T and T_d values are measured in or near the orchard at 7:00 p.m. (i.e., between 1-2 hours after sunset) and the predicted minimum T and T_d values are for 7:00 a.m. (i.e., between 0-1 hours after sunrise). The prediction of T and T_d just after sunrise can come from a weather service forecast or by developing a forecast model specific to your orchard using observed data. After entering the T and T_d data, a model, based on a square root function, is used to predict the T and T_d values expected at the end of each hour during the night. A T_w corresponding to the T and T_d pairs is calculated, and the hourly T, T_w, T_d, and T_c values are plotted on a graph. If the air temperature is predicted to go more than 0.5^oF below T_c for one hour or more, then start the sprinklers prior to the T_w falling below the T_c during the first night of freezing temperatures. If the T is predicted to go below 32^oF on subsequent nights, then start the sprinklers when T_w falls to just above 32^oF to avoid icing up the sprinkler heads.

A second approach to determining the trend line for T_w is to use National Weather Service (NWS) forecast of hourly air (T) and dew point (T_d) temperatures to calculate T_w each hour. Most National Weather Service (NWS) forecast offices have a “Weather Tables” product available on their websites where you can find hourly values for T and T_d. It is possible to highlight and copy the hourly data from 1-2 hours after sunset until 0-1 hours after sunrise the next morning into a spreadsheet developed in this project. The spreadsheet will automatically calculate the corresponding T_w values at the end of each hour, and a plot of T, T_w, T_d, and T_c is determined. Again, the plot T and Tc provides the information needed to determine if the sprinklers are needed, the comparison of T_w and T_c is used to determine when to start and stop sprinklers on the first night of freezing, and T_w and 32^{o}F is used to determine when to start and stop sprinklers on subsequent frost nights.

In addition to using forecasts of T and T_d to determine hourly T_w values, the ability to update the forecast trendlines using remote transfer of data from a weather station to your computer was also developed in this project. The program can update T and T_d data at 10 minute intervals during the night, and the T_c prediction model is adjusted up or down in response to the realtime updates. This increases accuracy as the night progresses.

Materials and Methods:

In this project, we used Microsoft Excel software to develop trends of air (T), dew point (T_d) using predictions from the NWS or an on-site forecast model, and wet-bulb (T_w) temperature calculated from the T and T_d values. Then, using a critical temperature (T_c), which depends on the crop development stage of the trees, the temperature trend lines are used to determine if sprinkler usage is needed and when to start and stop the sprinklers. We developed computer applications to update the temperature trend lines using observed real-time data and we are currently working with weather station vendors to develop commercially available systems.

Results and Discussion:

Observations of radiation frost nighttime energy balance curves and temperature trends were examined, and it was noted that the air temperature drops rapidly during the afternoon and evening as the net radiation drops. **Figure 1** shows the trends of energy balance components during a clear, calm night. The net radiation becomes negative about half an hour prior to sunset, and it reaches its most negative value (i.e., losing the most energy to radiation) shortly after becoming negative. During the night, the net radiation energy losses slowly decrease and, therefore, the air temperature drops slightly faster early in the night and then decreases at a slower rate until reaching the minimum temperature shortly after sunrise. In **Figure 1**, the red line (T_p) is the predicted temperature trend, which matches well with the blue observed temperature trend. The temperature prediction model is based on the equation:

$$T_p = T_0 + b\sqrt{t_i - t_0} \quad (1)$$

where T_p is the predicted temperature at time t_i in hours after time t_0=0, T_0 is the temperature measured at time t_0, which occurs the end of the hour between 1 and 2 hours after sunset, and the coefficient b is calculated as:

$$b = \frac{T_n - T_0}{\sqrt{t_n - t_0}} \quad (2)$$

where T_n is the predicted minimum temperature at time t_n (in hours after t_0) at the end of the first hour following sunrise. The times t_0, t_i, and t_n are automatically determined from sunrise and sunset calculated in the model.

It seems that the same trend model used for the air temperature trend prediction also works well for a dew point temperature trend model. The equations to predict the dew point temperature trend are:

$$T_{dp} = T_{d0} + b_d \sqrt{t_i - t_0} \quad (3)$$

where T_{dp} is the predicted dew point temperature at time t_i in hours after time t_0=0, T_{d0} is the temperature measured at time t_0, which occurs the end of the hour between 1 and 2 hours after sunset, and the coefficient b_d is calculated as:

$$b_d = \frac{T_{dn} - T_{d0}}{\sqrt{t_n - t_0}} \quad (4)$$

where T_{dn} is the predicted minimum dew point temperature at time t_n (in hours after t_0) at the end of the first hour following sunrise.

