MICROMETEOROLOGY OF AN APPLE ORCHARD: UNDERSTANDING LOCAL FROST CONDITIONS AND MITIGATING THEIR DAMAGE

A THESIS

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By

Nicholas Pearson

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Miro Kummel
Associate Professor, Director Environmental Science Program

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Mike Taber
Associate Professor, Chair of Education Department

Table of Contents

1) Introduction:

The damage associated with frost events causes more economic losses to the United States than any other weather-related phenomenon or biological hazard. (Ribeiro, 2006). Despite channeling considerable effort towards mitigating the negative impacts of frost on horticultural crops in recent centuries, little progress has been made in reducing the damaging effects of intense frost events (Rodrigo, 1999).

Low temperature is one of the primary mechanisms limiting the distribution and survival of plant species and horticultural crops across the globe (Rodrigo, 1999). In temperate climates where agriculture is widely practiced, such as the southwestern United States, the livelihood of farmers is directly attached to environmental conditions and the success of their agricultural yield. Given the potential for frost to adversely affect livelihoods and local economies, information on how to protect crops from freezing is important.

For example, in March of 2017, a severe freeze combined with an early blooming period heavily damaged the southeastern region of the United States and caused one billion dollars in estimated agricultural yield reduction (Smith, 2017). In addition, with perennial crops, these effects are often long-term. Severe frost events can damage tree structure permanently, rendering orchards subject to intense freezes altered for decades. Given that climate change has already altered the date of first blossom in parts of Colorado, it is likely that frost events will become more frequent. The earlier blossoms expose themselves in the spring the more vulnerable they are to experience frost conditions when the temperature fluctuates. Some resident farmers in Penrose and Canyon City (central Colorado) account that in their lifetimes the blossoming periods have shifted from mid-May to early-April (author's notes). This is due to the steady increase in average temperature in Colorado over the last 40 years (Collins, 2006).

Without being able to adequately prepare for cold events many different varieties of apples don't have the requisite defenses in place to resist frost damage from occurring. In the context of predicted climatic warming, earlier blossoming periods, and the subsequent escalation in risk of frost damage, agriculturists will have to become increasingly effective at forecasting localized weather phenomena and implementing cost-effective management strategies to mitigate their damage.

2) Relevant Theory:

2a) Climates Vs. Microclimates:

The atmosphere produces phenomena whose space and time covers a very large range. The space scales of these features are determined by their typical lifetime or period (Oke, 1987). Atmospheric features can range from penny-sized turbulent eddies (vortices of air) with short lifespans that are a fraction of a second to large-scale polar cyclones that navigate the globe and have lifespans of days. In most studies, the horizontal extent to which an atmospheric event ranges is usually the primary factor in its classification. Micro-scale is defined as an area .01 meters – 100 meters, whereas a macro-scale is defined as an area 10,000 meters – 10,000,000 meters (Oke, 1987).

2b) Energy Budget Equation:

The earth's surface and atmosphere are constantly receiving radiation and re-emitting it in a cycle alongside the sun. The apportioning of the radiative surplus or deficit is determined by the abilities of the soil and atmosphere to transfer heat, and the features of the surface of the earth in which radiation is striking (Oke, 1987). Incoming shortwave radiation from the sun drives all the processes which transfer heat throughout the earth. At any given location, the energy budget is as follows.

Q*= K(in) – K(out) + L(in) + L(out)
Q*= Qh + Qe + Qg

Variables:

Q*… Net All-Wave Radiation
Qh… Sensible Heat Transfer
Qe… Latent Heat Transfer
Qg… Ground Heat Flux
K(in)… Incoming Shortwave Radiation
K(out)… Outgoing Shortwave Radiation
L(in)… Incoming Longwave Radiation
L(out)… Outgoing Longwave Radiation

The variables of the earth's energy budget must constantly adjust and offset each other to maintain the temperature of earth's surface and atmosphere. Incoming shortwave radiation travels from the Sun and enters Earth's upper atmosphere far above the surface of the earth. As incoming shortwave radiation passes through water vapor and gases in earth's atmosphere towards the surface, 30 % is reflected by clouds, scattered by the atmosphere itself, and reflected by Earth's surface. The remaining 70% percent is either absorbed by the atmosphere (19%) or the Earth's surface (51%) (Donald Ahrens, 2009). Once incoming short-wave 'K(in)' radiation has been absorbed by the surface of the earth, the surface warms and begins to radiate in the form of longwave radiation ‘L(out)’ outwards. Because long-wave radiation emits a broader wavelength than short-wave radiation it is absorbed by greenhouse gases in earth’s atmosphere, which are then able to reemit them back towards the earth ‘L(in)’ or out to space ‘L(out)’.

During the day, there is a surface radiation surplus when the net shortwave radiation (‘K(in)’- ‘K(out)’) exceeds the net longwave radiation (‘L(in)’- ‘L(out)’). At night, in the absence of incoming shortwave radiation ‘K(in)’ from the sun, there is a surface radiation deficit when net longwave radiation ‘L(out)’ exceeds ‘K(in)’. At any given location, ‘K(in)’ and ‘L(in)’ are regulated by Earth-Sun relationships and meso-scale atmospheric temperature/composition, whereas ‘K(out)’ and ‘L(out)’ are driven by site specific factors like albedo (reflectivity), emissivity (radiative capacity), and surface temperature (Oke, 1987). Because of these varying elements, land in the same local area can differ in experienced microclimates despite their shared regional climate.

Alongside balancing incoming and outgoing radiation, the surface of the earth has various mechanisms to shed energy and stabilize the energy budget. Latent heat transfer ‘Q_e’ and sensible heat transfer ‘Q_h’ are key processes that regulate micro-climates of earth’s surface at a local-scale.

Latent heat transfer takes place when water changes into another phase and the transformation either absorbs or releases energy depending on if inter-molecular bonds are formed (condensation) or broken (evaporation) (Donald Ahrens, 2009). Sensible heat is converted to latent heat when water vaporizes into the atmosphere and it is converted back to sensible heat when the water re-condenses on earth's surface (Frost Protection, 2006).

Sensible heat transfer takes place when an object transfers energy through convection or conduction (Oke, 1987). When a solid warm object is placed on top of a very cold object, the warm object loses energy to the cold object through direct conduction. The same holds true for a warm air mass that is lying on top of a cold surface (Perry, 1998). In this case, energy is leaving the warm soil into the cold atmosphere through the convective diffusion of air, rather than direct conduction (Donald Ahrens, 2009). Diffusive heat transfer is very different from conductive heat transfer. Diffusion is when energy is convected through the physical movement of molecules themselves, as opposed to conduction where energy is diffused solely through a molecule's direct contact with other molecules. In this way, sensible heat transfer is less efficient when the wind speed is reduced; the diffusion of energy relies on the physical movement of molecules.

Aside from atmospheric energy transfers, the ground heat flux (Q_g) also plays an important role in determining local-scale microclimates. The size of the ground heat flux is not very different by day and night; however, the direction of the flux is the important factor that dictates local-climate (Perry, 1998). In daytime, a high solar energy input transfers heat downwards into the earth, whereas at night when there is no solar input the ground flux is directed upwards and replenishes heat lost by the surface of the earth to the atmosphere (Ahrens, 2009). The rotation and orbit of the earth combined with solar cycle gives rise to entirely different environmental conditions during 'day' and 'night' regimes. During the summer, ground heat storage during the day exceeds nocturnal output and the soil gradually warms over time. In winter months, nocturnal output exceeds ground heat storage during the day and the soil cools over time (Oke, 1987).

2c) <u>Energy Transfer: Advection vs Mixing:</u>

Energy is physically transferred through the atmosphere through two main processes called 'advection' and 'mixing'. Advection refers to the horizontal transport of an air mass due to density gradients, pressure gradients, or by the force of gravity (Oke, 1987). When cold mountain air chills at night and becomes denser than the warm valley air below, it begins to flow with gravity and replaces the warmer air through cold air advection or cold air drainage (Frost Protection Volume 1, 2005). Similarly, when a warm air mass expands to replace cold air, this process is called warm air advection. If an object inhibits cold air drainage and or warm air advection from taking place there can be adverse microclimatological effects like frost.

Conversely, 'mixing' or convection serves to diffuse energy in the vertical direction as opposed to the horizontal. Hot air is less dense than colder air, therefore, when warmer air is below a cold air mass, it will naturally rise through 'free convection' until it is above the cold air (Frost Protection Volume 1, 2006). When an orchard radiatively cools during the night and there is no advective heat replacement from adjacent land, mixing acts as the primary mechanism controlling energy transfer. In this inversion, denser cold air is trapped beneath a layer of warm air above the orchard and has difficulty diffusing upwards.

'Forced convection' takes place when mechanical (human made) mixing forces a transfer of energy when free convection and advection is not naturally occurring (Frost Protection Volume 1, 2006). Many active frost protection methods focus on increasing the rate at which 'free' or 'forced' mixing takes place during high risk frost events.

2d) Hoar Frost, Dry freeze, General Freeze

There are three general classes of frost associated with low temperatures. 'Hoar frost' forms when the temperature of the air above the surface of the earth is lower than the dew point and the dew point is less than 0°C (Reed, 1916). Ice begins to crystallize on the surface of the ground, blades of grass, and any low-lying vegetation that is also subject to the low temperature. However, instead of damaging plants, hoar frost can act to form an exterior shield of ice that protects plant tissues from ice crystals penetrating their vulnerable interior. When liquid/vapor water changes state into ice it releases energy in the form of latent heat (Oke, 1987). If the solutes inside the plants' cells have a lower freezing temperature than the water in the atmosphere, hoar frost will form only on the outside and warm the surface of the plant.

'Dry freezes' are a result of the temperature of the air above the surface of the earth falling below 0°C while the dew point is not reached (Reed, 1916). Rather than to forming on the outside of surfaces, Ice crystals form from water within sensitive tissues like flowers and fruits. Whether the ice formation is damaging to the plant depends on whether the ice formation takes place internally (within cells) or externally (between cells) (Rodrigo, 1999).

The last type of frost is a ‘general freeze’ in which the entire air mass is thoroughly mixed and has a consistent temperature well below 0°C (Reed, 1916). In this case, the entire structure of the plant is subject to cold temperatures for an extended period. General freezes typically occur during winter when plants are not active or exposing sensitive tissue, but they can also take place during sensitive developmental periods in which case they are especially devastating. Conversely, hoar frost and dry freezes generally occur during fall or spring when plants are either blossoming or exposing mature leaves, making them a nuisance for anyone trying to capitalize on their yield.

General freezes are the result of strong environmental forces that move at international scales, making them impossible to remedy in a practical way. However, both hoar frosts and dry freezes are related to air temperature inversions taking place on local scales.

2e) How Frost Forms: Advective vs. Radiative Frost

Aside from the three types of frost that can form on objects, there are differing mechanisms that control the conditions under which frost can even form. ‘Advective frosts’ are associated with regional-scaled incursions of cold air with a well-mixed (windy), cloudy atmosphere, and a temperature that is less than 32°F (Frost Protection Volume 1, 2006). These frosts occur when colder, denser air moves into an area to replace the warm, less dense air that has amassed there during some period. For example, air that has been warming in a low valley during the day is replaced at night by colder air from surrounding higher elevation. In the case of advective frosts there is not a temperature inversion because the entire air mass is in a 'general freeze', making active management techniques difficult to implement.

On the other hand, 'radiation frosts' are related to a clear sky, calm or little wind, low dew-point temperatures, and air temperatures less than 32°F. Under clear skies, heat is unimpeded as it is radiated away from the surface of the earth into space. As a result, the temperature of the air above the surface is chilled and the boundary layer of the atmosphere becomes strongly stratified (Frost Protection Volume 1, 2006). Once a temperature inversion forms in which cool air lies unmixed near the ground, a 'dry freeze' becomes likely. The height of the temperature inversion is the depth at which plants are subject to frost damage. Inversions can either have a high ceiling, in which the temperature of the surface is only slightly less than aloft, or a low ceiling, where the temperature rapidly increases with height aloft (Rodrigo, 1999). Because radiation frost is related to temperature inversions, active management strategies can be utilized to minimize 'dry freeze' damage on crops. Management strategies yield the best results during low-ceiling inversions in which the temperature profile is more feasibly changed.

2f) Frost Damage:

So, what is truly taking place when frost damages plants? Frost damage alters cell functionality through the crystalline formation of ice within the tissues of the plants. Ice formation can either be extracellular (between cells) or intracellular (in cells) depending on the temperature of the environment and the hardiness of the plant species (Rodrigo, 1999). Extracellular damage takes place when ice forms around the walls of cells and in open intercellular spaces, while intracellular damage occurs when ice crystals protrude into and puncture cells themselves (Rodrigo, 1999). Damage from intracellular ice formation is fatal and causes cell death, while extracellular ice formation can cause anatomical distortions or be avoided by internal defenses (Marchand, 1996). Plants have a mechanism to control where extracellular ice formation takes place called hardiness. It can prevent low-intensity frost events from damaging plants cells but it is difficult to prevent if the temperature is too low (Gutierrez, 2015). In addition to hardiness, vegetative structures like the trunk are far more prepared to combat the negative impacts of cold weather than are reproductive structures like flowers. By reducing their exposure of sensitive tissues, varieties of apple can remain undamaged during months in which they are dormant and acclimated to cold conditions.

2g) Acclimating and Hardening:

The extent to which frost damages a plant is highly dependent on the stage of development of the plant as well as the intensity and duration of the freeze event (Gutierrez, 2005). Acclimation is the process by which plants become resistant to freezing temperatures (Marchand, 1996). While they are not active, plants increase their hardiness, or the ability of the plant to resist freezing temperatures, in a variety of ways so that they are not vulnerable to frost damage during this period. For example, some varieties of apple can alter their cell membrane permeability so that water can be more easily withdrawn through them and freeze in intercellular places, as opposed to intracellular places (Marchand, 1996). The extent to which frost damages plants is dependent on their internal defense mechanisms, and their efficiency varies at different temperatures and between plant species and agricultural varieties (Gutierrez, 2005).

