Using Climatological Data to Identify Locations with Viticultural Potential in Colorado

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Abstract

Western Colorado's warm, dry summers and access to mountain river water for irrigation create ideal conditions for the growth of wine grapes, specifically cultivars of the European grape species *Vitis vinifera*. The largest limiting factor to *Vitis vinifera* production is nocturnal temperatures cold enough to damage crops, or Low Temperature Injury Events (LTIEs). LTIEs require producers to undergo the time-and-cost prohibitive venture of retraining vines. Eastern Mesa County Colorado has sustained large-scale grape production due to the area's relatively mild cold season weather. Areas with similarly hospitable conditions may exist elsewhere within western Colorado. Parameter-elevation Regressions on Independent Slopes Model (PRISM) temperatures (1981-2020) were used to estimate the frequency of LTIEs across Colorado, and identify trends associated with a warming climate. In the interest of comparing PRISM temperatures to observations over actual vineyards, thermometers were placed on current vineyards in Montezuma County from 2016 to 2020. Findings suggest additional areas of opportunity for *Vitis vinifera* production exist in Colorado, particularly western Montezuma County, and western Mesa and Montrose Counties. Like eastern Mesa County, these areas experience a LTIE in fewer than 20 % of years. PRISM data also suggest southeast Colorado is becoming more hospitable for *Vitis vinifera* growth over time. Temperature measurements in Montezuma County during potentially lethal weather events compared closely with PRISM data, with a mean absolute difference of 1.8 ˚C. This comparison suggests PRISM is a reliable tool for identifying areas of opportunity in spite of western Colorado's complex terrain.

1. Introduction

Western Colorado's climatology and water resources permit the growth of a number of specialty crops. Examples include sweet corn, peaches, and wine grapes. The Palisade and Grand Junction area in Mesa County, Colorado has been producing wine grapes since the late 1800s (Fig. 1). Interest in producing Colorado grapes has risen over time with acreage increasing about 2.5-fold between 2000 and 2022. A number of meteorological factors elicit high quality grape potential in western Colorado: Summers are warm and dry with a large diurnal temperature range, facilitating sugar production while maintaining acidity (Cohen et al. 2008). Snowmelt-driven water resources sustain crops through climatologically dry summers. The largest climate-driven limitation to wine grape growth in western Colorado is cold spells causing Low Temperature Injury Events (LTIEs).

Colorado grape producers are potentially vulnerable to several types of LTIEs, which occur at different points in the season: The first and most damaging type of LTIE is late fall and winter temperatures cold enough to cause high bud mortality and vine dieback to the ground. The temperature at which grape buds die is known as lethal temperature (LT), often expressed in percentile (e.g. LT_{10}, LT_{50}; and LT_{90} erring to the lethal temperature for a 10 %, 50 %, and 90 % bud kill). A grape bud's ability to withstand low temperatures is referred to as bud cold hardiness. Cold hardiness varies based on a number of factors: vine variety (e.g. Riesling, Cabernet Sauvignon, etc…), location, temperature, and individual plant physiology (Mills et al. 2006). Cold hardiness varies throughout the dormant season. Hardiness is low at the start of the dormant season and reaches maximum values during the middle of winter. As ambient temperatures warm in spring there is a gradual loss of cold hardiness. The process of gaining cold hardiness in fall and early winter is referred to as acclimation, whereas the loss of cold hardiness towards spring is referred to as deacclimation (Zabadal et al. 2007).

In recent years, mild fall conditions followed immediately by harsh, if not record-breaking, cold snaps have resulted in two notable LTIEs: in October 2019, and October 2020. The minimum temperatures at Grand Junction's Walker Field Cooperative Observing Network (COOP) Station on 30 and 31 October 2019 were -13.9 °C and -14.4 °C, the lowest October temperatures ever measured since record-keeping began in 1895 (previous record was -8.9 °C set in 1917). Primary bud damage to *Vitis vinifera* varieties ranged from >50 % for late acclimating varieties like Barbera and Cabernet Sauvignon to less than 5 % for early acclimating varieties like Cabernet Dorsa and Zweigelt. There was no damage to cordons or trunks and all varieties produced a crop in 2020, albeit a reduced one for varieties with high bud damage. On 26 and 27 October 2020, the minimum temperatures at Grand Junction's Walker Field were -8.9 °C and -11.7 °C (the fourth and third lowest October temperatures ever). Primary bud damage for most *Vitis vinifera* varieties was 100 % with extensive damage to trunks. An estimated 90 % of *Vitis vinifera* vines in the county required retraining from the ground in 2021.

Colorado grapes may be impacted by other freeze events as well. Freezing temperatures after bud break (typically in late April to mid-May) can be enough to damage a new crop. Similarly, a hard freeze before grapes are ready for harvest (late September) will end growth and any further ripening of the crop. Both of these freeze types impact yields, but are distinct from late fall and winter LTIEs in that temperatures generally remain above a threshold that would damage cordons or trunks and do not inhibit grape production in subsequent years.

Several select areas of Colorado have historically supported *Vitis vinifera* production due to milder fall and winter temperatures (Schlachter 2012). Well-known areas of grape production include Palisade and Grand Junction in Mesa County, and to a lesser extent the north Gunnison River Valley in Delta County, low-lying areas of Montezuma County, and Cañon City in Fremont County. These counties are shown in Fig. 1. What is not known is: 1. if there are other areas of Colorado where LTIEs are infrequent enough to make production of *Vitis vinifera* profitable, and 2. if a warming climate will expand the zone of viable grape production in the state of Colorado. This study seeks to address both questions, with special attention given to Montezuma County in southwest Colorado.

2. Methods

Parameter-elevation Regressions on Independent Slopes Model (PRISM) Model (Daly et al. 2008) daily minimum temperature data from water years 1981-2020 were used to identify the frequency of LTIEs across Colorado at 4 km resolution. A water year is a full calendar year that is tracked from 1 October – 30 September (e.g. Water year 2020 began 1 October 2019, and ended 30 September 2020). A water year calendar was used because it follows the cycle from one grape harvest to the next more closely than a standard calendar year. Four types of LTIEs were observed: Type I: Late fall cold snaps where LT was reached prior to full cold acclimation, Type II: Winter cold snaps where LT was likely reached despite time for cold acclimation, Type III: Hard freezes after bud break, and Type IV: Hard freezes prior to harvest. Qualifications for each freeze type are as follows:

Type I - Late Fall: $T_{min} < -12$ °C prior to November 1st, or $T_{min} < -15$ ° prior to November 16th, or $T_{min} < -18$ °C prior to December 1st

Type II - Winter (DJF): $T_{min} < -22$ °C

Type III - Post Bud-Break: $T_{min} < -2$ °C after May 15th, but before July 1st

Type IV - Pre-Harvest: $T_{min} < -2$ °C after July 1st, but before October 1st

Using these thresholds, the number of LTIE years (LTIEY)/decade was computed for each PRISM gridspace in Colorado. The fraction of Colorado experiencing each type of LTIE was also computed and plotted for each year. LTIEY/decade is examined for each freeze type to isolate the most common limiting factors for grape growth across Colorado by region.

None of the parameters for LTIEs are exact given LT occurs across a spectrum, not one single threshold, and that spectrum varies based on preceding weather. Additionally, timing of bud break and harvest may vary by up to several weeks depending on both the year and the grape variety. These thresholds were set based on a) long-term determinations of bud cold hardiness for a large number of varieties via controlled freezing tests at the Western Colorado Research Center, Grand Junction, Colorado; b) observed damage to European wine grape varieties in Palisade and Grand Junction from natural freeze events; and c) published literature (e.g. Dami et al., 2016; Ferguson et al., 2011, 2014, Mills et al., 2006; Zabadal et al., 2007).