Values for the air (T_0) and dew point (T_{d0}) temperatures at time t_0=0 and a forecast of the air (T_n) and dew point (T_{dn}) temperatures at time tn hours after start time t_0 are needed to compute the temperature trend lines. The T_0 and T_{d0} values can be measured in an orchard at the start time (t_0), which is found by going back to the end of the hour preceding sunset and adding two hours. In California, National Weather Service (NWS) regional offices provide a forecast table on their webpages. To find a NWS regional office website, search on the Internet (e.g., search for NWS Hanford to find the Hanford NWS Office). The webpages include predictions of T_n and T_{dn} for each hour during a night. The forecast of T_n and T_{dn} are selected from the webpage and input into the frost trend model. Alternatively, a spreadsheet to determine your own site specific T_n and T_{dn} forecast is included in the trend model application program.

A sample plot of the energy balance and observed and modeled temperature data is presented in **Figure 1**. Note that the temperature trend model for T_p works during the period when net radiation (R_n) is at its minimum value during the night. The upward (negative) ground heat flux (*G*) provides about half of the energy loss to R_n. The other half of the energy comes from downward (negative) sensible heat flux (*H*), which is heat loss from the air that causes the temperature (*T*) to drop. When sprinkler water freezes on the surface, it supplies additional energy that is used for R_n and it reduces the upward *G* and the downward *H*. The reduction in downward *H* slows the rate of air temperature drop and provides protection.

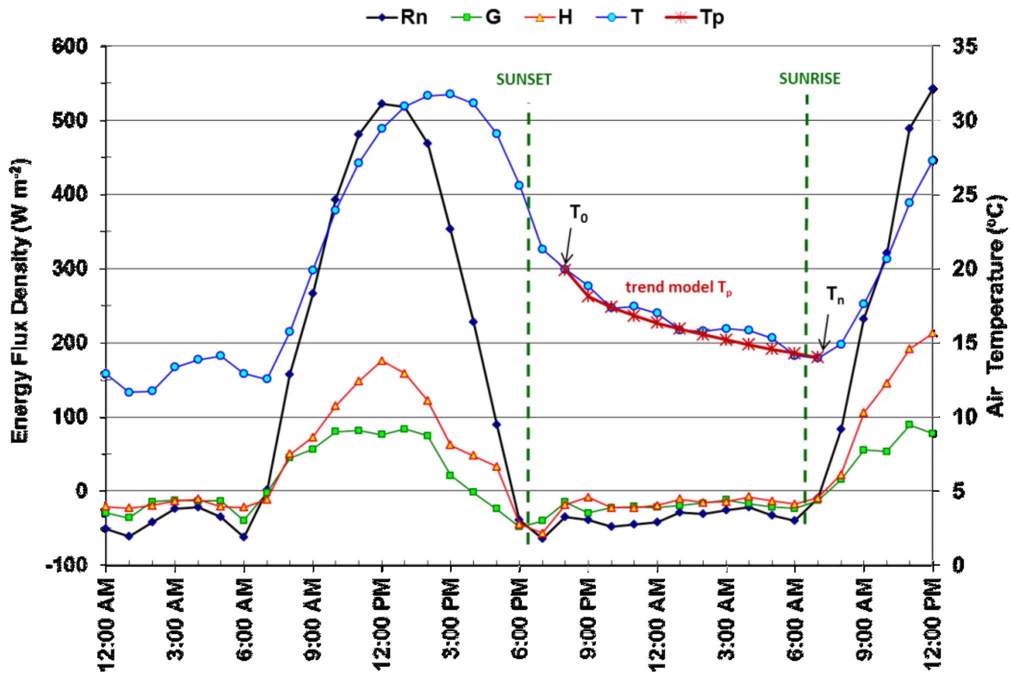

Figure 1. Energy balance (net radiation (R_n), ground heat flux (G), and sensible heat flux (H) and air temperature (observed T and predicted T_p) trends on a clear, calm night.