During winter, the effect that cold temperature has on plants is buffered by their gradually established resistance to freezing (hardiness). After the cold period comes to an end and flower buds start to de-acclimate (reduce their hardiness) for warm weather, they are more easily damaged by frosts associated with low temperatures events (Rodrigo, 1999). Apple orchards are more susceptible to frost damage in spring because the hardiness of apple blossoms is no longer acclimated for dormancy and winter, rather it is adapting to warming spring temperatures, with frequent cold snaps at night. In addition to these factors, bud development and pollination are temperature-dependent processes. This means that low temperature not only damages blossoms' physical structure, but it can also retard the progression of pollination and reproduction (Landsberg, 1973).

2h) <u>Climate Change:</u>

Climate change has the potential to disrupt the complex balance between microclimatic air temperatures and plants' ability to defend their cells against frost. Year to year variability in flower hardiness is a result of the year to year variability in seasonal temperatures (Gutierrez, 2005). The plants' ability to acclimate is reactionary to a mixture of average temperature and sunlight (Marchand, 1996). Therefore, quick temperature fluctuations are especially bad for non-acclimated blossoming flowers in spring. In the absence of a proper acclimation period, plants are more vulnerable to be internally damaged by low-intensity frost events (Rodrigo, 1999).

Our climate is changing and the predicted temperature increase will drastically alter the periods of development that horticultural crops undergo in the growing season. Given that spring-time temperatures are becoming more variable as the climate is changing, the subsequent risk of frost is increasing as well (Inouye, 2000). Flowers have mechanisms that allow them to resist frost damage as well as recover from it, however, horticultural crops are not able to internally adapt to the rate at which humans are altering the climate (Rodrigo, 1999). If climatic warming increases the variance in spring temperatures, the risk of frost occurring after budburst would increase because apple blossoms cannot defend themselves under extreme temperature fluctuations (Cannell, 1986).

3) Report Objective:

In this report, we explore the weather conditions that have the potential to damage agricultural crops through frost and what strategies can be used to mitigate them. Through the analysis of four separate experiments, this report will demonstrate the existence of a unique orchard microclimate that provides conditions for dangerous frost to develop on crops. Ultimately, we demonstrate, through the physical manipulation of the orchard microclimate, that localized weather phenomenon can be partially controlled through active management strategies.

4) Site Description:

Jenkins Farm Apple Valley Orchard is an apple orchard located in the small community of Penrose in the foothills of the south-central Colorado Rockies near the Pikes Peak region. The town of Penrose is elevated at 5,338 feet and the land to the north and east is considerably higher elevation. Cold air draining from higher elevated areas naturally flows through the valley and Penrose according to gravity. Nighttime katabatic winds from the northeast introduce cold air into the orchard, while during day the predominant wind direction is hot air from the west. One can therefore wonder whether it is advected cold air or strong radiative cooling that is causing the frost problem.

The orchard is an irrigated-flat plot of land that is 500 feet (East-West) by 300 feet (North-South). The farm's dimensions are 28 trees planted horizontally by 20 trees planted vertically. Individual rows are separate by about 15 feet and individual trees within rows are separated by 10 feet. There are many varieties of apple planted on the orchard, the most common being 'Golden Delicious' and 'Jonathon', while some of the rarer varieties include 'McIntosh' and 'Red Delicious'. A considerably sized shelter-belt (dense row of trees) consisting of Siberian elms covers two-thirds of the property's northern border.

In fall of 2014, the farm underwent a particularly intense advective frost which damaged nearly 30-40 % of the apples on the orchard. A powerful cold front in late fall introduced strong general-freeze conditions in which many apple varieties could not protect themselves against the cold. Once the orchard began blossoming in spring, there was a tide mark of dead and deformed blossoms marking the height at which the temperature inversion was. It is important to note that Jenkins Orchard experiences both radiative and advective cooling, often in combination with the other.

5) Experiment 1: Meteorological Tower and Preliminary Data

5a) *Objective:*

The spring study was implemented to record the microclimatic conditions of the apple orchard during a long period in which there was a potential for frost damage on blossoming apples. The objective of the spring study was to establish what type of frost Jenkins Orchard was experiencing and which processes were potentially responsible for its formation. Gaining information on how frost forms within the orchard allows us to create management strategies that disrupt those mechanisms.

5b) Methods:

A 15-foot meteorological tower (1) was placed just south of the leading edge of Siberian Elm trees along the northern border of the property (Figure 3). The tower was outfitted with wind/gust speed anemometers and temperature/ relative humidity sensors at 5 different heights (3 feet, 6 feet, 8 feet, 11 feet, 15 feet). Additionally, there was a wind vane at the top of the tower to distinguish wind direction above the orchard canopy. Data was logged from 3/21/2017 until 6/7/2017 during a critical period in orchard phenology and intervals of five minutes were used. See figure 3 for a map of the site with the locations of instruments

5c) Analysis:

The wind vane measurements over the course of the three months indicated that there were predictable regional wind patterns by day and night. Figure 4 depicts wind directions split between day and night regimes. Daytime wind direction (blue) is predominantly from the westerly direction, while nighttime winds (orange) tend to flow from the northeast. The daytime incursion of warm air from the west is of little importance regarding the formation of frost so there is no focus on it in this report. However, the introduction of frost into Jenkins Orchard may be associated with advection and night time wind direction.

At night, winter snows that accumulate on proximate elevated areas cool their overlying air masses and increase their density until they begin to sink with gravity (Bush, 1945). Even though the descending air warms while it is compressed, the air mass is extremely cold to begin with and can cause damage to vegetation as it passes by or has its passage blocked. In this study, frost could be the result of inhibiting katabatic (downhill) wind drainage from surrounding upper elevations, or by strong local radiative cooling. As cool air drains over the land, the stand of Siberian Elms may disrupt the continuous advective air movement and the result could be the entrapment of extremely cold air within the orchard. But even in the absence of wind from adjacent land the orchard still displays a very cold temperature. This is because the impact of radiative cooling is increased when there is a lower wind speed (Frost Protection Volume 1, 2006). Regarding Jenkins Orchard, we believe that frost is the result of a radiative cooling associated with low wind speeds and strong temperature inversions.

When observing the temperature over the course of the spring logging period it is evident that the average temperature steadily increases over time, even while there were still nights frequently below 0° C (figure 5). In some instances, the temperature difference between day and night regimes is nearly 20° C, a high-risk temperature fluctuation for blossoming flowers. One night (4/5/2017) experienced extreme temperature variation and even reached below -5° C for a solid portion of the early morning. This night was selected to be examined more closely as a representation of cold spring nights in which frost risk is high. Along with the cold night, one warm night (4/8/2017) was also selected to compare differences between the two. Figure 6 displays the temperature of tower one at five different heights over the course of the selected cold morning of 4/5/2017. The temperature is well below zero for most of the night and drops to -6° C just before sunrise. Tower heights are included so that inferences can be made regarding the coupling of air layers within the orchard.

The data suggests that during the coldest period of the night regime, the bottom three layers appear to have temperatures that are grouped separately from the top two layers' temperatures. This indicates to me that there is very little mixing taking place between the two layers, or an inversion; one colder layer ranging from 3 feet – 8 feet, and the warmer layer extending from 11 feet – 15 feet. The difference between the lowest sensor (3ft) and highest sensor (15ft) is about 2° C at maximum. For four hours during the night the bottom three layers are a full 1°C colder than the top two layers. Regarding the survival of blossoms within the orchard canopy, a one degree difference in temperature with height can mean life or death for a blossoming flower.

Radiative frosts can have either high or low ceilings depending on the height of the temperature inversion (Frost Protection Volume 1, 2006). In the case of this orchard, I hypothesize that the height of the ceiling is about 8-9 feet. In figure 6, the bottom three sensors display temperatures that appear to be coupled to the ground, and the top two sensors display temperatures that are coupled with air aloft the canopy. This suggests to me that there is a thermal internal boundary layer (TIBL) at 8-9 feet in which the characteristics of the lower atmosphere don't have strong effects on anything beneath that height.

When comparing this temperature profile to that of the warm night on 4/7/17 (figure 7), there is not such distinct coupling of layers. Air layers during the warm night are evenly separated by just less than a 1 ° C, with the gradient between the bottom and top sensors being 5° C, a gap quite larger than the cold night. Additionally, though they were two days apart, the temperature never dropped below 5° C for the entire warm night, so the risk of frost damage was effectively zero. It is possible that on the selected cold night there was a generally lower average temperature of regional air, but we expected that it was more complex than that.

To draw more accurate conclusions about the mixing taking place in the orchard, wind speed was analyzed during the same period on both nights. When comparing the cold night (figure 8a) to the warm night (figure 8b), the wind speed on the cold night is drastically lower, and, on both nights, wind speed increases vertically from the ground. However, wind speed on the cold night barely reached 0.1 m/s at any height on the tower while wind speed on the warm night never fell below 0.1 m/s at any height. This suggests to me that warm air is associated with a higher wind speed and more mixing, while cold air is associated with low wind speed and a lack of mixing.

Figure 9 displays the positive correlation between wind speed and temperature from tower one. When relating the wind graphs to the temperature profiles, the difference in wind speed between the two nights is accountable for the temperature difference between the two nights. During a spring night in this orchard, wind is the mechanism by which turbulent heat transfer moves energy into the orchard from adjacent land. In the absence of this wind, strong radiative cooling reduces the earth's temperature and the air laying on top of it is never convectively or advectively replaced by warmer air (Rodrigo, 1999). Figure 9 indicates to me that Jenkins Orchard is dealing with radiative frost associated with low wind speeds, not advection.

5d) <u>Synthesis:</u>

During night, low wind speeds allow the temperature of Jenkins Orchard's sub canopy to decrease significantly, promoting conditions favorable for the formation of radiative frost. The stand of Siberian elms along the northern border of the property also slows katabatic air movement descending from the mountains to the northeast. Without continuous advective heat transfer from adjacent land, air on Jenkins Orchard is cooled and it becomes difficult for stratified air to mix out of the lower canopy. Wind speed is an important factor in the formation of frost because it is the mechanism by which energy travels through the atmosphere. By disrupting the radiative inversion taking place on nights with low wind speed, farmers may be able to contribute to protecting the apple blossoms from low temperatures.

6) <u>Experiment 2: Comparative Analysis of Tower 1 vs Tower 2</u>

6a) <u>Objective:</u>

The objective of the two-tower spring study was to understand the differences in microclimatic conditions between the northern and southern portions of the orchard and what effect that would have on the formation of frost. The purpose of this experiment was to record the spatial differences within the orchard and make inferences about how the property management may have affected them. With two towers and twenty-one AVO temperature probes, more conclusions could be drawn about the effect of the Siberian Elms and how they influence air moving over the orchard.

6b) Methods:

Towers were placed on the same vertical row of apples with a tower in the north and a tower in the south portion of the orchard. Between these two meteorological towers, twenty-one AVO temperature probes were placed in the north-south direction to collect information on the spatial temperature profile of the orchard. Each tower was outfitted with wind/gust speed anemometers and temperature/ relative humidity sensors at 5 different heights (3 feet, 6 feet, 8 feet, 11 feet, 15 feet). Additionally, there was a wind vane at the top of the tower to distinguish wind direction above the orchard canopy. Data was logged from 3/21/2017 until 4/15/2017 during a critical period in orchard phenology, intervals of five minutes were used. See figure 3

6c) Analysis:

Figure 11 displays the north-south AVO temperature profile of the orchard averaged at 6:00 a.m. over the course of April. The graph displays a clear reduction in temperature in the middle of the orchard while the north and south are both slightly warmer. The change in temperature over a 10-foot horizontal distance could vary by almost a full degree Celsius, which can often mean the difference between a damaged and non-damaged blossom. In combination with the risk of frost associated with canopy height (radiative frost), it appears that blossoms in the middle of the orchard in the lower canopy are subject to the highest frost risk. They are in an area of the orchard in which wind speed and temperature is consistently the lowest.

Crowns in the central portion of the field are subject to the lowest wind speeds because the central portion of the orchard has the highest resistance to air movement. As a result, the central area of the orchard has the strongest radiatively cooling associated with it. Apple blossoms that exist near to the ground are more likely to experience colder temperatures than blossoms that exist at the top of crowns (Frost Protection Volume 1, 2006). The closer blossoms are to the cold radiative surface, the lower their temperatures become.

Figure 12 depicts the temperature of tower 1 and tower 2 during the selected cold night on 4/5/17. As shown by the figure, tower 1 and tower 2 differ in their temperature throughout most of the night. Even though they are on the same plot of land, tower 1's area of the orchard is consistently colder than tower 2's. This is likely a result of the wind speed difference between the north and south portions of the orchard. The northern border is covered by a large blockade of trees (shelter-belt) and it is likely inhibiting advective air movement into the orchard. At 6:00 a.m. on 4/5/17, the temperature of tower 1 (-6.5° C) was a full degree below the temperature of tower 2 (-5.2° C). Shelter-belts have the capacity to diminish the rate at which air drainage can pass through an orchard during night (Oke, 1987). As a result, the shelter-belt could be reducing the northern orchard's temperature during the night regime. Regarding the southern portion of the orchard, Tower 2 is far enough down row that it is beyond the effect of the shelter-belt and is available to receive some heat transfer from adjacent land.

Figure 14 demonstrates the relationship between both towers' wind speed from 8:00 p.m. to 9:00 a.m. on 4/4/2017 - 4/5/2017. Tower 2 consistently had a higher wind speed. When comparing figure 14 with the graph of tower temperatures (figure 12), tower 1 has a lower temperature because it has a clearly lower wind speed. Figure 13 displays the relationship between tower 1 wind speed vs. tower 2 wind speed. As shown by the figure, wind speed is not correlated between the towers, indicating to me that the northern and southern portions of the orchard are subject to significant microclimate differences.

6d) Synthesis:

Blossoms in the orchard are subject to variable temperatures depending on their spatial distribution within the orchard and their height from the ground. In Jenkins Orchard, mixing is the primary mechanism regulating the temperature profile of the air on cold nights. The northern portion of the orchard has its natural air flow disrupted by a large shelter-belt of Siberian Elms and as a result it frequently displays lower temperatures than the southern portion. Regarding the formation of frost, a one degree disparity in temperature can result in deformity for certain blossoms, and safety for others (Marchand, 1996). Given there is lower wind speed and less mixing taking place in the northern portion of the orchard, it would be practical to focus active protection methods towards that area. Because temperature is correlated to wind speed (figure 9), providing forced convection in any portion of the orchard should increase the temperature in that area and decrease the subsequent risk in frost.

