[**This is an interim report and the final report will be submitted in 2012**]

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:

Perennial questions that beset almond growers are (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 (T_w) temperature and comparing with the orchards critical damage (T_c) temperature, which depends on the phenological stage of the trees. The project uses three approaches to predict how much the temperature (T) will fall below T_c and how long it will be below T_c. We also provide a trend line of T_w and compare T_w with input T_c. Sprinklers should be turned on before T_w falls below T_c and turned off when T_w rises above T_c or 0^oC, depending on conditions the following day. One approach is to use National Weather Service (NWS) Forecasts of hourly air (T) and dew point (T_d) temperatures to calculate T_w each hour. Another approach is to input the air and dew point temperatures between 1 and 2 hours after sunset and at the end of the first hour

following sunrise. A model is used to predict the T and T_d trends during the night, and T_w is calculated at the end of each hour. Plots of the data and T_c are used to make recommendations on starting and stopping the sprinklers. Finally, the project aims to develop a realtime update from observed T and T_d data at five minute intervals during the night and using the prediction model to project changes from the current reading until the minimum temperature is reached the first hour after sunrise. In the realtime model, the T_w is calculated every five minutes during the night using observed T and T_d and predicted T and T_d prior to the observations. Using the realtime model will improve accuracy of the frost prediction model. At this time, the real-time update approach is still under development.

Materials and Methods:

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 phenological stage of the orchard.

In this project, we used MicroSoft Excel software to develop predictions of air (T), dew point (T_d), and wet-bulb (T_w) temperatures using a model and/or inputs of predictions from the National Weather Service. Then, using a critical temperature (T_c), which depends on the phenological stage of the trees, the temperature trend lines are graphically used to determine if sprinkler usage is needed and when to start and stop the sprinklers. Finally, the ability to update the temperature trend lines using observed real-time data from a weather station is under development. We will investigate the use of wireless and cell phone methods to transfer data.

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:

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

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:

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

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.

While the results are preliminary, 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:

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

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:

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

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 t_n 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. The webpages include predictions of T_n and T_{dn} for each hour during a night. The values for the T_n and T_{dn} forecast can be selected and input into the model. Alternatively, a spreadsheet to determine your own site specific T_n and T_{dn} forecast is included in the trend model application program.

At this time, an iteration method to determine the wet-bulb (T_w) temperature from the air (T) and dew point (T_d) temperature was developed, and the method is used to calculate the wet-bulb temperature at each time step. The method uses the equation:

$$e = 0.6108 \exp\left(\frac{17.27 T_d}{T_d + 237.3}\right) \qquad (5)$$

to calculate the air vapor pressure (e) in kPa from the dew point temperature (T_d) in ^{o}C, and the equation:

$$e = e_w - 0.00115 T_w (T - T_w) P \qquad (6)$$

where e_w in kPa is the saturation vapor pressure at the wet-bulb (T_w) temperature in ^{o}C, which is calculated as:

$$e_w = 0.6108 \exp\left(\frac{17.27 T_w}{T_w + 237.3}\right) \qquad (7)$$

and P is the barometric pressure in kPa. Thus, we are able predict the wet-bulb temperature trend from the air and dew point temperature trends.

The Excel application program was set up to have three worksheet components. One component, allows for the input of hourly NWS predicted T and T_d during the frost night and calculates the T_w from those inputs. The critical damage temperature (T_c) is also input and a plot of the temperature trends and the T_c during the frost night provides the information to help with sprinkler frost protection decisions. A second component of the application program is to input the T_0, T_{d0}, T_n, and T_{dn}. The start time (t_0) and end time (t_n) are automatically determined from input location information. Then the model, using equations 1-4, is employed to determine the temperature trends. At the end of each hour, the T and T_d values are used with the iteration method and equations 5-7 to determine the T_w values. The three temperature trends and the critical temperature T_c are plotted to provide information for making frost protection decisions (see **Figure 2**). The third component of the application program uses the first temperature trend lines generated by the second component, but updates the prediction every five minutes using observed data.

The decision about whether to use under-tree sprinklers or not depends on how low T is predicted to go below T_c and for how long. Once the decision is made, the sprinklers should be started before the T_w trend temperature falls below T_c. If the air temperature is predicted to go well above T_c during the next day and no frost is predicted for the following night, one can stop the sprinklers when T_w rises above T_c the next morning. If a frost is predicted during the following night, then the sprinklers can be turned off when T_w is above 0^{o}C during the day, but the sprinklers should be started again before T_w falls below 0^{o}C in the following night.

Research Effort Recent Publications:

The real-time component of the project is designed but not yet completed because of problems with the weather station purchased to provide the observed data for the updates. However, another station is available and communications equipment will be used to complete the third component during 2011-12. The third component is the most important for use of model to make decisions because it uses the forecast model but it updates the T and T_d data every five minutes. This will force the model to provide a better prediction of T, T_d, and T_w with time during a frost night.