An iteration method is used to determine the wet-bulb (T_w) temperature from the air (T) and dew point (T_d) temperature, and the method is used to calculate the wet-bulb temperature at each time step. The wet-bulb temperature is determined from air and dew point temperatures following Campbell Scientific (1995). The actual vapor pressure is calculated using the equation:

$$e = e_w - 0.00066(1 + 0.00115\,T_w)(T - T_w)P \qquad (5)$$

where:

e = actual vapor pressure (kPa)
T = air (dry-bulb) temperature (^oC)
T_d = dew point temperature (^oC)
e_d = Saturation vapour pressure (kPa) at the dew point temperature (T_d)
e_w = saturation vapour pressure (kPa) at the wet-bulb temperature (T_w)
T = air (dry-bulb) temperature (^oC)
P = atmospheric pressure (kPa)
z = elevation (m above msl)

The barometric pressure (P) in kilopascals (kPa) is computed as a function of elevation (z) in meters (m) above mean sea level using and equation from Burman, Jensen and Allen (1987):

$$P = 101.3\left(\frac{293 - 0.0065\,z}{293}\right)^{5.26} \qquad (6)$$

An equation from Tetens (1930) is used to calculate e_d (kPa) from T_d (^oC):

$$e_d = 0.6108\,exp\left[\frac{17.27T_d}{T_d + 237.3}\right] \qquad (7)$$

Note that one can determine the actual vapor pressure (e) using Eq. 5, which uses T, T_w, and P or from Eq. 7, which uses T_d. Since the values for T, T_d, and P are known a priori, one can determine the value for T_w by iterating values of T_w until e from Eq. 5 equals e_d from Eq. 7. The saturation vapor pressure at the wet-bulb temperature (e_w) in kPa is calculated from T_w (^oC) using:

$$e_w = 0.6108 exp\left[\frac{17.27T_w}{T_w + 237.3}\right] \quad (8)$$

Starting with the air temperature (T_o) and the dew point temperature (T_d), we calculated the first iteration for T_w ($T_{w(1)}$) as the mean of T_o and T_d using Eq. 9.

$$T_{w(1)} = \frac{T_o - T_d}{2} \quad (9)$$

The second T_w estimate ($T_{w(2)}$) is found by comparing the e from Eq. 5 with the e_d from Eq. 7.

For $e < e_d$, $$T_{w(2)} = T_{w(1)} + \left|\frac{T_d - T_{w(1)}}{2}\right| \quad (10)$$

For $e = e_d$, $$T_{w(2)} = T_{w(1)} \quad (11)$$

For $e > e_d$, $$T_{w(2)} = T_{w(1)} - \left|\frac{T_d - T_{w(1)}}{2}\right| \quad (12)$$

For the following iterations up to n=20, $T_{w(n)}$ is estimated by entering $T_{w(n-1)}$ into the appropriate formula of Eqs. 13-15 shown below:

For $e < e_d$, $$T_{w(n)} = T_{w(n-1)} + \left|\frac{T_{w(n-2)} - T_{w(n-1)}}{2}\right| \quad (13)$$

For $e = e_d$, $$T_{w(n)} = T_{w(n-1)} \quad (14)$$

For $e > e_d$, $$T_{w(n)} = T_{w(n-1)} - \left|\frac{T_{w(n-2)} - T_{w(n-1)}}{2}\right| \quad (15)$$

Twenty iterations of T_w are adequate to obtain a value for "e" within 0.000001 kPa of "e_d".

The goal of the wet-bulb temperature trend model is to provide growers with an initial estimate of how the wet-bulb temperature will change during a frost night. Then, observed air and dew point temperature data are used to update and the model during the night. The idea is illustrated in **Figure 2**, which shows the initial model prediction from 7:00 p.m. until 7:00 a.m. in (a) and how the predictions change when observed data are substituted for the predicted data until (b) 11:00 p.m., (c) 3:00 a.m., and(d) after sunrise at 7:00 a.m. With the computer program, a user will input the observed air and dew point temperatures on the hour following the first hour after sunset and will enter a prediction of the temperatures at the end of the first hour following sunrise. The prediction can come from a site-specific derived equation or from a meteorological service. During the night observations will update the air, dew point, and wet-bulb temperature every 5 minutes, which will force the trend prediction to become more accurate with time during the night. This will provide the best possible information for growers to determine when to start and stop sprinklers for frost protection.

Research Effort Recent Publications:

There are no publications at this time related to this research.