PRISM daily T_{min} data were then compared with observational data on current and prospective vineyard sites in Montezuma County (Fig. 2). Montezuma County was chosen as a test case for several reasons: 1. It has a history of horticultural activity with crops of similar hardiness to *Vitis vinifera*. 2. Several vineyards have begun operating here, especially in McElmo Canyon. 3. The lowest-lying areas of the county are not flat. Canyons and ravines are scattered across the county in and around areas potentially suitable for grapes, thus modeled data are of insufficient resolution for determining the best spots for grapes. Observations can be used to help validate a location's suitability. PRISM T_{min} observations have been shown in previous studies to have a cold bias on the order of 0.75 ˚C in some mountainous locations (Strachan and Daly 2017), which may lead to a slight overestimation of LTIEs. While it is unclear how long-term observation may bias PRISM in Montezuma County, it should also be noted that PRISM, and similar modeled temperature products, are subject to biases in complex terrain based on where long-term climate stations used in the data ingest process are located (Strachan and Daly 2017). Newer downscaling projects such as Mital et al. suggest that even finer resolution downscaling could be utilized over complex terrain for more spatially accurate minimum temperature estimates.

USB-501-PRO thermometers (Logicbus 2022) were placed at over 15 locations around the county including current and prospective vineyards. Sensor placement began in December, 2016 and ended in May, 2021. Observing sites were not completely constant throughout the period of study due to some landowners opting in or out throughout the duration. Participation increased in the later period of observation. Thermometers were not protected with radiation shields, so low temperatures occurring during daytime hours may not be captured. Thermometers were installed at “vine height” 1.5m. The COOP standard observation height is 2m. Under nighttime inversion conditions where the coldest air pools at surface level this could lead to a cold bias in site-specific observations relative to observations from other networks. This setup is still preferential as it provides prospective producers with accurate estimates of how cold air at vine level will become. Observed and gridded temperature data were compared.

Some of the Montezuma County observing sites experienced a LTIE on three occasions: 20 May 2017, 25 September 2017, and 31 October 2019. PRISM temperature estimates and observed temperatures across the county were mapped for each event. Daily minimum temperature observations came from the Cooperative Observing Network (COOP) (US Dept. of Commerce 2022) and the Colorado Agricultural Meteorological Network (CoAgMET 2022) as well as project-specific observing sites. For meteorological context, the large-scale weather pattern for each event was analyzed using ERA5 temperature, sea level-corrected pressure, and wind data for each event (Hersbach et al. 2022).

The differences between observed T_{min} and T_{min} from the overlapping PRISM gridpoint was recorded to identify patterns in these differences based on observing network, elevation, and geographic location. The average absolute difference between observations and accompanying grid spaces $|T_{min\_obs} - T_{min\_PRISM}|$ was computed for all LTIEs. Special attention is given to the project-specific observation sites as these weather stations are not used to create PRISM maps.

Finally, a trend analysis using ordinary least squares regression was completed to answer the question of whether or not LTIEs are declining in wine country and statewide. LTIE Trends in wine country were computed using daily Grand Junction Walker Field COOP weather station data, which is located in the portion of Colorado where grapes are most prevalent. This analysis spans water years 1951-2021. The station has no missing daily minimum temperature data. Statewide trends in LTIEs were analyzed using 1981-2020 PRISM data. The fraction of Colorado not experiencing each type of LTIE is computed and reported for each year.

3. Results

Freeze Potential Maps: LTIEs are a concern everywhere in Colorado. Every PRISM gridpoint in the state met one or more LTIE criteria at least twice since 1981. Most of Colorado is too cold in fall or winter to consistently produce European wine grape varieties. Over two thirds of Colorado experienced a LTIE in 80 % or more years from 1981-2020. Only 1 % of grid cells met LTIE criteria in fewer than 20% of years. These areas are found exclusively in western Colorado at low elevations relative to the rest of the region (< 2000m). The Grand Junction/Palisade area of Mesa County, western Montrose County, and portions of western Montezuma County experienced a LTIE in fewer than 20 % of years from 1981-2020 (Fig. 3).

Elevation and latitude are both important determinants of LTIEs statewide, each explaining over 40 % of variance in the number of LTIEYs/decade. The highest elevation portions of Colorado are subject to LTIEs every year, sometimes all four types. Elevation being equal, the southern portion of the state is warmer and less prone to LTIEs. Longitude is important too. Western Colorado is less prone to LTIEs, particularly type II LTIEs, than eastern Colorado. Eastern Colorado experiences more intense cold air outbreaks in winter when arctic high pressure systems migrate southward off the Canadian Shield (e.g. Waugh et al. 2016). Western Colorado is sheltered from these shallow cold airmasses by mountains, and records warmer annual low temperatures as a result (USDA 2022).

The most common LTIEs are types I and II (Fig. 4). These are also the most destructive freeze types due to the severity of damage. The spatially averaged statewide probabilities of each freeze type are 45, 65, 37, and 32% respectively. Where winter freezes are the primary concern, cold-hardy hybrids may be grown with greater success, but winter cold remains a major limiting factor for *Vitis vinifera* across all of eastern Colorado and most of western Colorado. All freeze types are possible even in the milder portions of western Colorado. Low elevation portions of Montezuma County have experienced freeze types I, III, and IV since 2017.

Killing Freeze Observations: Observed temperature data were collected for three LTIEs impacting Montezuma County: 20 May 2017 (event one), 25 September 2017 (event two), and 31 October 2019 (event three). Not all of these events were LTIEs everywhere in the county. Event one did not meet LTIE criteria for the southern portion of Montezuma County, and event two was not a LTIE for portions of western Montezuma County according to PRISM data. Observations suggest the west end of McElmo Canyon, and portions of the County on hillsides north of Cortez did not experience LTIEs in events one and two. Stations on top of Mesa Verde did not meet the LTIE threshold during event two despite exceeding 2500 m elevation. Event three was a LTIE county-wide.

All three LTIEs occurred under similar synoptic (regional)-scale weather conditions. Each event occurred under high pressure atmospheric conditions within 48 hours after a cold frontal passage. Figs. 5-7 show synoptic-scale weather maps from each event. While these maps are not of sufficient resolution for analyzing topographically driven drainage winds, the weather maps do show calm, or near calm (less than five knots), winds across western Colorado in each case. Calm winds are conducive to cold air pooling in valleys, where most vineyards reside.

Observation site elevation was significantly correlated with temperature difference between observations and PRISM gridded data on 20 May 2017 at 99% confidence. This is largely because the Cortez 8 SE COOP station, which is the highest elevation station used, was 5 ˚C cooler than suggested by PRISM observations. There was not a significant correlation between site elevation and difference between observations and PRISM data on 25 September 2017 or 31 October 2019 (Table 1). The average absolute difference between observations and the overlaying PRISM grid value was 1.8 ˚C. The average absolute difference was smaller for project-specific sites than COOP or CoAgMET sites. This was an unexpected result given COOP and CoAgMET T_{min} measurements are used in the PRISM map generation process, whereas project-specific T_{min} measurements are not.

The spatial patterns for each LTIE, as seen in Figs. 8-10, are quite different, but PRISM temperature patterns closely match observations in each case. Higher elevations observed lower nighttime temperatures in both the May 2017 and October 2019 LTIEs. In the September 2017 LTIE, higher elevations were warmer. This produced some of the largest differences between PRISM and observations. Fig. 11 shows the differences between observed and modeled temperatures for each LTIE. Observations were cooler than PRISM data by an average of 1.3 ˚C on 20 May 2017. Observations were warmer than PRISM on 25 September 2017 by an average of 1.0 ˚C. 31 October 2019 saw the lowest difference between observation and reanalysis: observations were cooler than PRISM by an average of 0.4 ˚C. Observed temperatures for the westernmost two stations in Montezuma County were warmer than PRISM data in every case. PRISM data already indicate low occurrence of LTIEs in this area. Observations during these events suggest temperatures may be even higher, and LTIEs more infrequent

LTIE Trends: Colorado has warmed faster than the national and global average over the last 50 years (NOAA 2022). Warming is occurring in all seasons. With warmer winters, the average fraction of Colorado not experiencing a LTIE in a given year is increasing. The average fraction of Colorado without a LTIE/year has increased from 13 % in the 1980s and 1990s to 21 % in the 2000s and 2010s. In 2012, 2016, and 2018 the state was over 40% LTIE-free. This mark had only been reached once in the previous three decades (1990). Every part of the state remains susceptible to LTIEs. Fig. 12 shows that in some years 100 % of Colorado experiences a LTIE (e.g. 2020).

