Topographic heterogeneity and the spatial pattern of air temperature in a mountain landscape

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Abstract

The objective of this study was to compile, validate, and map minimum and maximum mean monthly temperature and temperature ranges for periods of 10 to 14 months between July 2009 and June 2012, measured using 16 to 182 sensors distributed over the HJ Andrews Forest, a mountain landscape of 64 km^2. Maps were created using inverse distance weighting (IDW) as an extrapolation method in Arc GIS 10.1.

We found that temperature was dominated by lapse-rate, topographic shading, and cold air pooling effects, depending on the time of year. Both minimum and maximum monthly temperature in spring (some Mar, April, May, and even June) and fall (Oct, Nov) tends to be lapse-rate dominated. Late summer (Aug, Sep, Oct) maximum temperature tends to be dominated by topographic shading, despite interannual variation in precipitation. Cold air pooling appeared in July, August, and September minimum temperature, but in maximum temperature only for a dry December (2011).

Additional sensors (from 16 to 40 or even 56) increase the ability to identify topographic shading patterns and the associated heterogeneity in temperature, with weak indications of cold air pooling. Even more sensors (from 40/56 to 166/182) increase the ability to identify very small scale variability, including cool air pooling in the main-stem valley of the Andrews Forest.

For a given month, temperature spatial patterns were fairly consistent from one year to another. For a given month, temperature values between years vary with interannual variation in precipitation.

Some sites in the Andrews Forest have a very large diurnal temperature range (mean monthly min to mean monthly max) while other sites have very small ranges. Sites close to each other may have very different mean monthly temperature, due to the effect of topography. Sites with the largest temperature ranges were on the south-facing slopes of Carpenter Mountain, and those with the smallest ranges were along the north-facing slope of the south side of Andrews Forest (Lookout Ridge) and northwest of the upper end of Lookout Creek. North-facing slopes on Lookout Mountain and Roswell Ridge may also have very small temperature ranges, but these areas were not instrumented. Sites with small temperature ranges may serve as refugia for organisms in response to climate change.

For mountain environments subjected to climate change, these findings imply that different parts of the landscape experience climate change differently. There may be "refugia" from climate change in mountain landscapes, defined as locations with small diurnal and seasonal temperature ranges.

1. Introduction and research questions

Localized temperature patterns in complex mountain landscapes are difficult to ascertain using widely spaced instrumentation. Likewise, assuming homogeneity among closely geographically positioned temperature sites is unwise. The elevation, vegetation, type of terrain, proximity of the landscape to other land features, and aspect all affect local temperature.

Dowbrowski (2010) identified three principal factors affecting local influences on air temperature and water balance in a complex terrain: cold air pooling, slope and aspect, and elevation.

With respect to topographic shading influence on air temperature, Fridley (2008) noted that temperature in the Great Smoky Mountains National Park is only partially linked with synoptic weather and elevation. Landscape controls minimum temperature by soil moisture content, and maximum temperature was controlled primarily by insolation differences due to topographic shading and vegetation cover.

Many studies have attempted to create models for air temperature that include these environmental factors, but none of these approaches accurately recreate the complexity of temperature patterns encountered in small-scale forested mountain landscapes.

Lundquist et al. (2008) developed an algorithm for identifying locations in the landscape that are most likely to experience cold air pooling. She used Digital Elevation Models (DEMs) at resolutions of 10-500 meters to calculate slope, percentile (rank of site elevation in relationship to neighboring terrain), and curvature for each pixel. The model was designed to help locate temperature sensors in sites prone to cold air pooling. When compared with real-time ground measurements in complex terrain in the Pyrenees, France; Rocky Mountain National Park, Colorado; and the Sierras of California, air temperature based on the algorithm of Lundquist et al. (2008) produced a 3^{O}C increase in accuracy at some individual sites, and a 1^{O}C increase in overall mean accuracy compared to other more basic model algorithms such as inverse square weighting, truncated Gaussian filters, kriging, and multiple regression models.

One of the most complex studies compared 12 different methods of regression-based and weighted-average approaches to interpolate daily maximum and minimum temperature using data from nearly 2000 sites in British Columbia (Stahl, 2006). Multiple linear regression combined with weighted average interpolation performed the best when compared to measured temperature, and multiple linear regression alone was the second most accurate method. Stahl (2006) also found that kriging was only slightly more accurate than inverse-distance weighting (IDW).