7) ***Experiment 3: Nighttime Energy Transfer with a Sonic Anemometer***

7a) *Objective:*

The objective of the sonic anemometer study was to gain insights to the mechanisms of energy transfer (advection/mixing) within the orchard and how powerful they are in relation to each other. To better understand the transfers of energy taking place a nine-point grid was devised in the east half of the orchard to capture the vectors (direction and magnitude) of advection and mixing. By recording vectors at 9 individual locations, we attempted to capture the natural energy transfers that take place during the night regime.

7b) *Methods:*

A sonic anemometer is an instrument that captures 3-dimensional vectors of air movement in horizontal (x), vertical (y), and lateral (z) directions. The sonic anemometer was placed at 9 different locations in a 3x3 grid that captured air transfers in only the eastern half of Jenkins Orchard. The anemometer tower was toured around the entire expanse of the eastern orchard so that comparisons could be made about air flow in different sections of the orchard and how they relate to topography of the orchard or the apple trees. Measurements were gathered on 9/15/17 starting at 6:30 a.m. to accurately represent the night regime. The sonic anemometer was continuously recording so it had to be manually transported to each of the 9 locations with careful measurements on the exact time of each desired logging period. Data values were collected at 10 intervals per second for 5 minutes at each point in the grid. See figure 18

7c) *Analysis:*

Air flow vectors from the sonic anemometer were used to calculate heat transfer within the orchard by calculating averages of advective wind speed (U), temperature (T), and vertical mixing (W). Once the averages Ubar (average U), Tbar (average T), Wbar (average W) were calculated, they were subtracted from the measured values to produce a deviation from the mean called a prime' (U'/T'/ W'). The covariance value between T'U' or T'W' can reveal the positive or negative correlation between temperature and vertical/horizontal wind speed. Once the average covariance is calculated it is then multiplied by the density (ρ) and specific heat (c) of the air to calculate energy transfer. Advective heat transfer is calculated by multiplying U' and T' by specific heat and density of dry air, while mixing heat transfer is calculated by multiplying the W' and T' by specific heat and density of dry air.

The fluxes calculated from the sonic anemometer experiment revealed that advection is the main mode of energy transport during night regimes in which frost is likely to form. Figure 19 displays the ratio of the average mixing energy flux divided by the average advective energy flux at all 9 points in the grid. Values greater than one signify that mixing is greater than advection at that location, and values less than one signify that advection is greater than mixing in that location. 7/9 grid points reveal that advection is the more dominant transporter of energy within the orchard. The grid also demonstrated that the spatial structure of energy transfer is at a smaller scale than what we measured in our grid. There is little or no spatial structure to the ratios in figure 19. More grid points are necessary to draw a more complete story.

In the absence of strong wind, advective heat transport from adjacent land is not introducing energy into the orchard. With no heat replacement, the orchard radiatively cools until its boundary layer becomes powerfully stratified (Oke, 1987). Once the air is stratified, mixing is restricted and the main form of energy transfer left is an advective gravity flow (Bush, 1945). Figure 17 displays the slope of the orchard in a digital elevation model. It demonstrates that the elevation of the orchard decreases as you travel from the northwest to the southeast. During periods of low advective air transfer and or temperature inversions, cold air may only move by way of drainage alongside gravity.

This hypothesis is reinforced by the average direction in which air transfer is taking place on the orchard. Figure 20 displays the average wind direction of horizontal (x-axis) and lateral (z-axis) taken by the sonic anemometer. By averaging the sine and cosine of the wind direction at each of the 9 grid points, inferences could be made about the directional movement of air within the orchard. The figure 20 suggests that air is introduced over the northern property border into the eastern orchard and drains out of the southeastern portion of the orchard. Some air travels into the western section of the orchard, but the majority (6/9 grid points) suggest that air drains similarly to the slope of the orchard. In the absence of advective or convective energy transfer, air has a tendency drain southeast out of the orchard.

7d) <u>Synthesis:</u>

Within the context of this report, the sonic anemometer study was integral in understanding energy movement within the orchard during night regime periods in which the radiative frost we are concerned with is most likely to form. In the absence of wind, cold air amassed from strong radiative cooling has a difficult time dispersing away from the surface of the orchard floor. In the logging period we recorded, mixing was restricted by a temperature inversion and if there was advective air transport it was slowed by the shelter-belt and flowed alongside gravity. Given these results, introducing mechanical air movement (mixing or advection) within the orchard will reduce the effect radiative cooling has on the temperature of the sub-canopy.

8) ***Experiment 4: Drone Flights and Mitigation Strategy***

8a) Objective:

The objective of the drone experiment was to apply an active method of frost protection and test its efficiency with thermal imagery. To understand the utility of using industrial fans to increase mixing on small-scale apple orchards, this experiment was designed to observe the effects of mechanical mixing through a small movie. Thermal imagery provided us with a visual representation of the range and efficacy of industrial fans in a way that is easy to relay to farmers who need assistance protecting their crops. It also offers us quantitative data on the rate of temperature change with each management strategy.

8b) Methods:

A 36' inch industrial fan was placed in three different positions and observed by a thermal drone from 30 meters above. The fan was upright and pointing down row (position 1), propped off the ground and pointing upwards (position 2), or propped of the ground and pointing downwards (position 3). Once the fan was placed in its desired location, the drone hovered at 30 meters and recorded control conditions for a minute before the fan was active, then, recorded fan activity at 1 frame per second for 5 minutes while it was active. Between each experiment time was given for the orchard air to partially reset so that the effects of one experiment did not influence the next. Additionally, there was preliminary drone flights using a camera fitted with both Thermal and Normalized Difference Vegetation Index (NDVI) imagery that provided us with photos of vegetative health and temperature.

8c) Analysis:

The thermal image (Figure 16) captured by the drone reveals that the orchard has a variable temperature profile that differs spatially throughout the property. The eastern section of the orchard is noticeably colder than the western section of the orchard. This may be a result of the shelter-belt of Siberian elms planted north of the property. As air flows southwest from surrounding higher elevations the shelter-belt slows it through turbulent friction and the outcome is low wind speeds and strong radiative cooling on the eastern portion of the orchard.

Consequently, when comparing the Normalized Difference Vegetation Index image (Figure 15) with the Thermal image (Figure 16), areas with unhealthy vegetation also experience some of the lowest temperatures. Aside from water availability, temperature is the primary mechanism regulating the health of the apple trees within the orchard. Areas subject to lower temperatures within the orchard are more vulnerable to being adversely effected by frost. Quickly-fluctuating warm to low temperature events during the growing season retard growth and lessen the yield of orchard’s overall apple production. The drone images demonstrate that high night time temperatures are associated with healthy vegetation and low night time temperatures are associated with unhealthy vegetation. With this information in mind, active protection methods can be targeted to specific areas that experience lower temperatures and have less healthy vegetation.

The images captured by the thermal drone during the fan experiment revealed to us that any increases in wind speed from the fan caused the temperature of the canopy to increase as well. We expected this to be true given the relationship shown by Figure 9. Wind will transfer heat into the orchard at night during radiative inversions. So, when the fan was pointed down row the temperature of a selected tree in the middle of the fan's path increased by almost 2 °C in less than 4 minutes. When the fan was pointed upwards in position 2, a selected tree in the proximate area close to the fan experienced a 3.2 °C increase in temperature over 4 minutes. Finally, when the fan was pointed downwards in position 3, a selected tree near the fan experienced a temperature increase of 1.9 °C in just 4 minutes. In other words, one 36' inch industrial fan was able to increase the temperature of the orchard in proximate areas by up to 3.2 °C in a very short time. In terms of application and utility, this fan cost $30 to rent for the night and could contribute to the potential protection of apple blossoms very feasibly.

8d) Synthesis:

Regarding which position is most useful for protecting crops during frost events, it is evident that position 2 (Figure 22) effects the largest area of the orchard, as well as increasing the temperature by the greatest amount. Because the fan was propped off the ground and aiming upwards, it created a source of low pressure at the rear of the fan that sucked cold air in from the orchard sub-canopy and dispersed it aloft. This is an ideal movement of air considering that we want to disrupt the radiative inversion taking place on an orchard. By pointing the fan upwards, we mechanically mixed cold air aloft through the layer of warm air and instigated free convection near crowns within the orchard. Position 1 (Figure 21) was not nearly as effective because air solely blew horizontally out of the orchard as opposed to churning the air vertically. Because temperature inversions are height related, a fan in this position could potentially just pump cold air sideways as opposed to truly promoting the desired vertical air movement. Position 3 (Figure 23) was not as effective as position 2 either. The downwards motion of air instigated mixing in the sub-canopy, however, the fan was not propped up high enough to even reach warmer air aloft. Ultimately, the upward position produced the most desirable movement of air in terms of disrupting radiative frost inversions, and it is shown by the temperature difference and area of impact by thermal drone imagery.

9) <u>Further Experiments:</u>

Additional thermal imagery on the impact of an active Agrofrost heating and circulation unit would have contributed substantially to our understanding of the efficacy of larger-scaled frost prevention methods. Given more time to test the machine on a spring night , we could have conducted research and included analyzed data in this report. Furthermore, given the chance to collect sonic anemometer intervals in the spring as opposed to fall, we would have been more accurate in our interpretation of small scale wind movement during radiative frost inversions. The next step in this research would involve tampering with the shelter-belt, implementing a more thorough sonic anemometer grid, and analyzing the impact larger-scaled protection methods in use.

10) Conclusion:

This research was an attempt to understand the mechanisms by which local orchards become exposed to dangerous frost conditions, while at the same time commenting on the efficacy of strategies used to mitigate their impact on agriculturalists. Through the analysis done through the two spring experiments, we concluded that Jenkins Orchard is subject to radiative frost when there is a low wind speed at night. In the absence of turbulent heat transfer provided by wind, cold air produced by radiative cooling in the sub-canopy of the orchard does not naturally mix out of the lower layers (Frost Protection Volume 1, 2006). Once it is trapped there its temperature can drop until it becomes damaging to the sensitive tissue of plants. Experiment three demonstrated that during radiative inversions vertical mixing of air is restricted, while advective air flow is the dominant mechanism by which heat is transferred through the orchard. Prompted by this information, the fourth experiment was an attempt to test the efficacy of a small-scaled protection method specifically aimed at disrupting radiative temperature inversions.

Although intense regional frost events are nearly impossible to remedy, focusing on smaller scaled frost events is a means for farmers to protect their land. Conscious of the predicted impact of climate change and the effect of early budding periods on frost vulnerability, farmers are going to have to become increasingly effective at paying attention to the meteorological conditions that proceed frost events, as well as implementing protection methods to reduce their damage. Given the opportunity to buy a multitude of industrial fans, farmers could enable themselves to become more resilient to potential frost events through a very low cost protection method. With a little more capital, farmers could invest in machines like an Agrofrost, a machine which generates hot air as well as circulates it through the orchard's sub-canopy.

Whatever the protection method may be, it is more important for agriculturalists to understand what conditions cause frost to form, and how they personally can manipulate their orchards microclimate to avoid that damage. By investing in meteorological equipment used in this experiment, paying closer attention to federally issued weather advisories, and implementing protection methods, agriculturalists could become far more resilient to spring frost damage in a rapidly-changing period of our climate.

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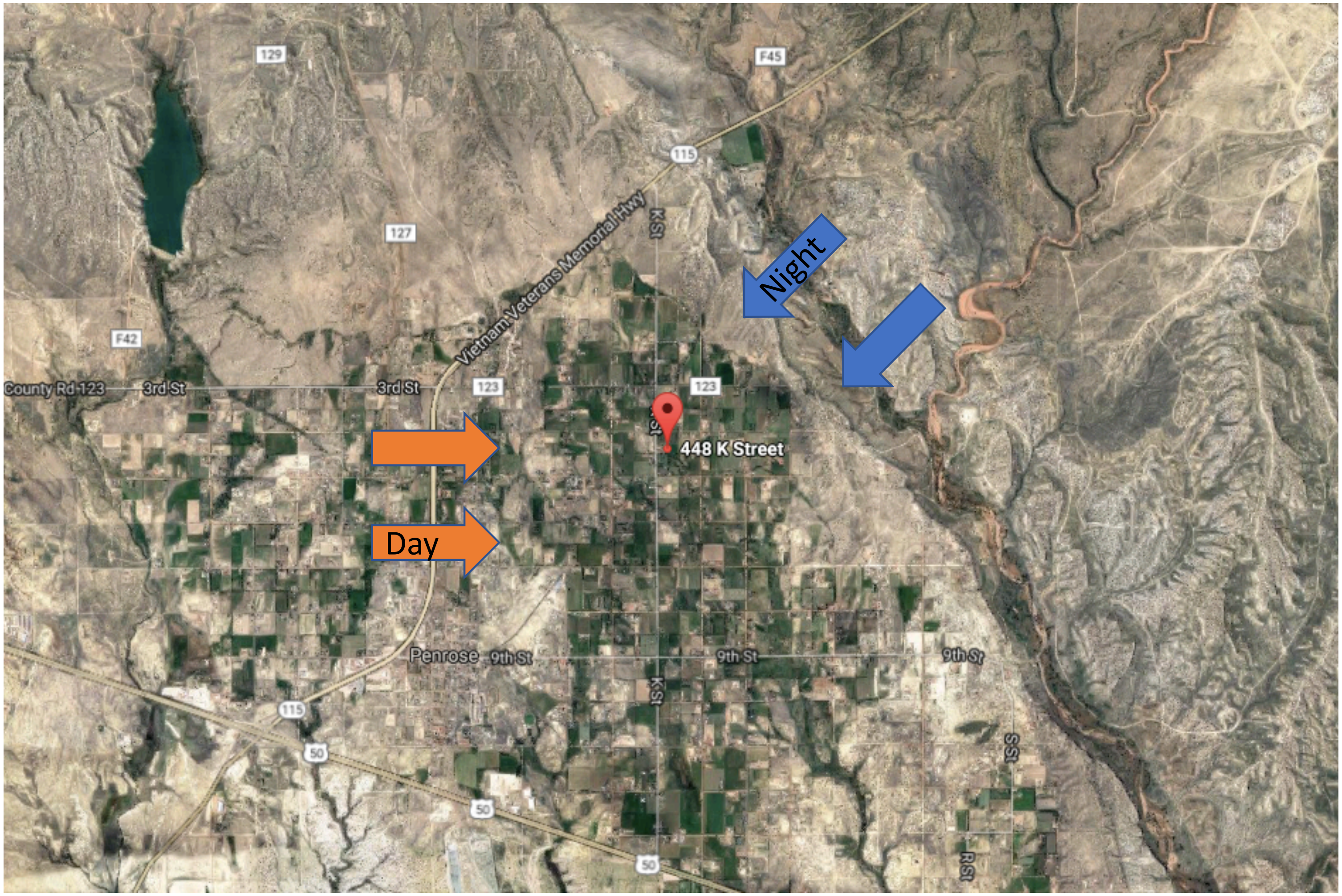