There is no clear trend in PRISM data towards fewer LTIEs in eastern Mesa County, the area historically producing the most grapes. There is a small, statistically insignificant, positive trend in the number of LTIEYs/decade at Walker Field (p=0.874), (Table 2). Water years 2020 and 2021 were both impacted by type I LTIEs. 2020-2021 is the only instance of back-to-back type I LTIEs at Walker Field on record.

4. Discussion

PRISM daily T_{min} were used to estimate the frequency of LTIEs for years 1980-2020. These data: 1. Identify portions of Colorado with grape growing potential, and 2. Detect trends in LTIEs. Not all areas of Colorado with a low number of LTIEs are currently utilized to produce *Vitis vinifera* at scale. Montezuma County, and western Montrose and Mesa Counties are estimated to have experienced fewer than two LTIEYs/decade from 1980-2020, but are not leveraged for large-scale grape production. Montezuma County does have several vineyards, but grape production remains small. There are currently no vineyards in Western Mesa/Montrose County. Depending on soil quality and water availability, which are not universally problematic in these regions (Dolores

Water Conservancy District 2022, Mellick et al. 1998), these areas may be fertile ground for expansion of Colorado's wine industry.

Observations from current and prospective vineyards in Montezuma County suggest PRISM is a reliable data source for capturing county and division-wide variations in temperature. However, open-source PRISM data (4 km resolution) is limited in its ability to capture microclimatic variations in T_{min}, especially in the rugged and heterogeneous terrain of western Colorado. Despite the complex topography, data from three LTIEs in Montezuma County show similar temperature patterns between gridded and observed data, with an average absolute difference between gridded and observed temperature of 1.8 ˚C.

While this study estimates the likelihood of LTIEs for a specific area, it cannot predict the severity of the damage resulting from such events. Other information is needed, especially data on bud/vine cold hardiness. This can be illustrated by comparing the damage from the two extreme cold events in Western Colorado in October 2019 and October 2020 (Type 1 events). The minimum temperatures in late October 2019 were much lower than those in late October 2020, yet cold damage was much more severe in 2020. In fact, the October 2020 cold damage largely occurred at temperatures above the threshold used for a Type I LTIE in this manuscript. It is, therefore worth reiterating that LTIE spatial variability and trends shown here are based on estimates, and that LT_{50}, and other LT percentile thresholds, are moving targets, and a function of antecedent weather conditions.

Freezes remain a challenge to *Vitis vinifera* producers anywhere in Colorado. Grand Junction recorded its two coldest October low temperatures in 2019 and 2020 (ACIS 2022). Both were LTIEs. PRISM data did show an increase in years where LTIEYs do not occur across a large fraction of Colorado, especially southeast Colorado. The area is still too cold in winter for production of *Vitis vinifera* at scale, but current trends in wintertime temperature indicate more small scale experimentation, especially with hardier hybrid grape varieties, may be worthwhile. More climate modeling is necessary to understand how this will change in the future. Given the scientific consensus of an overall warming climate (Jay et al. 2018), it is possible that a trend will emerge towards fewer LTIEs in the coming decades.

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TABLES

	Correlation (Station Elevation vs Temperature)	p-value		Correlation (Station Elevation – PRISM Elevation vs Temperature)	p-value
20 May 2017	-0.631	0.007		0.498	0.042
25 September 2017	0.346	0.174		0.418	0.095
31 October 2019	-0.066	0.758		0	8

Table 1: Correlation (and corresponding p-value) between station elevation and difference between observed T_{min} and PRISM T_{min} (left). Correlation (and corresponding p-value) between station elevation – PRISM gridpoint elevation and difference between observed T_{min} and PRISM T_{min} (right) for 20 May 2017 (top), 25 September 2017 (middle), and 31 October 2019 (bottom).

	Type 1	Type 2	Type 3	Type 4	Any Type
1950s	0	1	0	0	1
1960s	0	3	0	0	3
1970s	1	7	0	0	8
1980s	0	2	0	0	2
1990s	0	2	0	0	2
2000s	1	2	0	1	3
2010s	1	3	0	0	4
2020s*	1	0	0	0	1

*Table 2: LTIEYs/decade at Grand Junction Walker Field COOP station. * = only includes 2020 and 2021.*

FIGURES

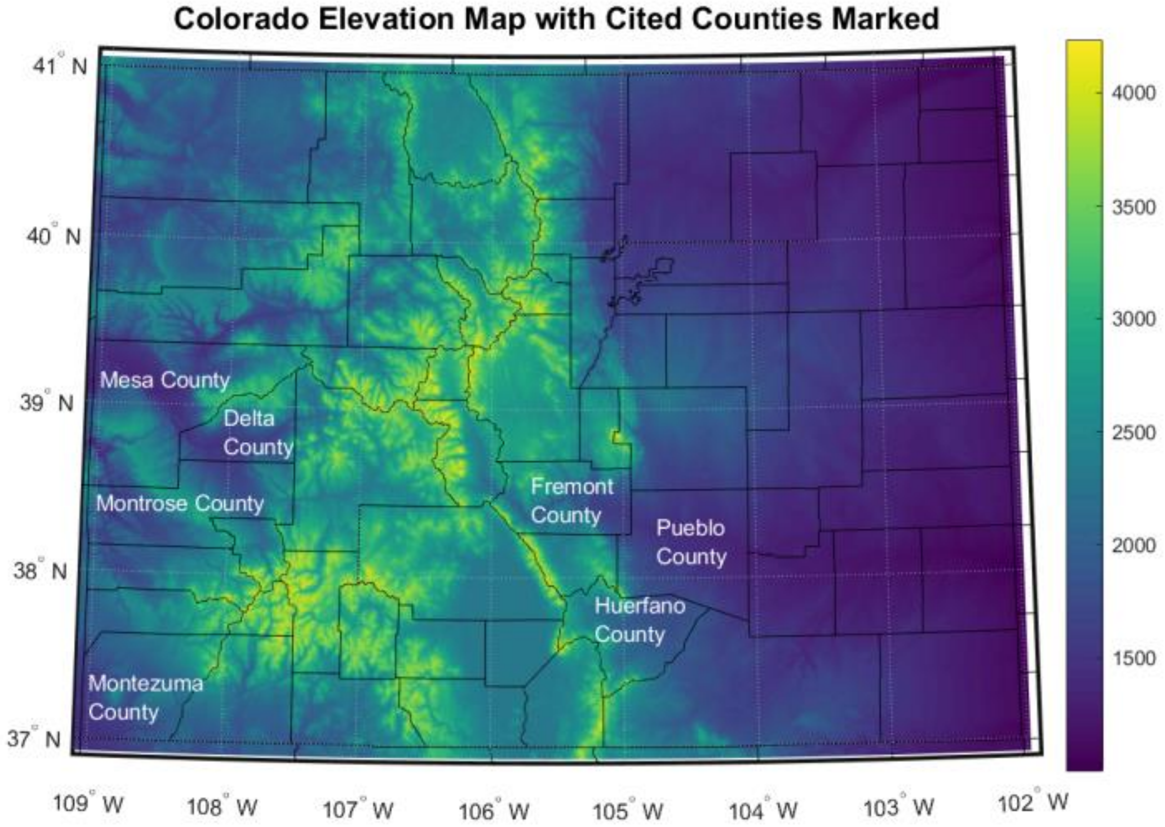

Figure 1: Elevation map of Colorado (meters). Counties referenced in texted are labeled in white.