Geospatial climatology was incorporated into an interpolation technique developed by Chris Daly called Parameter-Elevation Regressions on Independent Slopes Model (PRISM), incorporating principally elevation, but also aspect, topographic shading, windward or leeward side of mountains, and coastal proximity (Daly, 2002).

IDW is one of the simplest interpolation techniques for spatial interpolation. It is strictly two-dimensional and encompasses no other variables affecting temperature including elevation, terrain, cold air pooling, and nearby bodies of water (Daly, 2006). IDW was used in this study because the goal was not to exclude other environmental variables, but rather to depict temperature as affected by all possible conditions, including elevation, topographic shading, cold air pooling, and canopy cover.

Several studies have also found that measured temperature dynamics within a complex environment such as the forest canopy cannot be easily modeled. Climatological aided interpolation (CAI) performs poorly compared to real-time temperature observations within the canopy (Wilmott, 1995). Interpolation techniques are less relevant to the overall results than the accuracy of the measurement technique (Jarvis 2001).

The objective of this study was to create maps of air temperature under the forest canopy in the Andrews Forest using spatio-temporal data collected between 2009 and 2012. The specific objectives of this study were to use mean monthly temperature data to

(1) Determine the dominant spatial pattern of temperature in each month of the year. Patterns could be (a) lapse-rate dominated, (b) topographic shading dominated, or (c) cold air pooling dominated.
(2) Test the effect of numbers of stations on the apparent spatial patterns of temperature.
(3) To test the consistency of temperature patterns for each month from year to year, controlling for number of sensors.

1.1. Types of spatial pattern of temperature in the Andrews Forest

Three different types of spatial patterns of temperature were apparent in the Andrews Forest (Figure 1).

Lapse-rate dominated. A spatial pattern of temperature dominated by the lapse rate has the following characteristics: Air cools with elevation by approximately 6.4^{o} C/1000 m. Lower valleys are warm and mountaintops are cool.

Topographic shading. A spatial pattern of temperature dominated by topographic shading has the following characteristics: Areas exposed to solar radiation because of equator-facing slopes or due to sparse or absent vegetation are characterized by warm daytime readings, even in the cooler winter months when the weather is dominated by high pressure. These parts of the landscape also often experience colder minimums due to the ground's ability to release more heat, resulting in large temperature ranges. Areas in densely vegetated old-growth regions show much less variability with cool daytime maximums and warm nighttime minimums.

Cold air drainage or pooling. A spatial pattern of temperature dominated by cold air drainage or pooling has the following characteristics: air warms with elevation until the boundary layer height is reached. Cold air near the surface in higher regions of the terrain sinks because it is denser than the warm air around it. As it sinks, it cools further until it reaches an area where there is no outlet, as in a valley.

A **temperature refugium** can be defined as: An area that has the least temperature extremes and variability, generally in landscapes characterized by dense vegetation that prevents mixing from external sources.

1.2. Research Questions:

1) What are the spatial patterns of temperature in the Andrews Forest?

2) How does the density of temperature sensors affect the ability to identify these spatial patterns of temperature?

3) What temperature patterns occur consistently during different times of year, repeated in multiple years?

4) What places in the Andrews Forest might be called "temperature refugia"?

2. Study site

The H J Andrews Experimental Forest (hereafter, "Andrews Forest") is situated on the western slope of the Oregon Cascades covering the entire drainage basin of Lookout Creek (Figure 2). Elevation ranges from 412 to 1627 meters, exemplifying the region's mountainous, rugged terrain with primarily coniferous forests and their associated wildlife and stream ecosystems. Established in 1948, the Andrews Forest is administered cooperatively by the USDA Forest Service's Pacific Northwest Research Station, Oregon State University, and the Willamette National Forest. It is one of only 26 major ecological research sites funded by the National Science Foundation's (NSF) Long-Term Ecological Research (LTER) Programs (Andrews Forest website). The climate is Mediterranean, characterized by wet winters and dry summers with most precipitation occurring in winter when moist frontal systems originating in the Gulf of Alaska bring orographically enhanced precipitation (Daly, 2009) from 2200 mm/year at the lower elevation up to nearly 3000 mm/year at the higher west-facing slopes. Temperature was relatively mild due to the marine influence from the Pacific. Mean 1971-2000 temperature range from -1.3 to -2.5^{o}C for minimums in January to 22.1 – 28.6^{o}C for the July maximums (Daly, 2009). The rivers and streams and their valleys experience cold air drainage and pooling (Daly et al., 2007; Pypker et al., 2007). When there is a negative radiation balance (as during night and winter months with little to no sunlight), and low wind speed, the conditions are prime for temperature near the ground surface to cool much more quickly than the free air, resulting in cool, dense air close to the surface that drains into the local valleys (Daly, 2009).