Figure 1) Assumed Night and Day Wind Direction Over Penrose Colorado During Logging Period

Figure 2) Satellite Image of Jenkins Farm Apple Valley Orchard

Figure 3) Locations of Meteorological Towers and AVO Temperature Probes During Spring Study

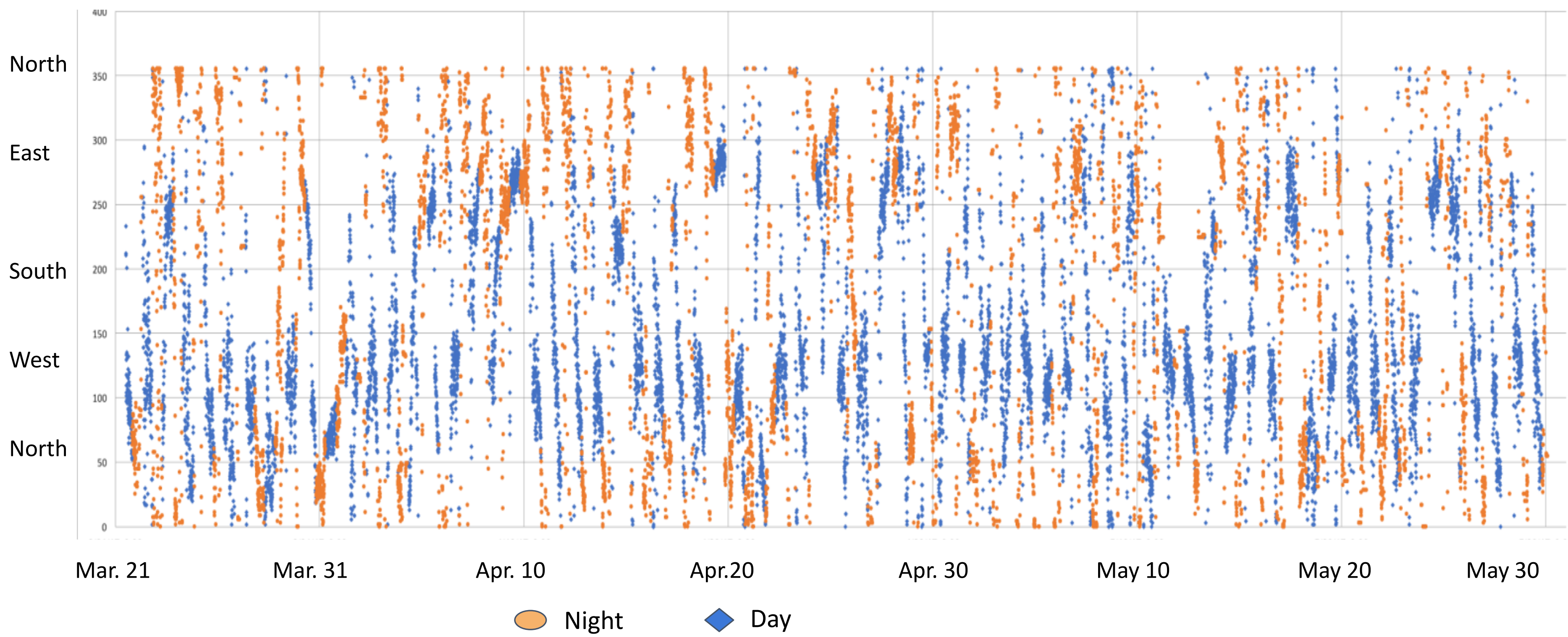

Figure 4) Tower 1's Recorded Night and Day Wind Direction From March 21st – May 30th (2017)

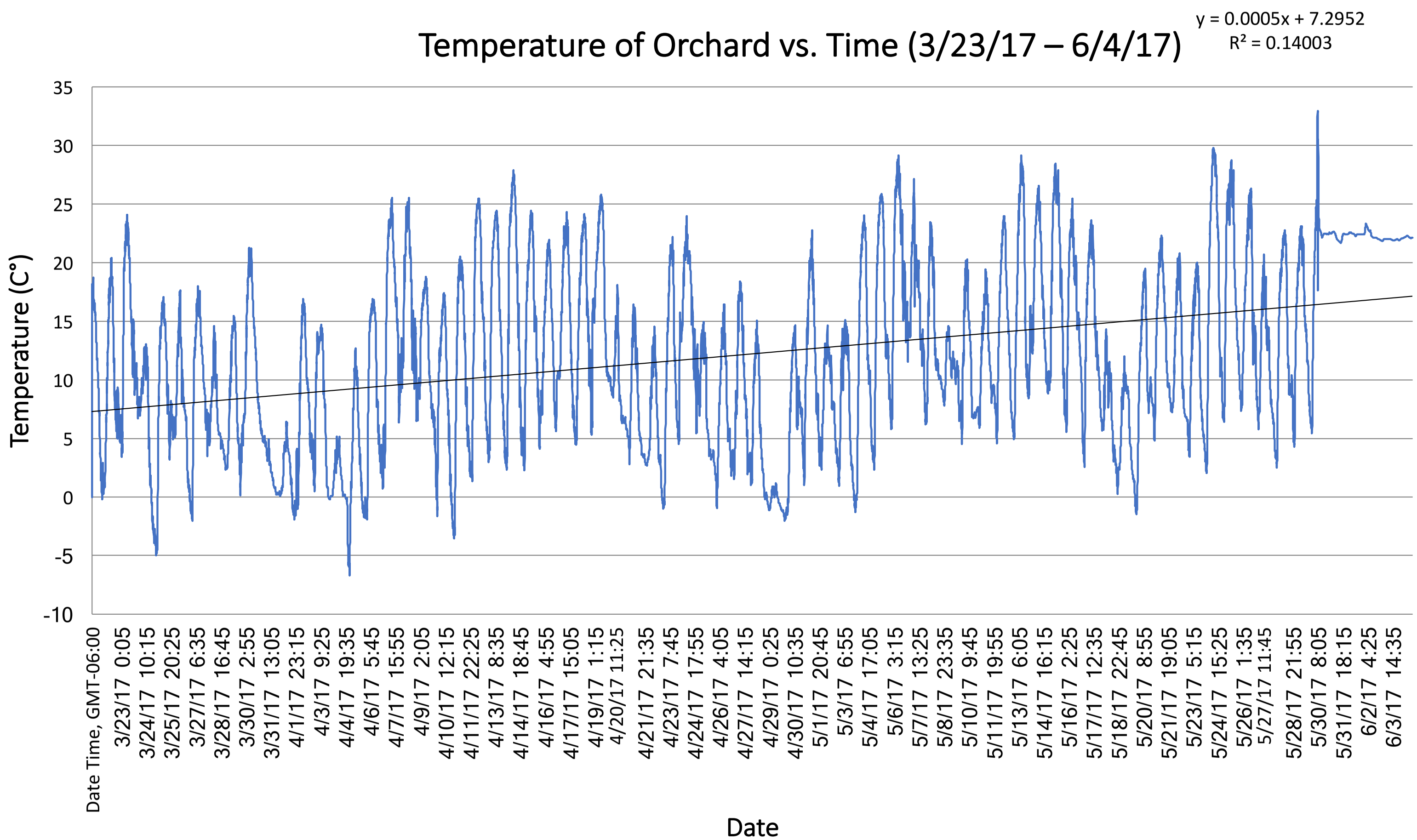

Figure 5) Temperature (C°) Profile from 2/23/17 - 6/4/17 Displaying Trend Line

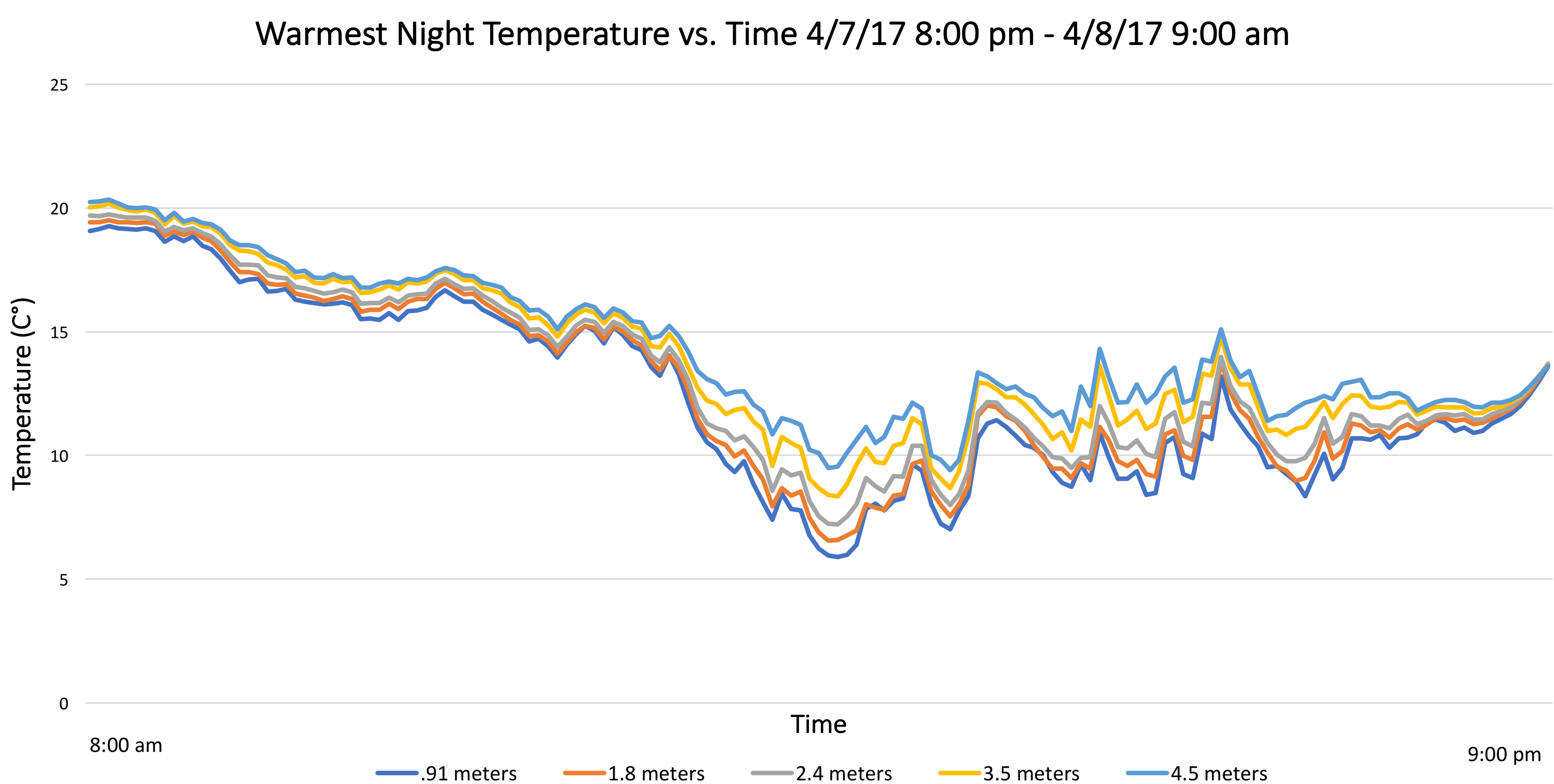

Figure 6) Temperature (C°) at Five Differing Heights from 8:00 P.M 4/7/17 through 9:00 A.M 4/8/17