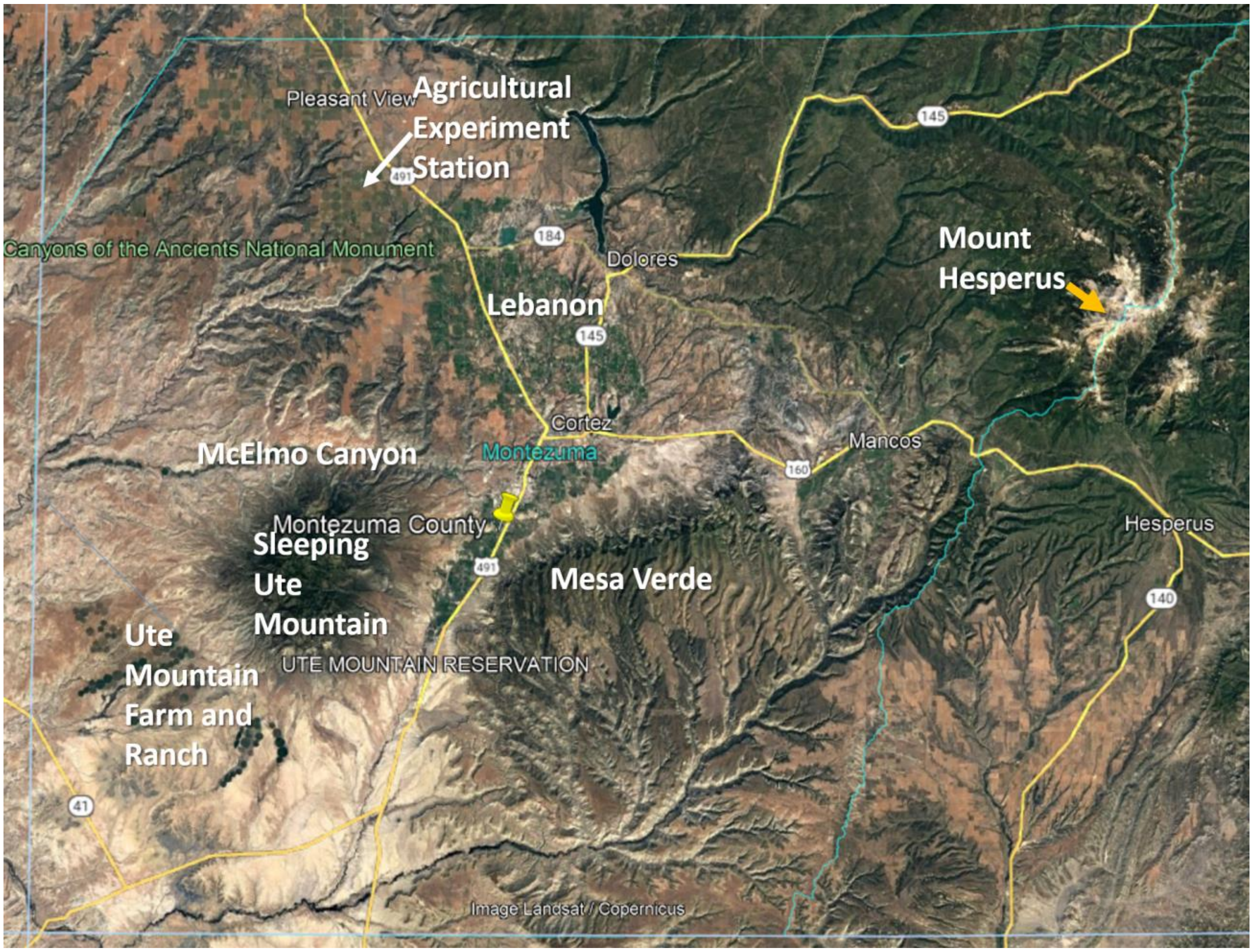

Figure 2: Google Earth image of Montezuma County. Landmarks referenced in text labeled in white.

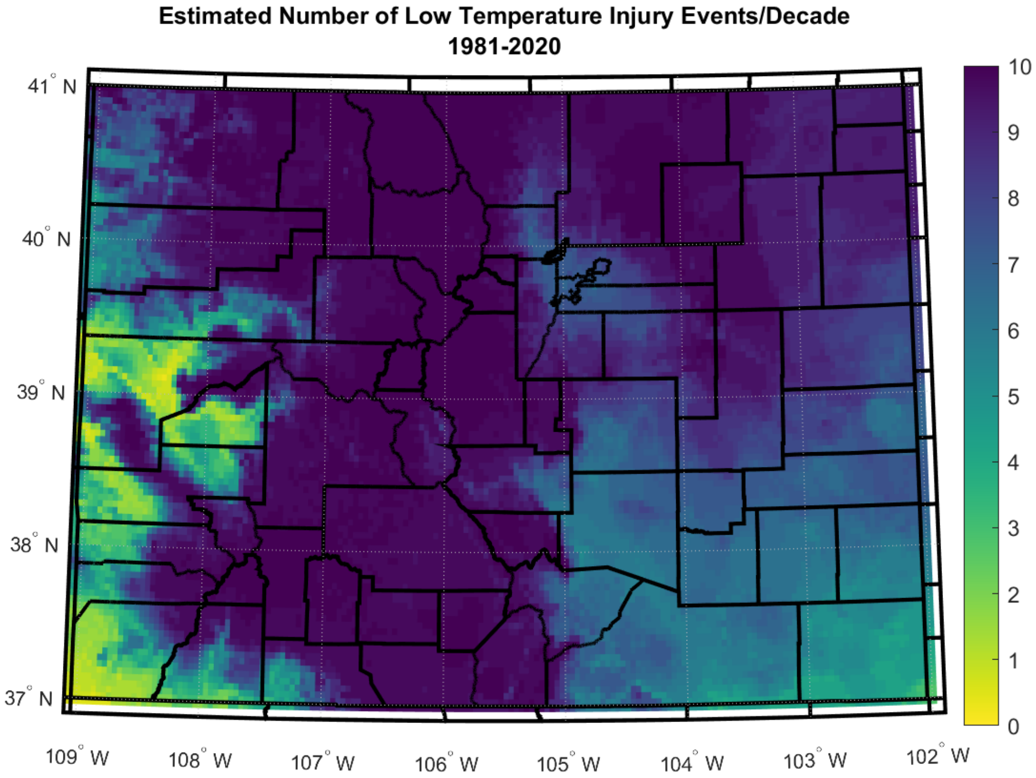

Figure 3: Number of LTIEYs/decade. LTIEs estimated using PRISM data for water years 1981-2020. LTIEYs = years in which at least one of the four LTIE types occurs.