3. Methods

<u>3.1 Sensor locations and periods of instrumentation</u>

The Benchmark and Reference Stations are both principally scattered around the perimeter of the Andrews boundary (Figure 3).

The original 40 BIRD sensor sites follow a similar periphery pattern but also incorporate several sensors in the valley of Lookout Creek (Figure 4). With the addition of the other 126 sensors, the pattern becomes much more north to south oriented encompassing the rise and fall of the landscape without the influence of topography, thereby instilling the topographic shading influence more strongly on the sensors (Figure 4).

BIRD sites were selected using a method that allotted an equal number of sites per designated elevation, distance to road, and age of forest. Transect points (running in columns north and south) were selected using a GIS grid. They are 600 meters east to west and 300 meters apart north to south. Other sites were selected using road versus trail designations (Figure 4).

When sighting elevation as a function of Easting, the sensor pattern shows a smaller and lower range of elevation in the west and a higher and broader range on the east side of Andrews. Looking at the sensors from a Northing statute shows that there is a broad range of sensor elevation along the south portion of Andrews and a much narrower range in the north – principally just a single path (Figure 5).

Five different datasets were used (Table 1): (1) the 16 Benchmark and Reference stands from July 2009 to April 2010, (2) the initial 40 BIRD sites from July 2009 to June 2012, (3) the 16 Benchmark and Reference stand datasets combined with the initial 40 BIRD sites from July 2009 to April 2010, (4) all 166 BIRD sites from May 2011 through June 2012, and (5) the 16 Benchmark and Reference stand dataset combined with the 166 BIRD sites from May 2011 to June 2012.

3.2 Instrumentation - sensors

The temperature sensors used for the "BIRD" site stations were HOBO Pendant® Temperature/Light Data Loggers Type 64K - UA-002-64. The sensors are small, waterproof, two-channel ambient temperature and relative light level data loggers. The sensors have a temperature range of -20^{o} to 70^{o} C, a declared accuracy of +/- 0.53^{o} C from 0^{o} to 50^{o} C, and a resolution of 0.14^{o} C at 25^{o} C. The drift was less than 0.1^{o} C/year (Fig. B-1).

The sensors used in the field for the BIRD sites were removed in July 2011 and calibrated at the HJA Headquarters overnight before being replaced back to the BIRD sites the following day. The calibration consisted of an ice bath and a room-temperature comparison. The instrument used in the calibration was a Fluke thermometer Type K with an accuracy of +/- 0.05 percentage of reading + 0.5 degrees Fahrenheit and a resolution of 0.1. Evan Miles assisted in the calibration and analyzed the results and found that all sensors were accurate within +/- 0.5^{o} C within three standard deviations of the mean (Appendix B, Table 2).

These sensors are used for the numerically numbered "BIRD" sites from #2 to #400. The maximum number of sensor BIRD sites used in this analysis was 166.

Sixteen other sensors have been employed for decades within HJ Andrews Research Forest. Six stations are Benchmark Stations and have been employed since 1957. An additional ten sites are referred to as Reference stands and have been in use since 1971. These sites use various Campbell Scientific temperature probes. Information regarding the Benchmark Stands is available online at:

http://andrewsforest.oregonstate.edu/lter/data/abstractdetail.cfm?dbcode=MS001&topnav=97.

Information for the Reference Stands is available online at: http://andrewsforest.oregonstate.edu/lter/data/studies/ms05/meta/template.cfm?page=instlist&topnav=135#TMP_CHT2.