References Cited:

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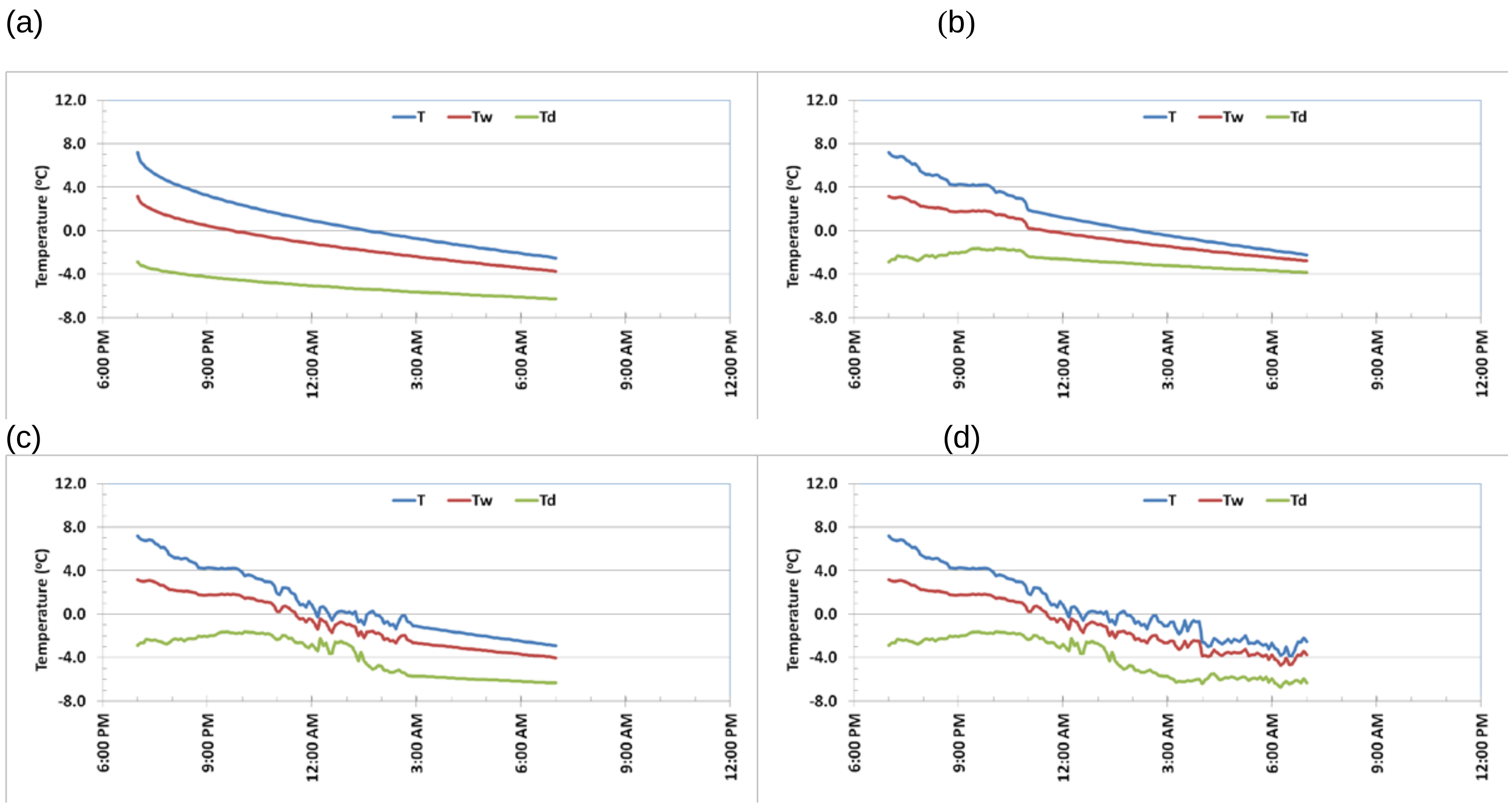

Figure 2. Plots of (a) the frost trend model estimates of temperature (*T*), wet-bulb temperature (T_w), and dew point temperature (T_d) and how they change with observed *T* and T_d data for (b) up to 11:00 pm, (c) up to 3:00 am, and (d) through 7:00 am; showing how the model provides an initial estimate of the wet-bulb temperature trend and how the real-time observed data improve the trend model accuracy during a frost night.