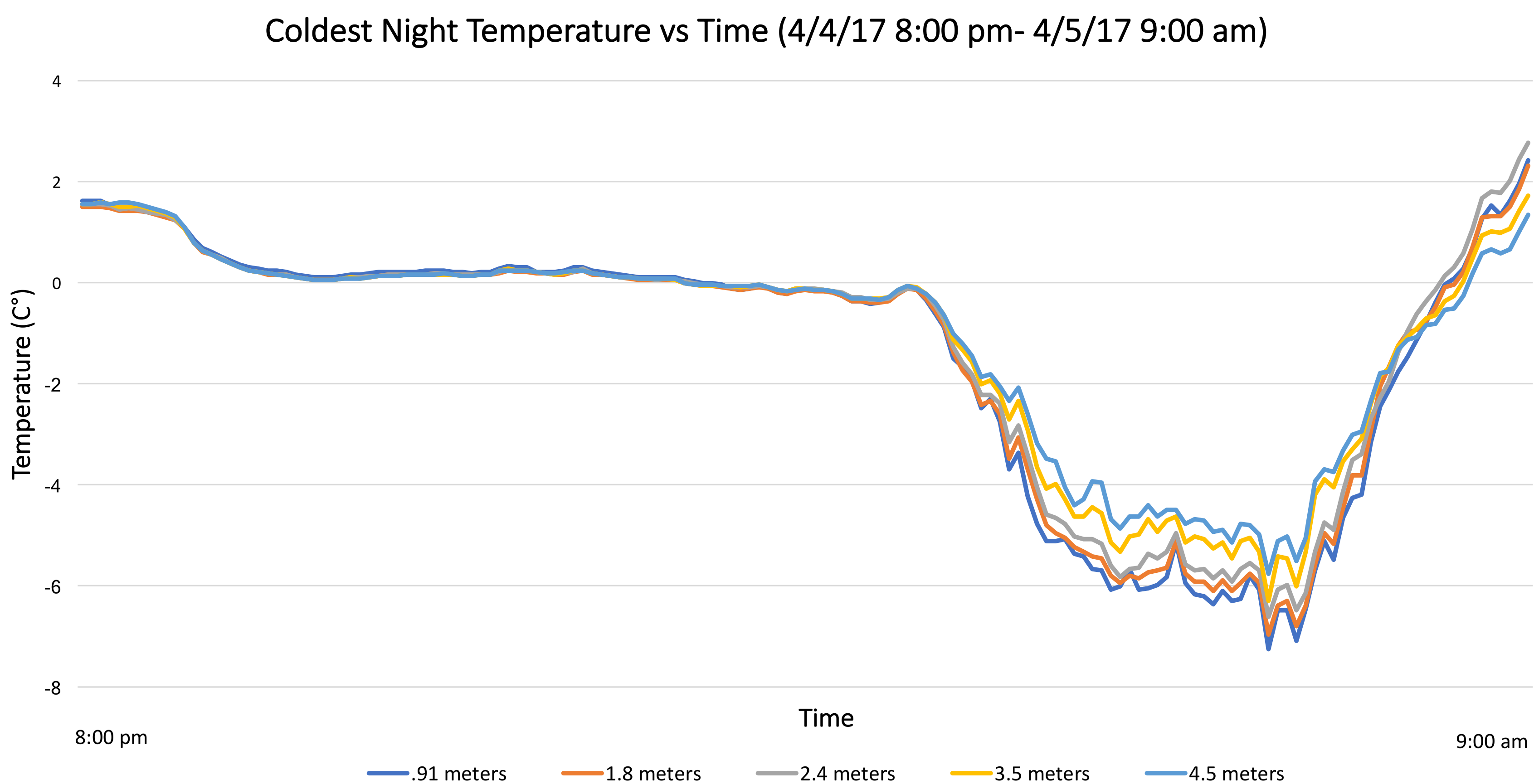

Figure 7) Temperature (C°) at Five Differing Heights from 8:00 P.M 4/4/17 through 9:00 A.M 4/5/17

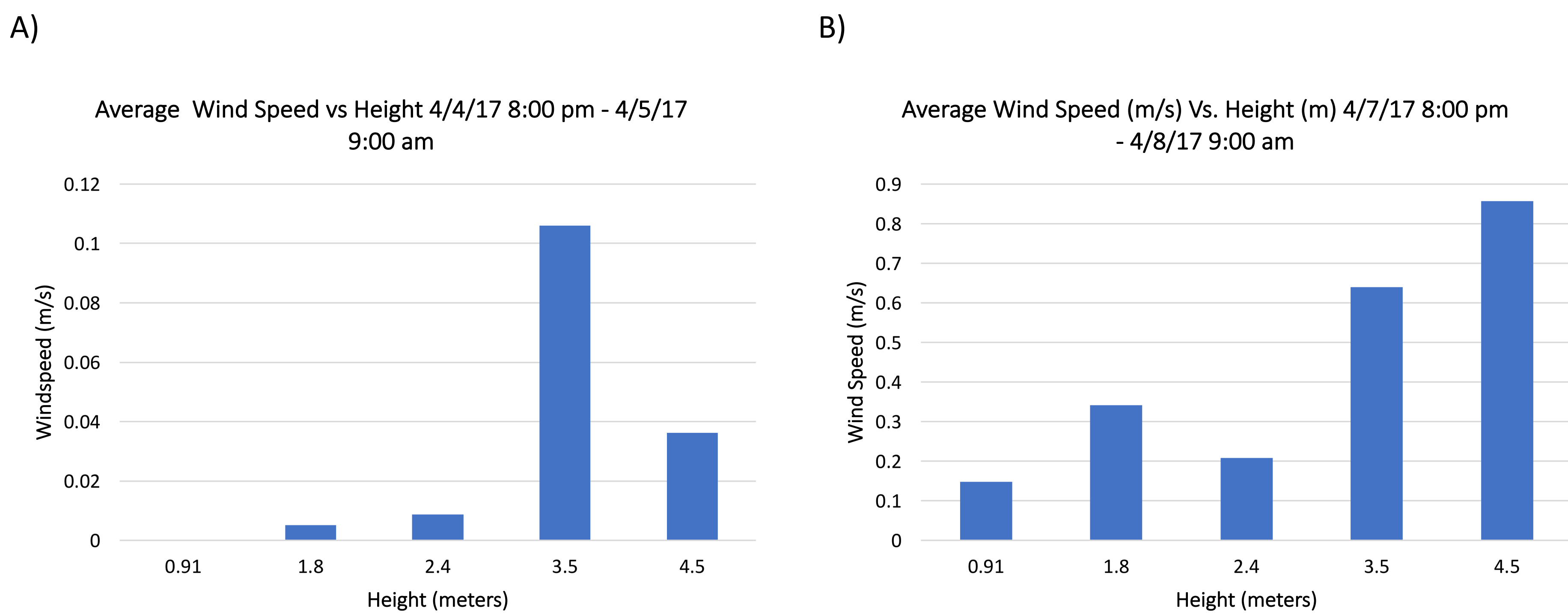

Figure 8a) Average Wind Speed of 5 heights at Tower 1 from 8:00 P.M 4/4/17 – 9:00 A.M 4/5/17

Figure 8b) Average Wind Speed of 5 heights at Tower 1 from 8:00 P.M 4/7/17 – 9:00 A.M 4/8/17

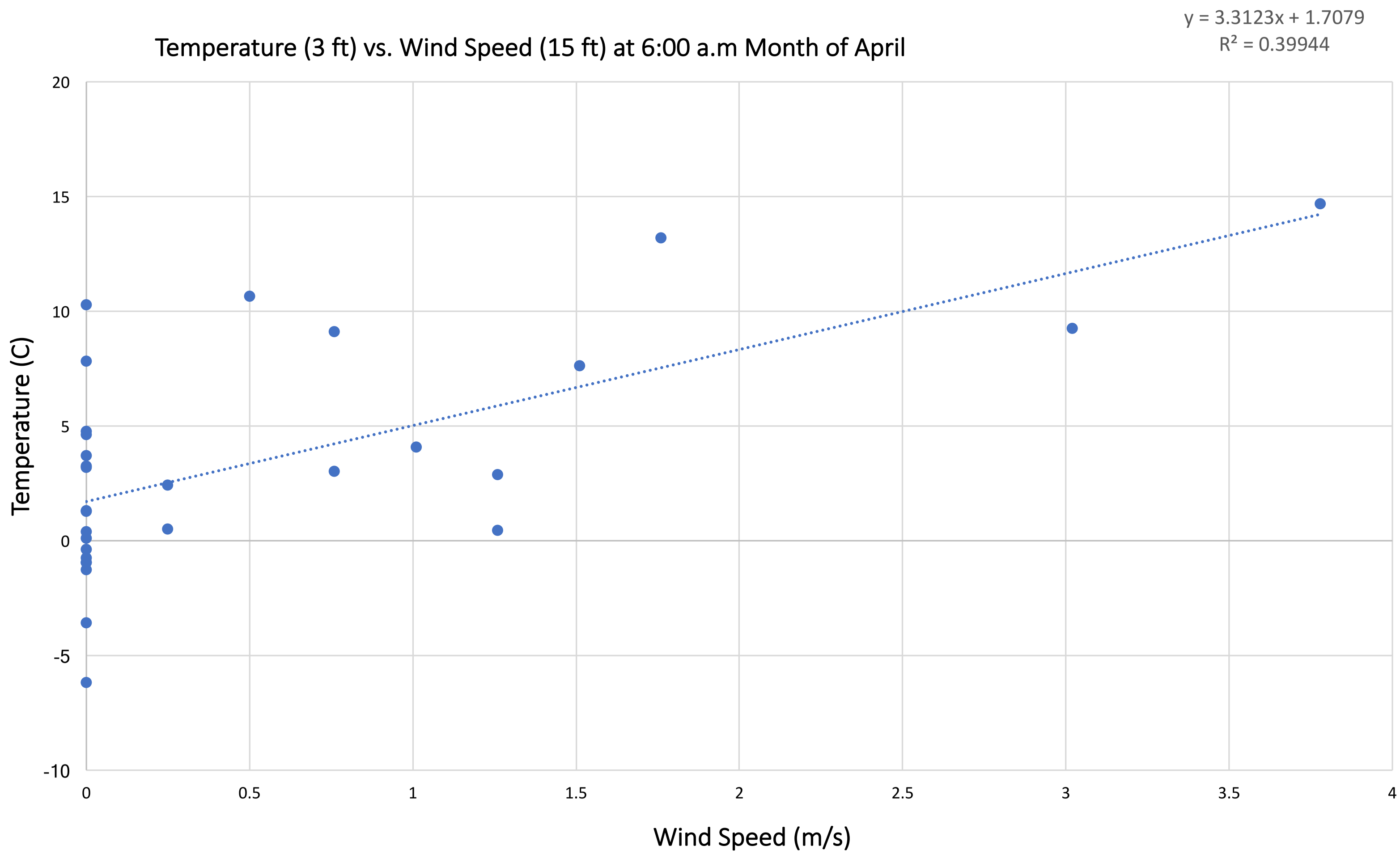

Figure 9) Temperature (C°) Vs. Average 6:00 A.M Wind Speed (m/s) During April Displaying Trend Line

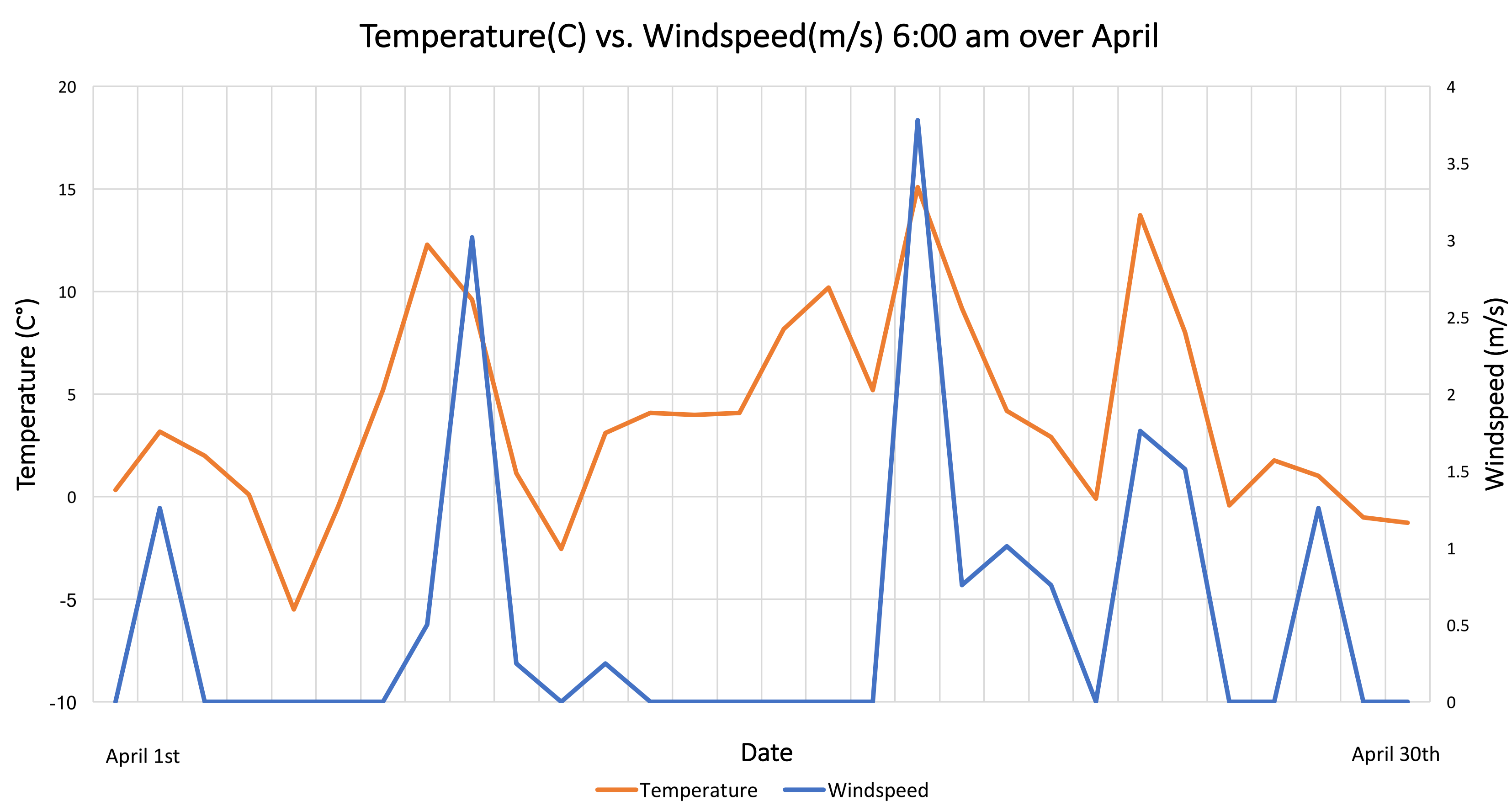

Figure 10) Temperature (C°) and Average 6:00 A.M Wind Speed from 4/1/17 through 4/30/17