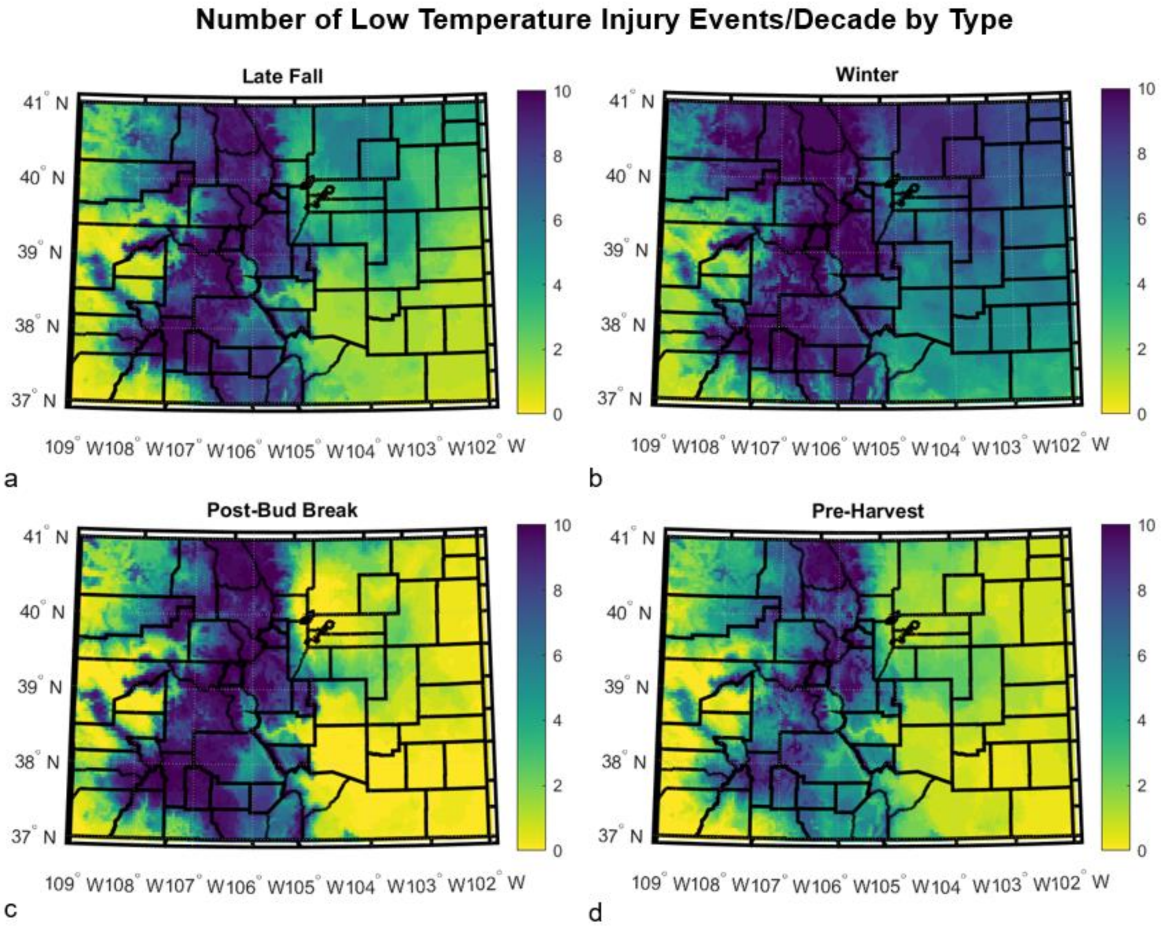

Figure 4: Number of LTIEYs/decade for each freeze type. LTIEs estimated using PRISM data for water years 1981-2020. Killing freeze counts for panels determined as follows: a. $T_{min} < -12$ ˚C prior to November 1st, or $T_{min} < -15$ ˚C prior to November 16th, or $T_{min} < -19$ ˚C prior to December 1st b. $T_{min} < -22$ ˚C December-February c. $T_{min} < -2$ ˚C after May 15th, but before July 1st d. $T_{min} < -2$ ˚C after July 1st, but before October 1st.

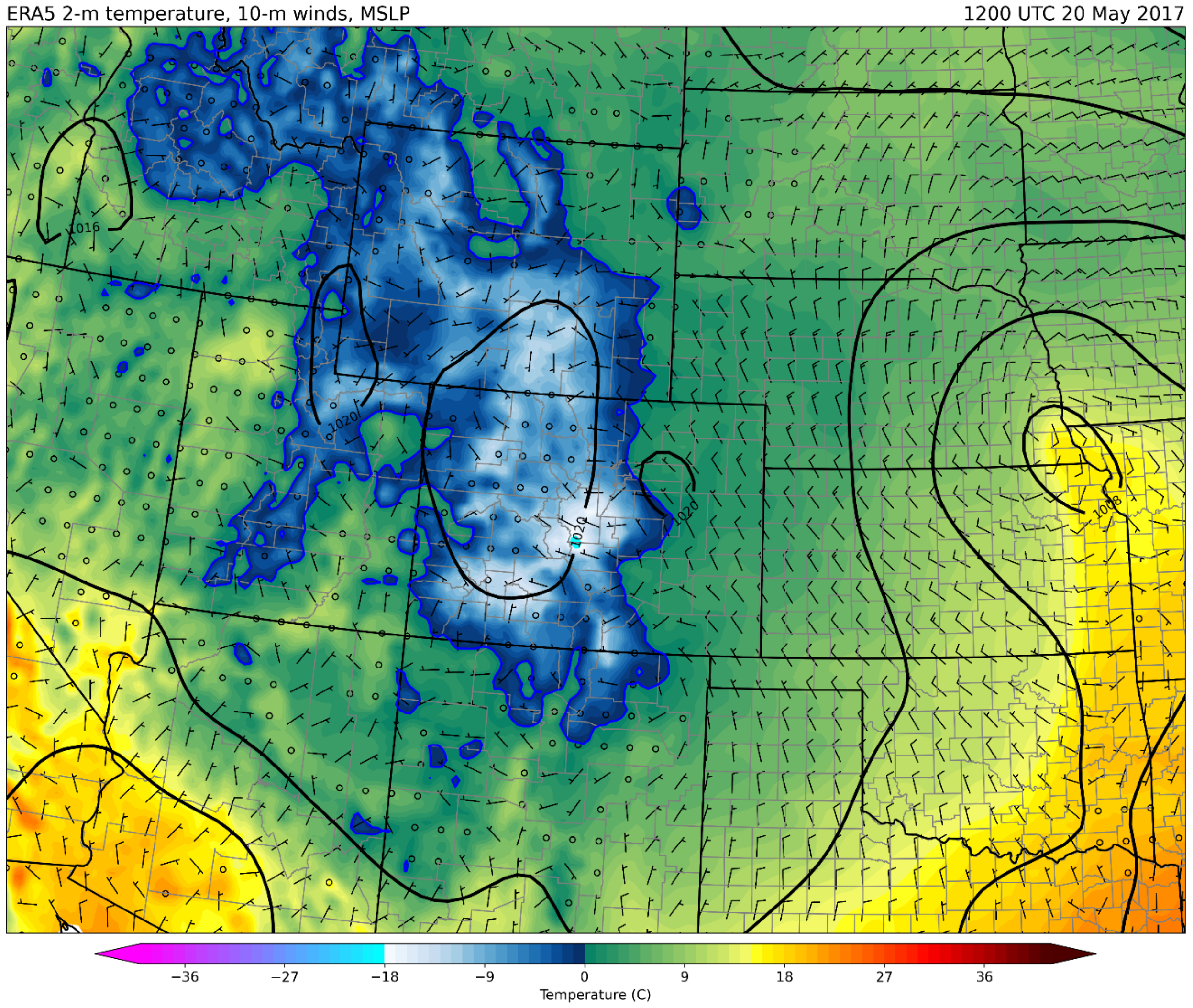

Figure 5: ERA5 reanalysis temperature (color contours), pressure (black contours), and wind patterns (black barbs) for 1200 Universal Time Coordinatore (UTC) 20 May 2017. Wind barbs indicate wind direction of origin. Flags on wind barbs indicate speed. One flag = 10 knots. ½ flag = 5 knots. Open circles indicate calm winds. Local time is UTC -6 hours.