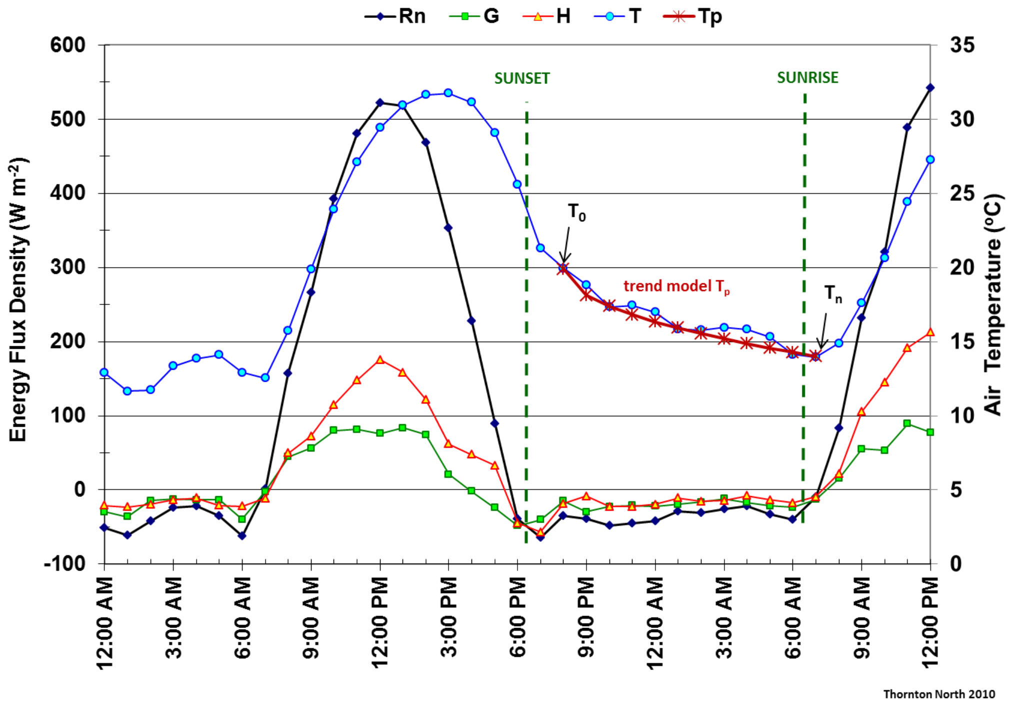

Figure 1. Energy balance and air temperature trends on a clear, calm night.

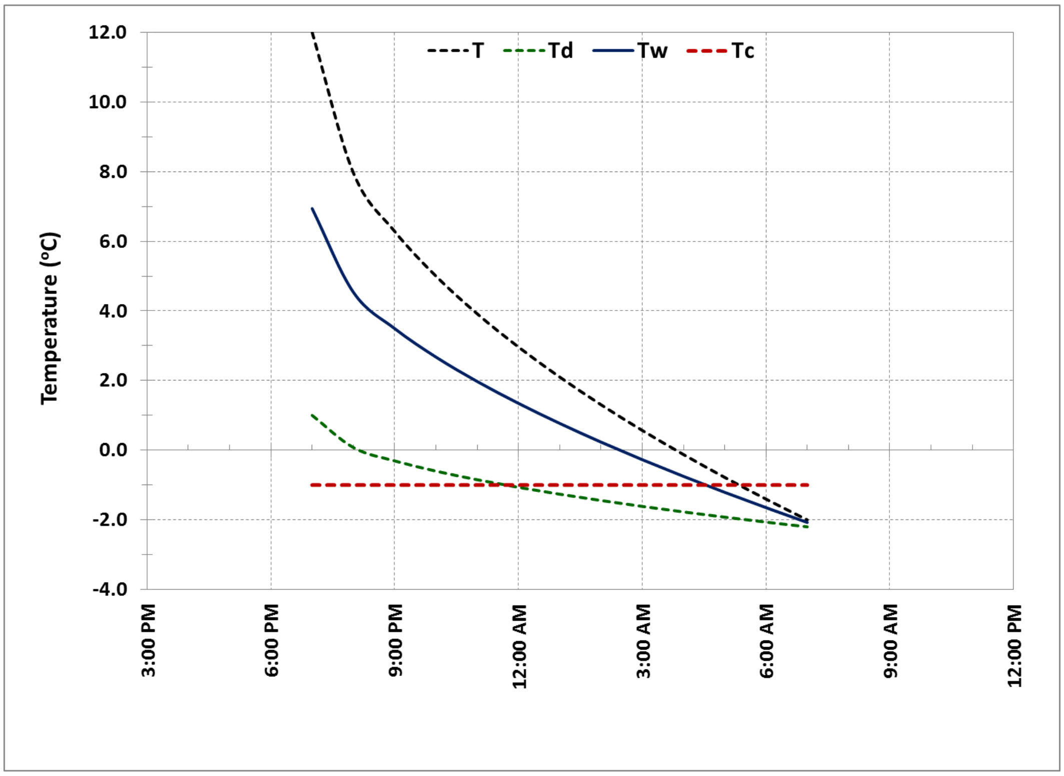

Figure 2. Sample of the temperature trend lines produced using the model equations and inputs of temperature and dew point temperature between 1-2 hours after sunset and 1 hour after sunrise.