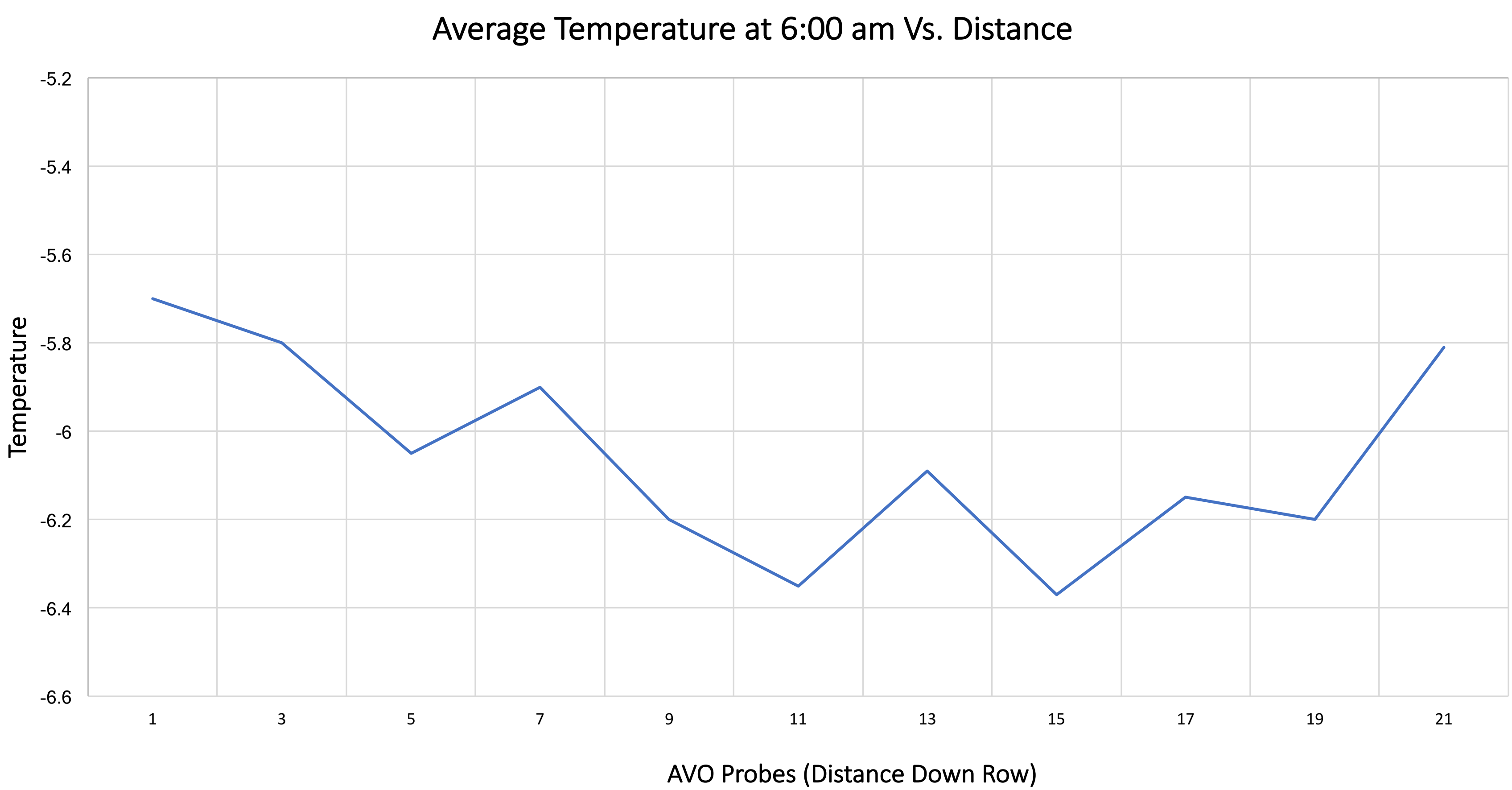

Figure 11) Average Temperature (C°) at 6:00 A.M throughout April by AVO Probe (Horizontal Temperature Profile)

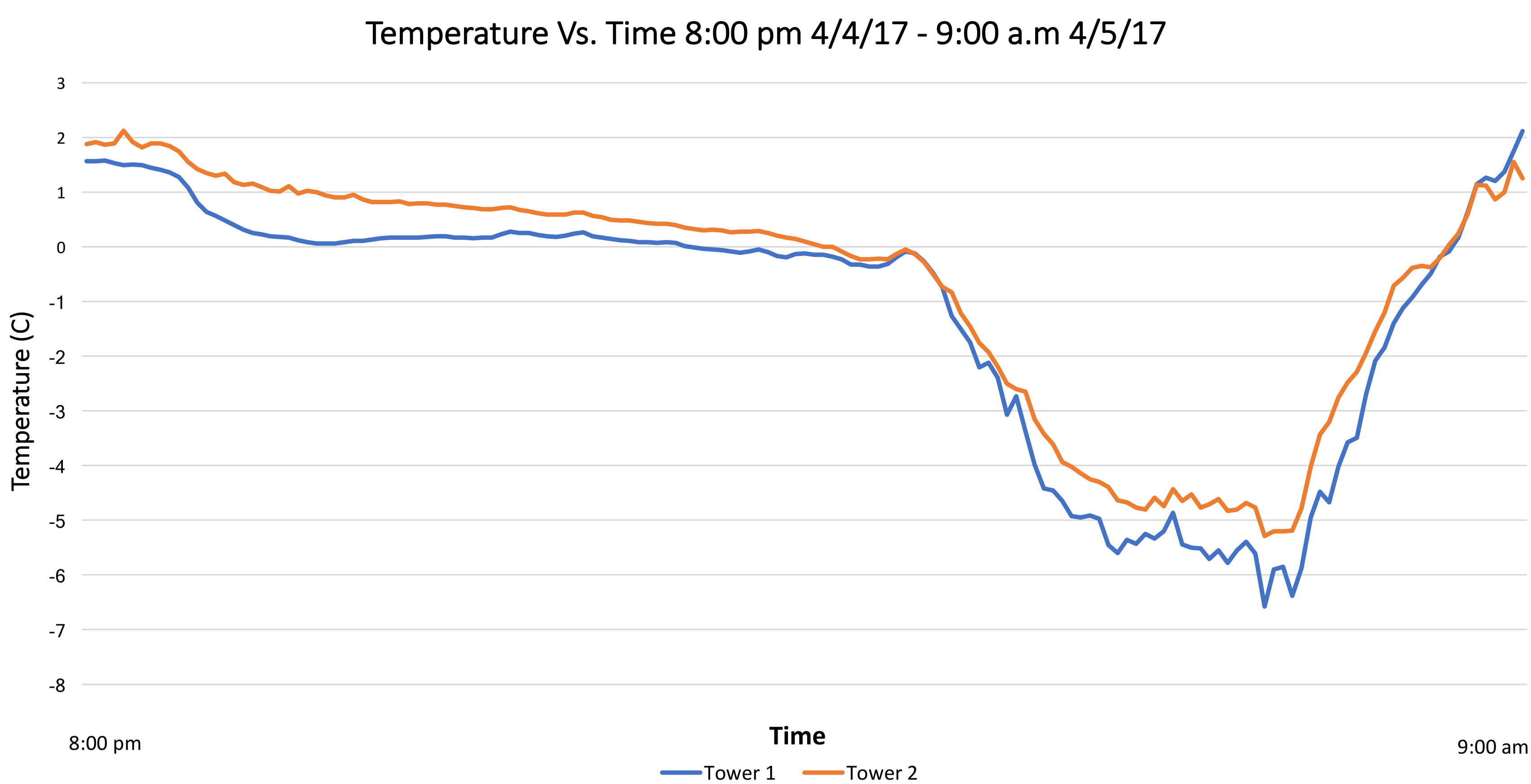

Figure 12) Temperature (C°) of Tower 1 Vs. Temperature (C°) of Tower 2 from 8:00 P.M 4/4/17 through 9:00 A.M 4/5/17

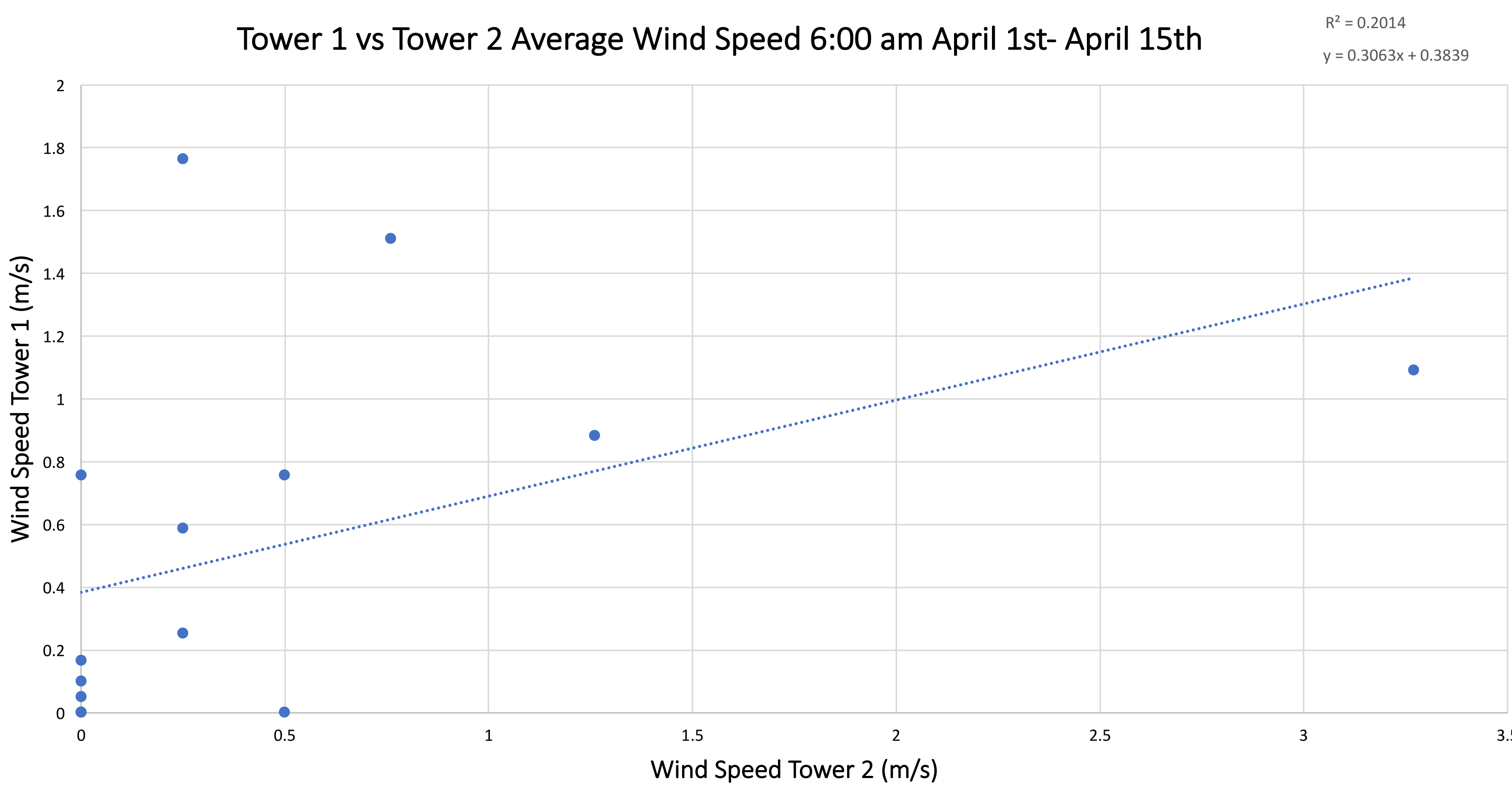

Figure 13) Average 6:00 A.M Wind Speed (m/s) of Tower 1 Vs. Wind Speed (m/s) of Tower 2 from 4/1/17 – 4/15/17

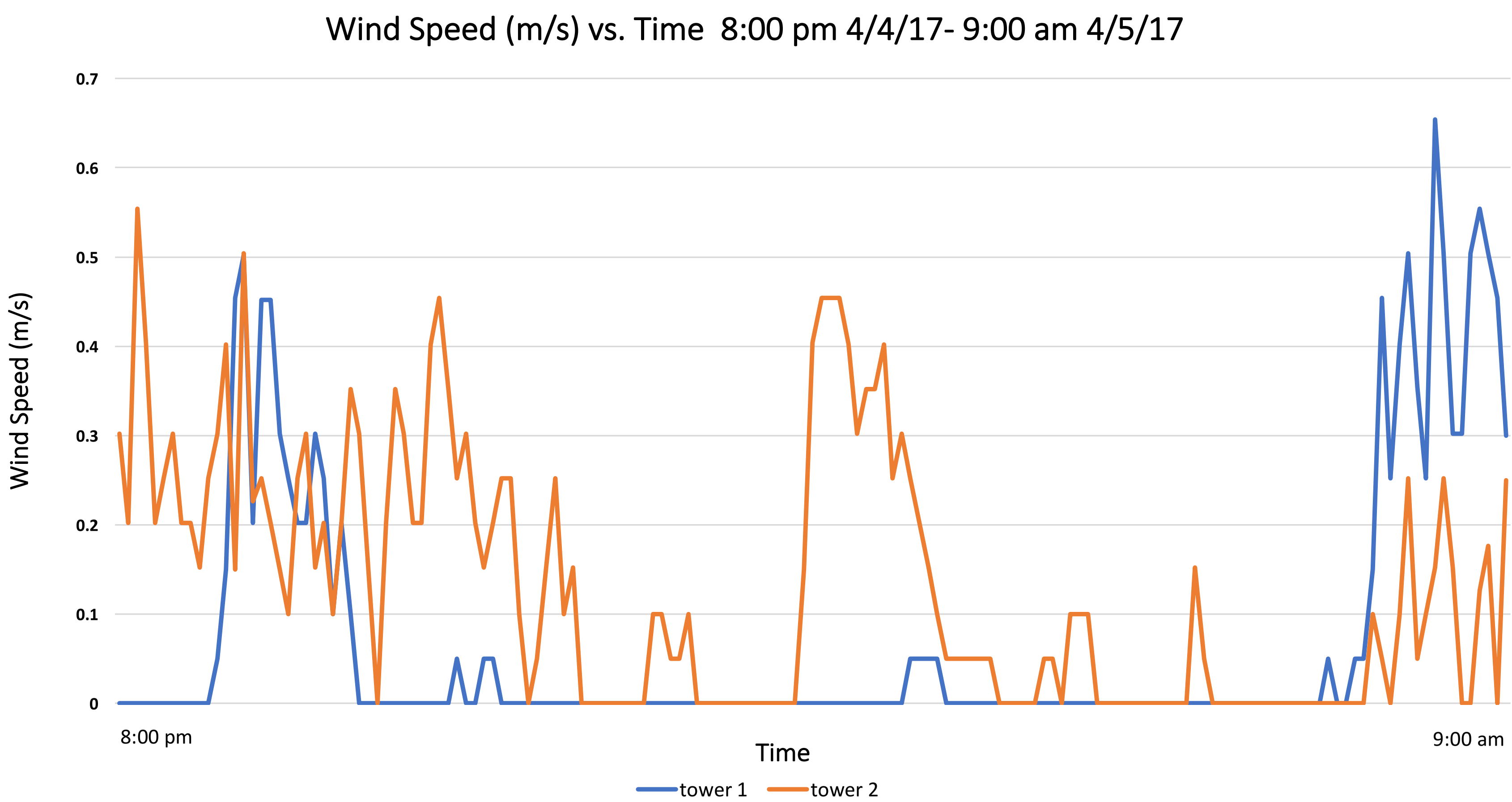

Figure 14) Wind Speed (m/s) of Tower 1 Vs. Tower 2 from 8:00 P.M 4/4/17 through 9:00 A.M 4/5/17