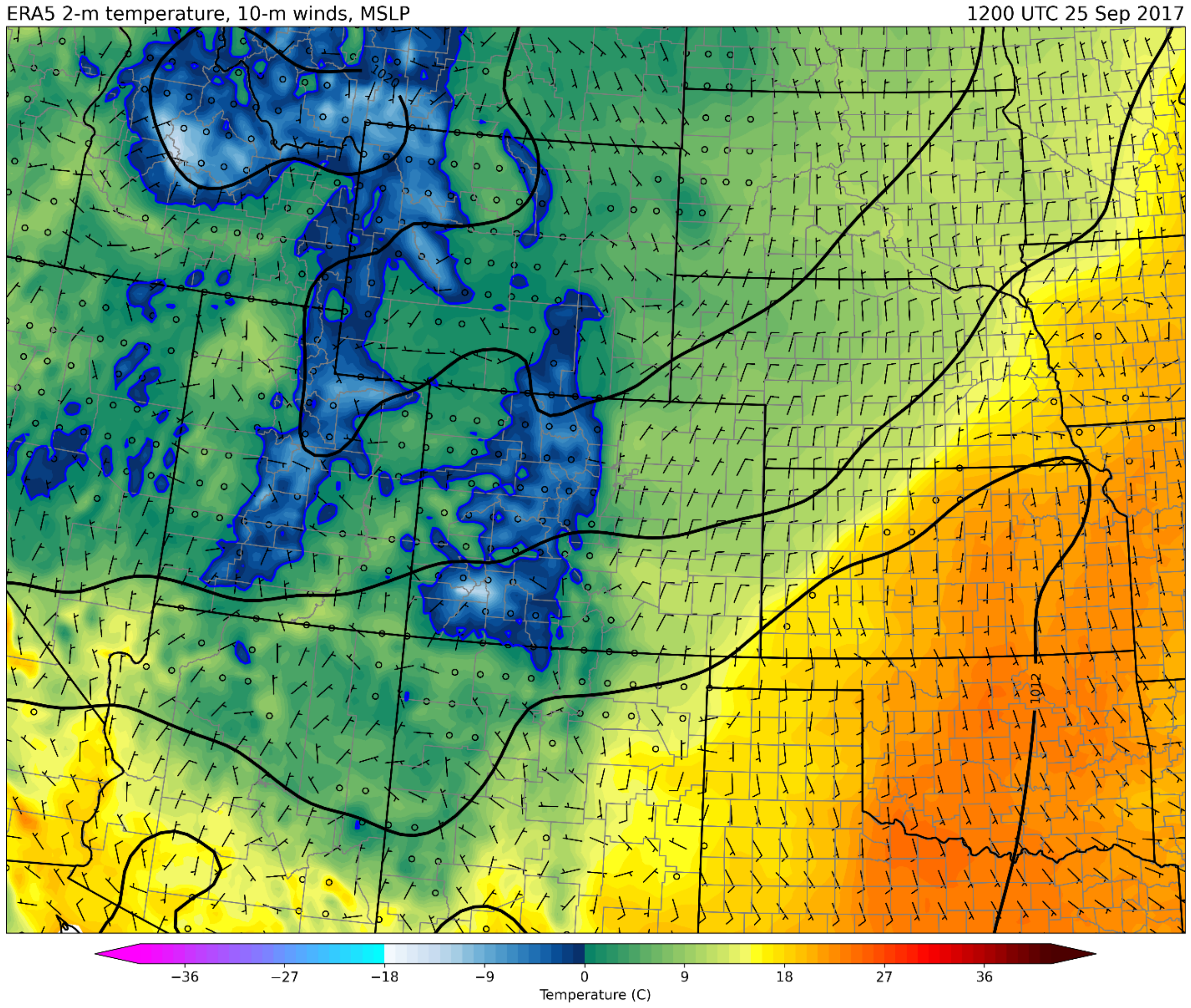

Figure 6: ERA5 reanalysis temperature (color contours), pressure (black contours), and wind patterns (black barbs) for 1200 Universal Time Coordinatore (UTC) 25 September 2017. Wind barbs indicate wind direction of origin. Flags on wind barbs indicate speed. One flag = 10 knots. ½ flag = 5 knots. Open circles indicate calm winds. Local time is UTC -6 hours.

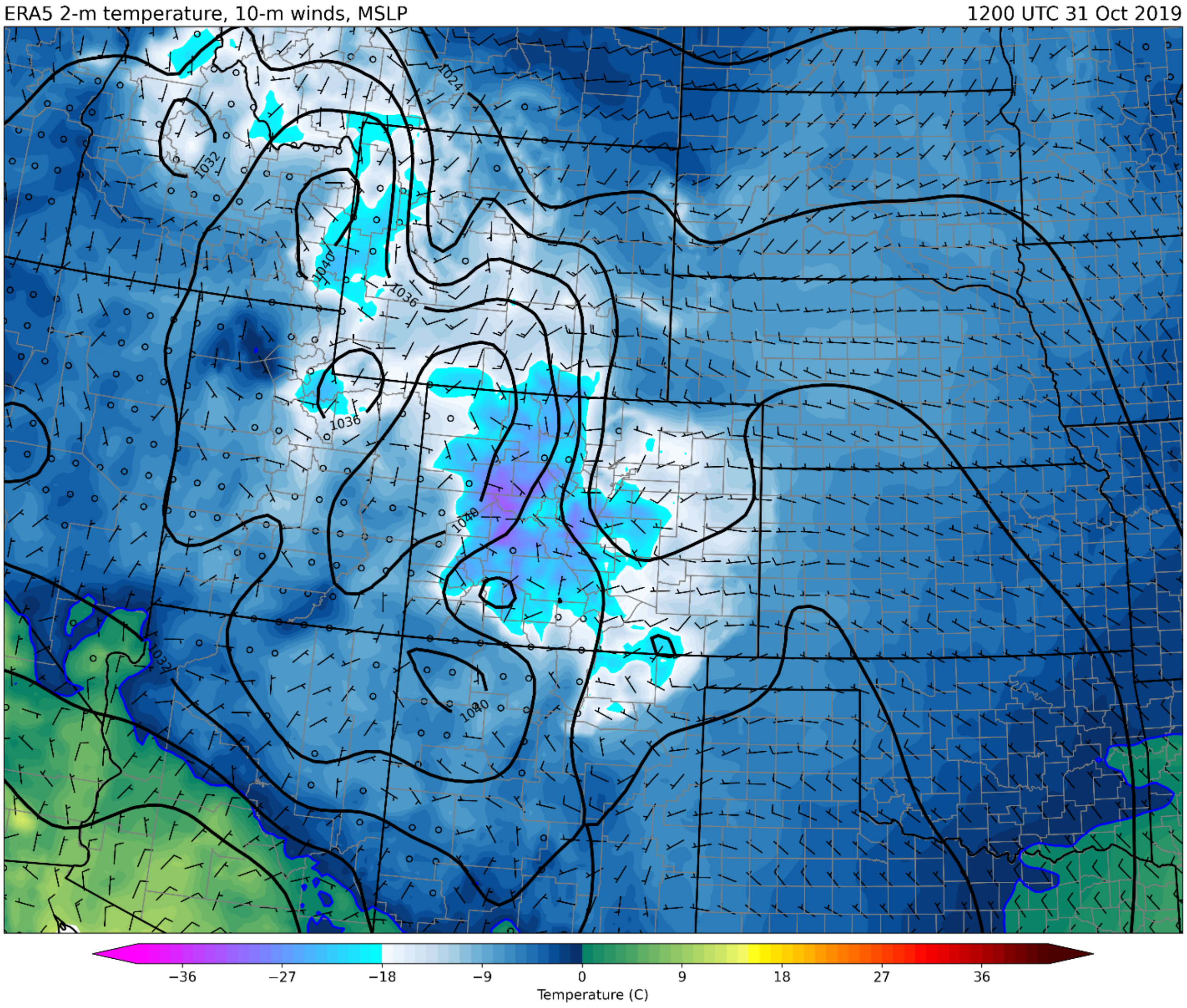

Figure 7: ERA5 reanalysis temperature (color contours), pressure (black contours), and wind patterns (black barbs) for 1200 Universal Time Coordinatore (UTC) 31 October 2019. Wind barbs indicate wind direction of origin. Flags on wind barbs indicate speed. One flag = 10 knots. ½ flag = 5 knots. Open circles indicate calm winds. Local time is UTC -6 hours.