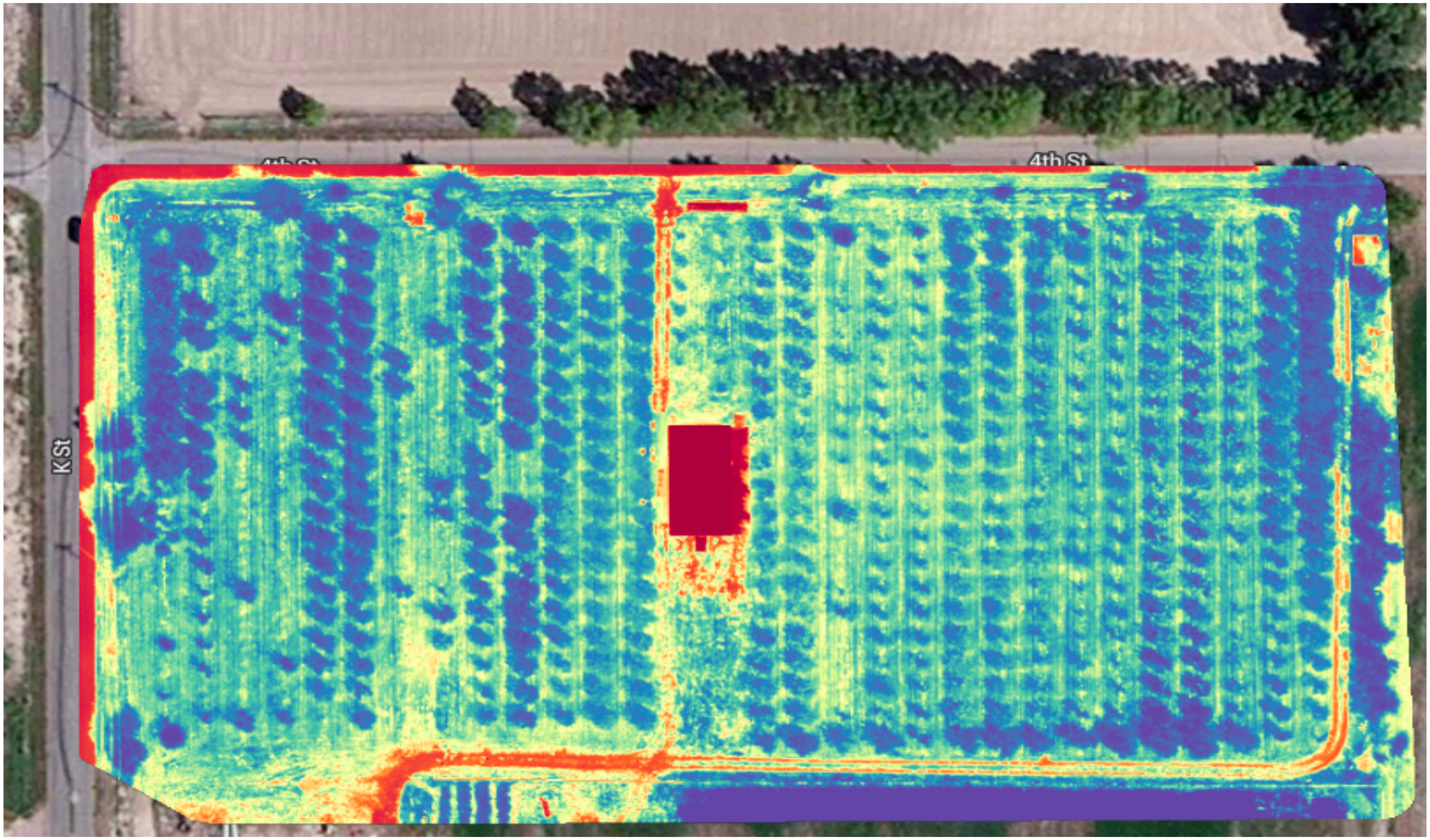

Figure 15) Normalized Difference Vegetative Index Imagery of Jenkins Orchard (Dark Green is Healthier Vegetation)

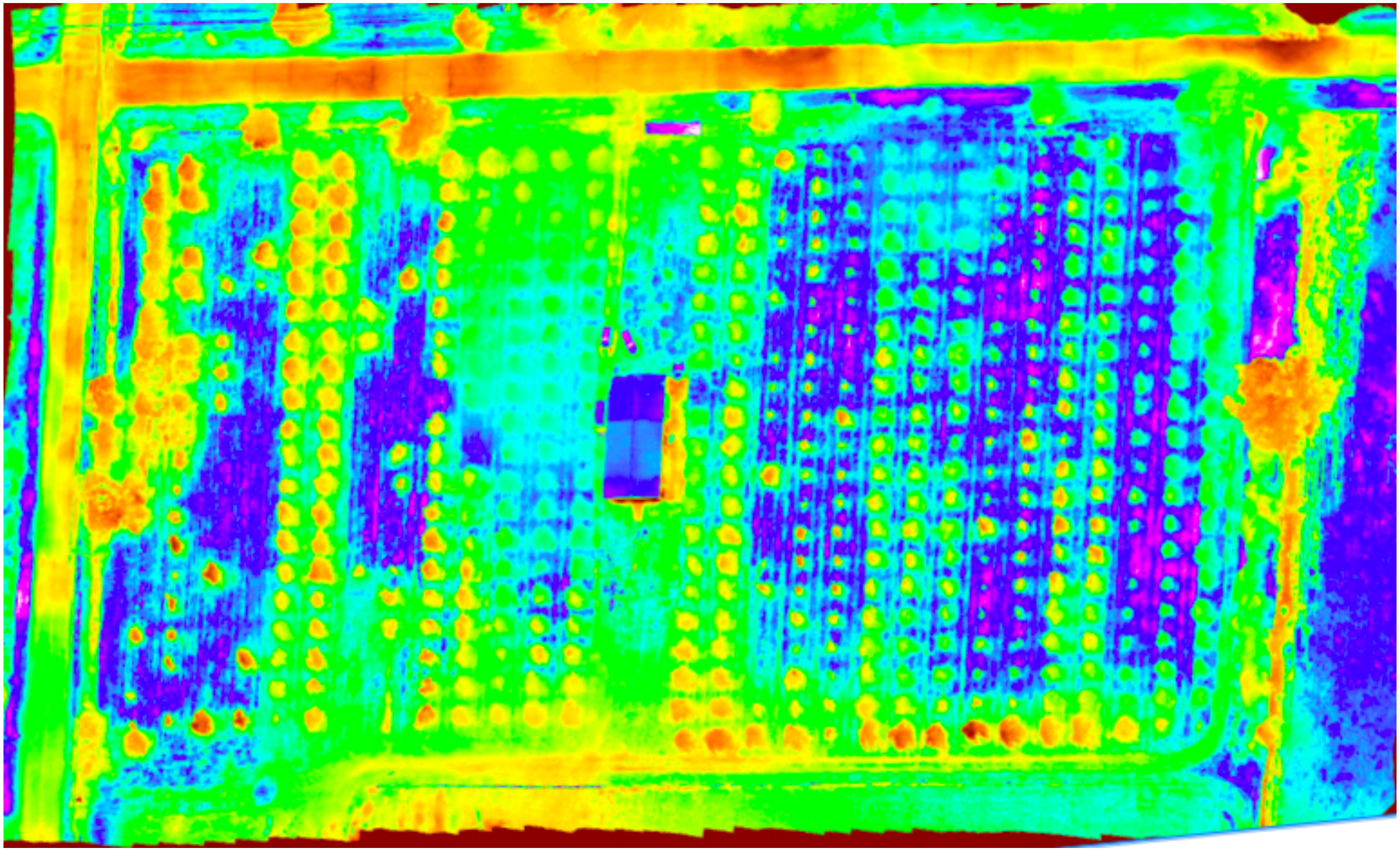

Figure 16) Thermal Image of Jenkins Orchard on 9/15/17 around 6:00 A.M (Blue/Purple is Colder)

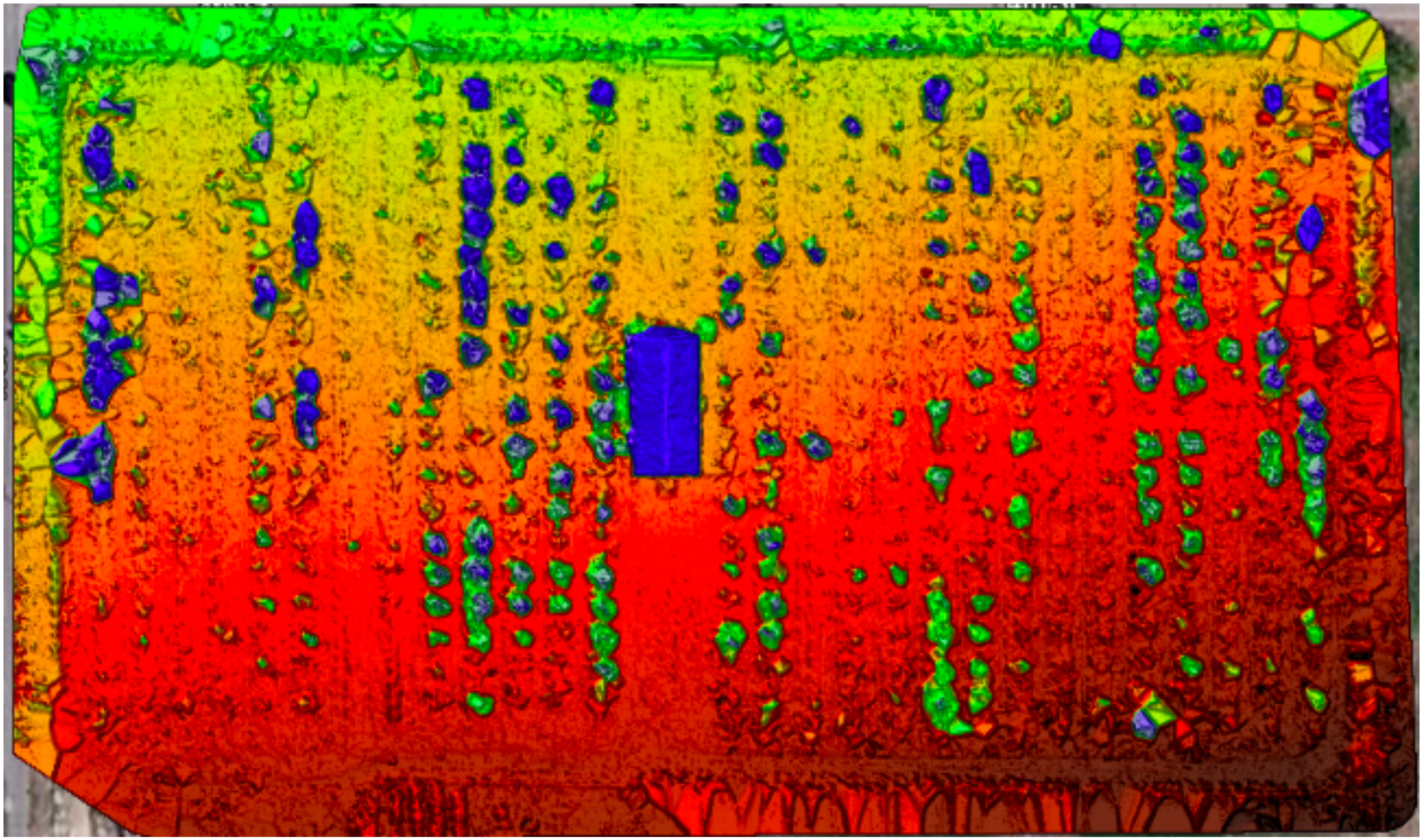

Figure 17) Digital Elevation Model of Jenkins Orchard (Red is Lower Elevation)