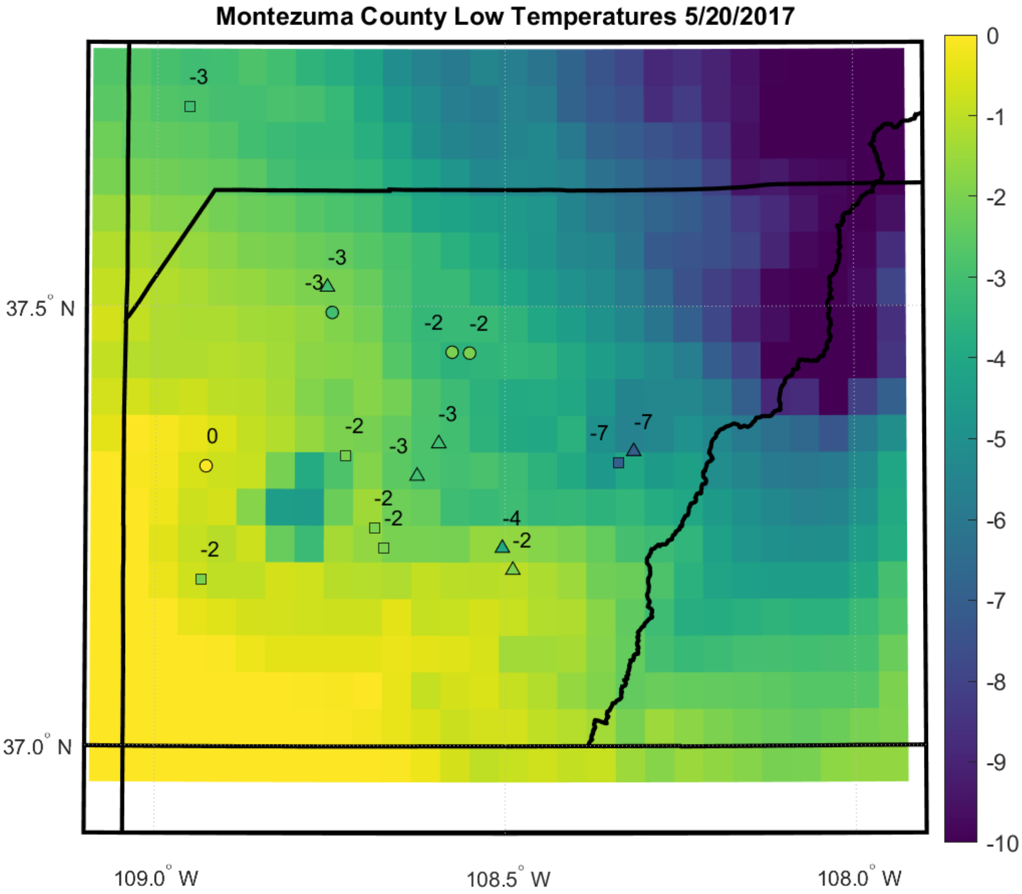

Figure 8: Daily T_{min} across Montezuma County (˚C) 20 May 2017. Background color is PRISM T_{min}. Filled symbols are station temperatures. Triangles are COOP stations, squares are CoAgMET stations, and circles are project-specific stations. Numbers also indicate T_{min}.

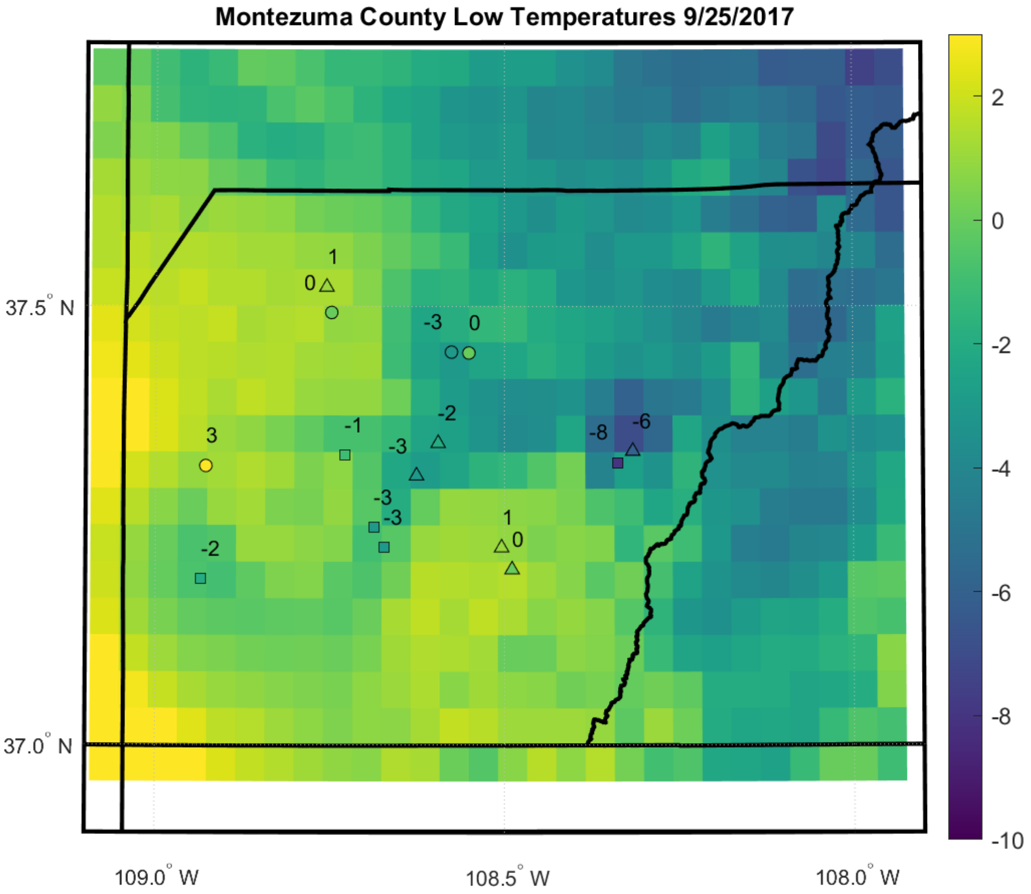

Figure 9: Daily T_{min} across Montezuma County (˚C) 25 September 2017. Background color is PRISM T_{min}. Filled symbols are station temperatures. Triangles are COOP stations, squares are CoAgMET stations, and circles are project-specific stations. Numbers also indicate T_{min}.

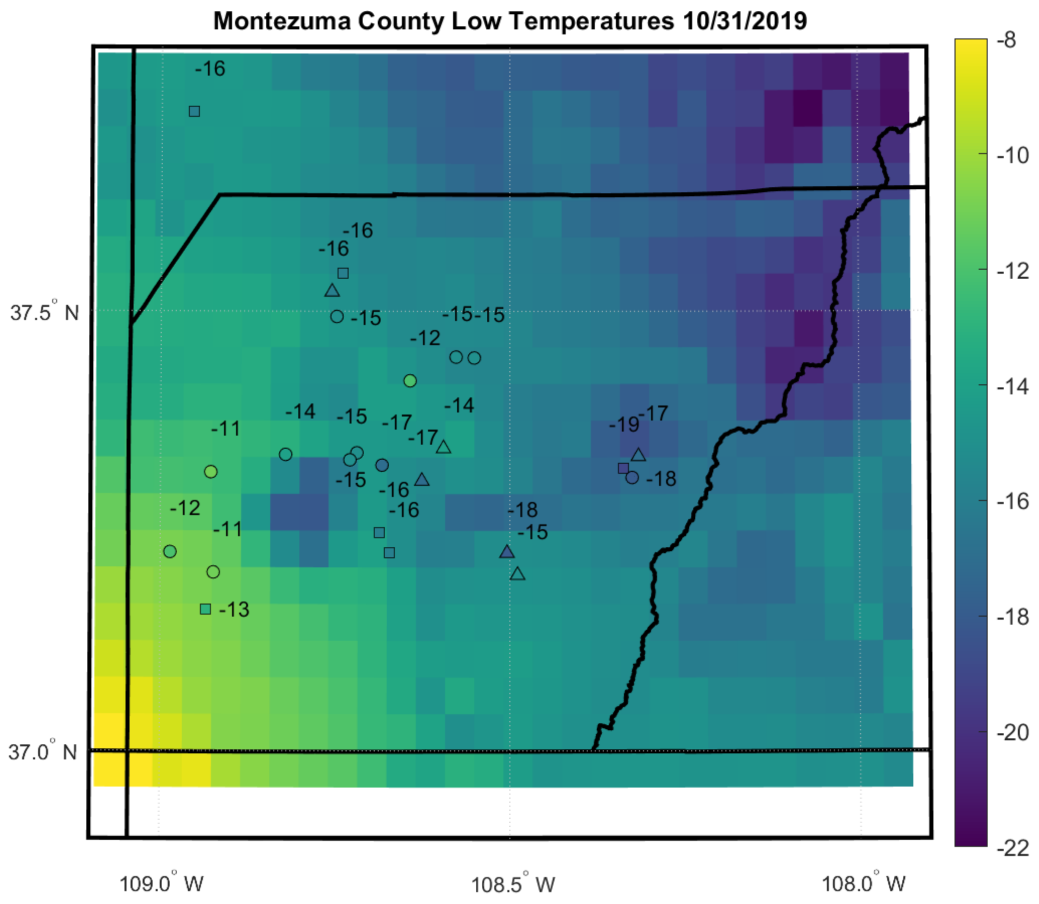

Figure 10: Daily T_{min} across Montezuma County (˚C) 31 October 2019. Background color is PRISM Tmin. Filled symbols are station temperatures. Triangles are COOP stations, squares are CoAgMET stations, and circles are project-specific stations. Numbers also indicate T_{min}.