Figure 18) Locations of Grid Sonic Anemometer Placement

Figure 19) Average Mixing/Advection Ratio at each Grid Point

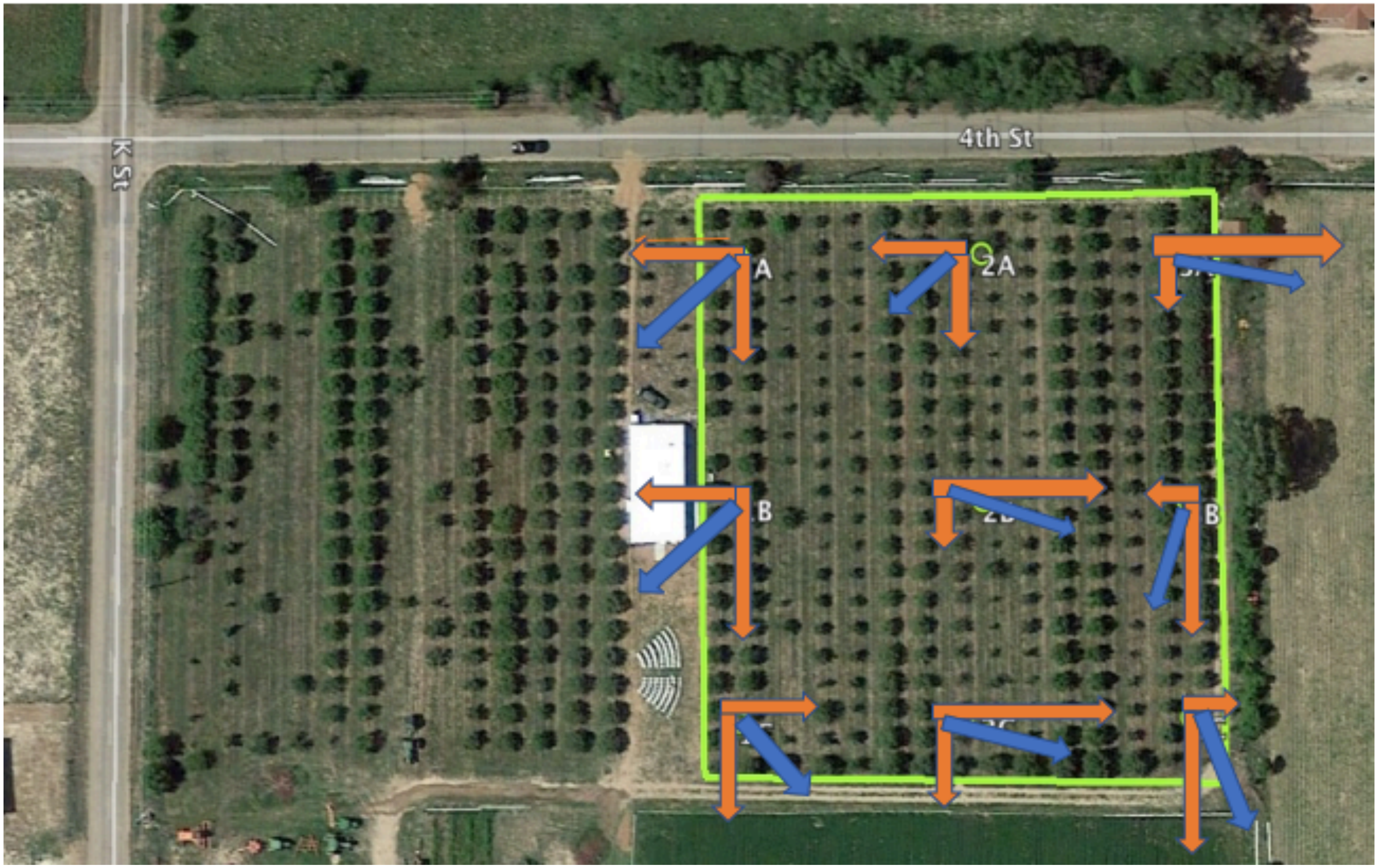

Figure 20) Approximate Air Flow Vectors (Orange Arrows) at each Grid Point (Blue Arrows Display Net Vector)

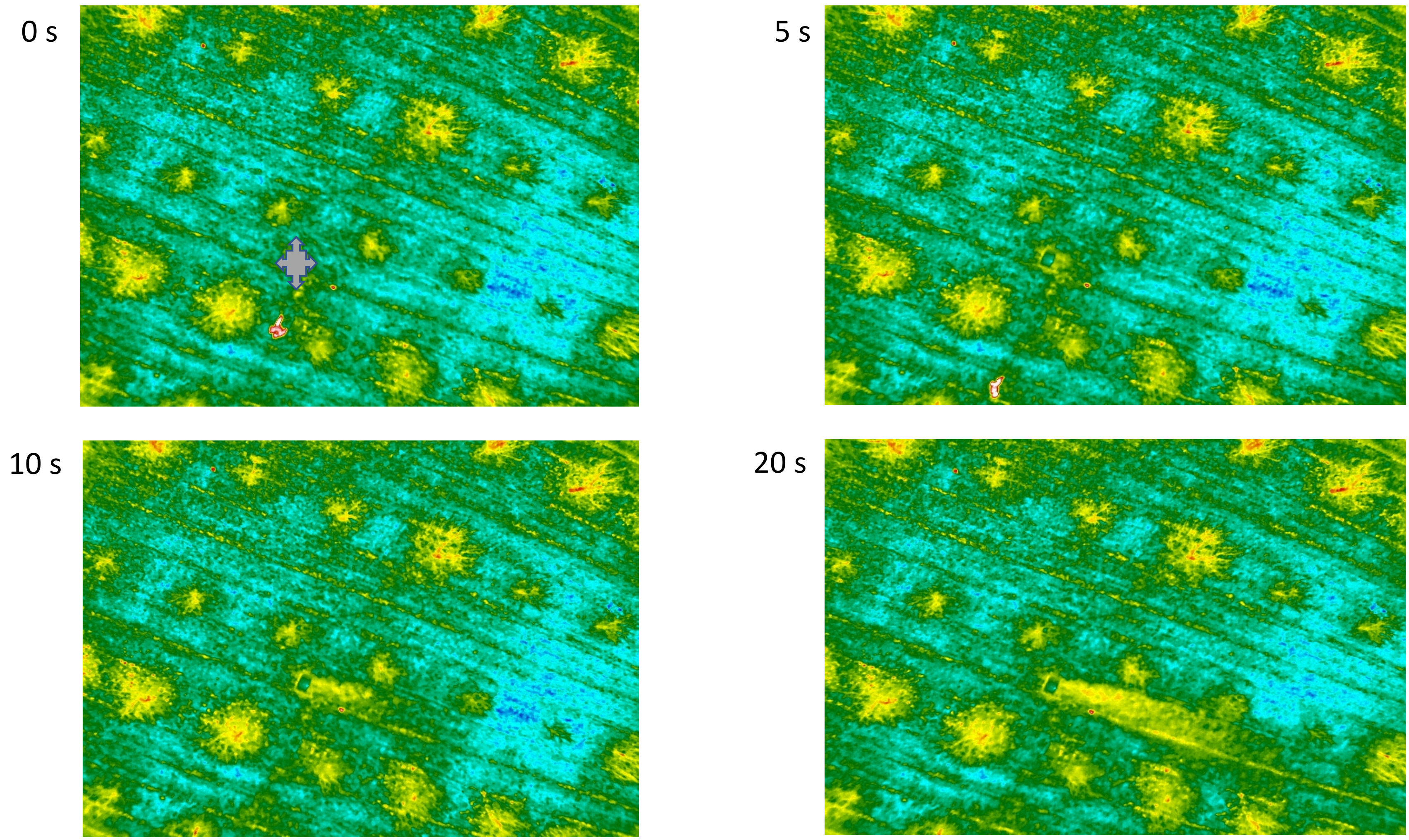

Figure 21) Thermal Images of Jenkins Orchard after Initiation of Fan (Gray Symbol) until 20 Seconds (Fan Pointed South Down Row)

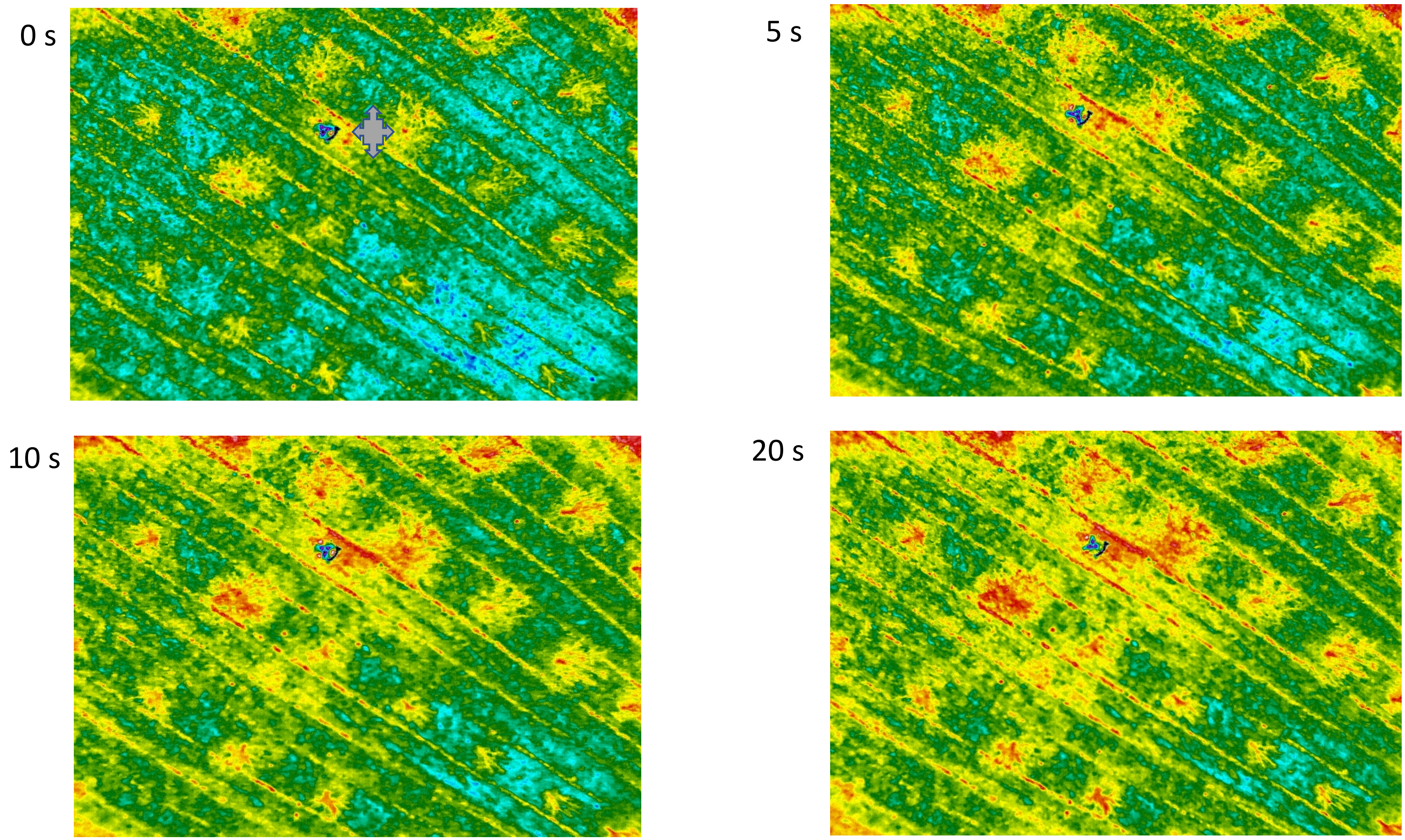

Figure 22) Thermal Images of Jenkins Orchard after Initiation of Fan (Gray Symbol) until 20 Seconds (Fan Pointed Upwards into Sky)

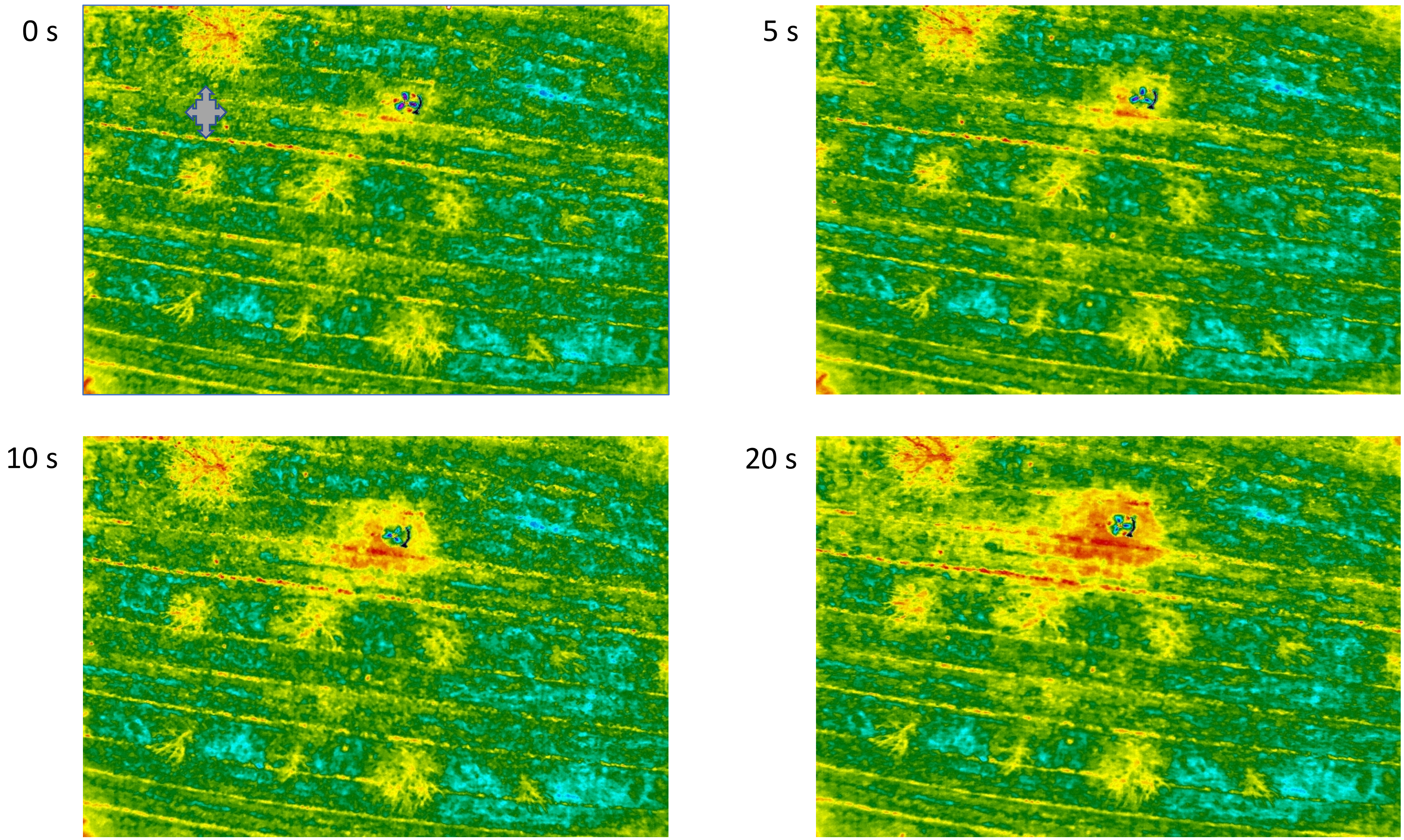

Figure 23) Thermal Images of Jenkins Orchard after Initiation of Fan (Gray Symbol) until 20 Seconds (Fan Pointed Downwards into ground)