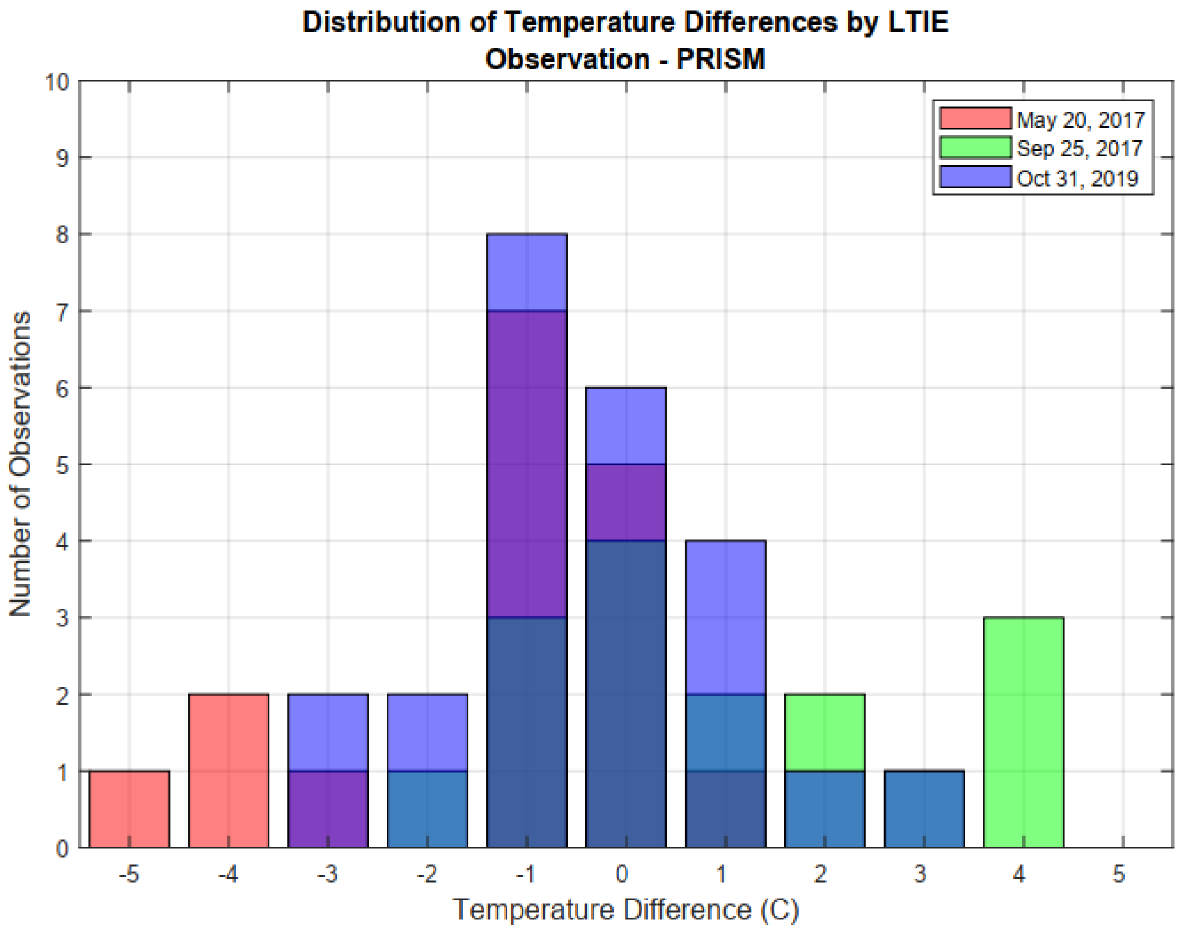

Figure 11: Observed daily T_{min} *– PRISM daily* T_{min} *(˚C) for three LTIEs in Montezuma County: Red = 20 May 2017. Green = 25 September 2017. Blue = 31 October 2019.*

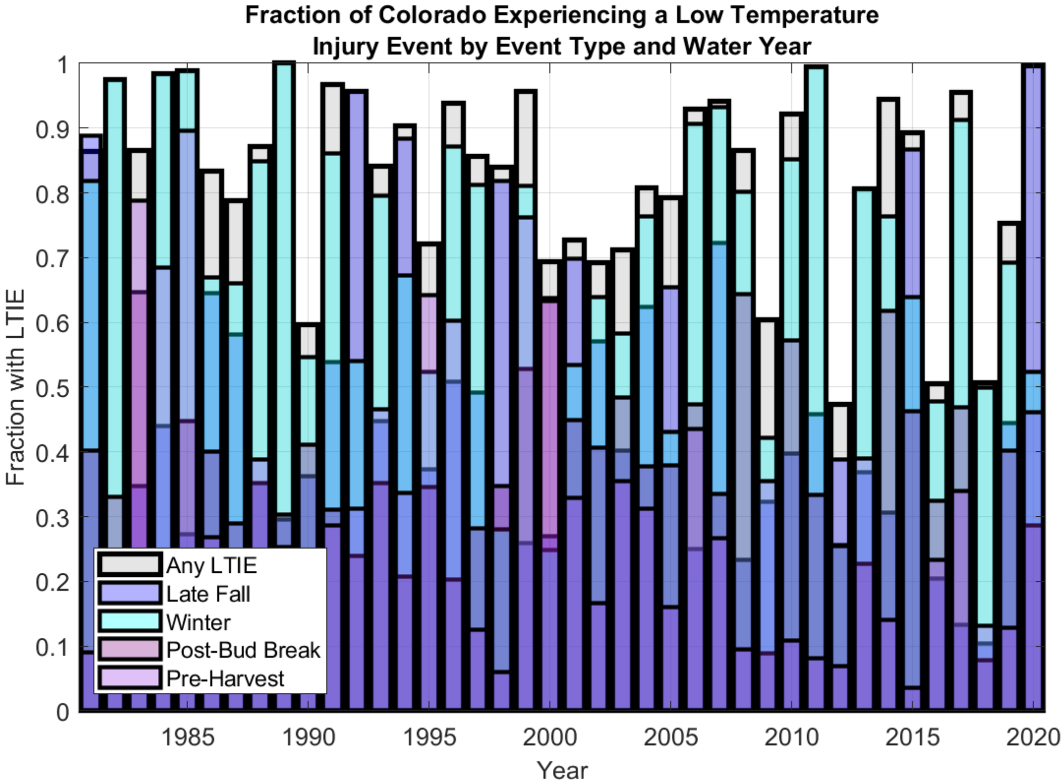

Figure 12: Fraction of Colorado experiencing a LTIE by event type and water year. Killing freezes counted as follows: Late Fall: $T_{min} < -12$ ˚C prior to November 1st, or $T_{min} < -15$ ˚C prior to November 16th, or $T_{min} < -18$ ˚C prior to December 1st. Winter: $T_{min} < -22$ ˚C December-February. Post-Bud Break: $T_{min} < -2$ ˚C after May 15th, but before July 1st. Pre-Harvest: $T_{min} < -2$ ˚C after before July 1st, but before October 1st