3.3 Measurement Period

Data for this project were obtained over the period from July 1, 2009 through June 30, 2012. Initially, 40 BIRD sites were monitored from June 2009 to April 2010. These were supplemented with the 16 Benchmark and Reference Stand sites for the same period of time. All 166 BIRD sites were used from May 2011 to June 2012. Lastly the combined BIRD, Benchmark, and Reference Stand sites were used from June 2011 to July 2012 for comparisons between 40, 166, and 182 sites (Table 1).

3.4 Data sources and processing

Mean daily maximum and minimum temperature from the 16 Benchmark and Reference Stand stations are available online at:

http://andrewsforest.oregonstate.edu/data/abstract.cfm?dbcode=MS005&topnav=97

http://andrewsforest.oregonstate.edu/lter/data/abstract.cfm?dbcode=MS001&topnav=97

These daily maximum and minimum values were used to calculate the monthly mean maximum and minimum by simply adding the values and dividing by the number of days in the month. Medians were determined for each month by taking the mid-point temperature range from months with an odd number of days and the average of the difference of the two mid-point days on months with an even number of days.

Data from the BIRD sites were handled in a slightly more complex method. Data from 40 BIRD sites from June 2009 to April 2010 downloaded from the HOBO sensors provided temperature data for randomly assigned minutes. Data for these 40 BIRD sites was transferred into an Excel file, scanned for erroneous temperature resulting from the handling of the sensors and/or immediately obvious departures from nearby readings, then run through a Matlab program (developed by Evan Miles) to parse the data into regular 15-minute intervals. The data were then retrieved and exported into an Excel file to generate the monthly mean values.

3.5 Identification of outliers

Outliers were identified based on the mean and standard deviation of maximum (or minimum) temperature for each month. Then the standard deviation was multiplied by 3 and added to/subtracted from the mean. This produced the expected interval containing 99% of the observations assuming a normal distribution. Any value falling outside this interval was removed (Appendix A, Table 3).

3.6 Mapped properties

Maps were created for each month for each of these 5 properties: maximum temperature, minimum temperature, maximum anomaly (difference from the mean), minimum anomaly, and temperature range (maximum minus minimum).

For each subset of data and the corresponding period, five types of maps were created:

- Mean monthly maximum temperature
- Mean monthly minimum temperature
- Mean monthly temperature range
- Anomalies from the mean monthly maximum
- Anomalies from the mean monthly minimum

Anomaly maps are not included in this paper.

3.7 Interpolation

The Excel files were then examined to be compatible with ArcGIS 10 by removing any conflicting characters, and then mean monthly temperature maps encompassing the entire HJ Andrews Research Forest boundary were produced. Maps were created using Inverse Distance Weighting (IDW).

Inverse distance weighting (IDW) is an interpolation method that extrapolates values of a variable from a known set of location points into an estimate of values at unknown locations. The weight of these new unknown values is a function of inverse distance. This method postulates that the numeric variable being extrapolated decreases in influence as the distance from the origin becomes greater.

The default value for the inverse from the origin is set to two, this being the inverse of the distance raised to a positive real number. A higher power value would therefore increase the emphasis on closer points to the original point.

The number of points used in the interpolation, and the distance from the origin can also be limited, but this equation was not used in this analysis (ArcGIS 10.1 Help "How inverse distance weighted interpolation works").

3.8 GIS Analysis

Digital elevation rasters of HJA and the surrounding terrain were entered into a base map. The HJA boundary line was entered for reference, and the sites were entered from an Excel document containing the number, geographic coordinates, and elevation of each temperature sensor. A second Excel document with the temperature data was then added. The data were then interpolated using the Inverse Distance Weighting (IDW) Geostatistical Analyst tool.

3.9 Statistical analysis

3.9.1. Mean elevation and temperature as a function of the number of sensors.

For each month, the effect of the number of sensors on mean elevation and temperature was evaluated by plotting mean elevation (or temperature) versus the number of sensors.

3.9.2. Regression of temperature versus elevation.

Using the 166 BIRD sites from May 2011 to June 2012, linear regression was used to show temperature as a function of elevation. These relationships (shape, slope, r-squared values) were interpreted to determine the dominant weather pattern in the Andrews for each of these months. The slope of the linear regression was the change in temperature in Celsius for every kilometer of rise.

3.9.3. Interpretation of temperature pattern

An R-squared value exceeding 0.5 indicates a lapse-rate dominated pattern (Figure 1). An inverted U-shaped pattern is indicative of cold air pooling; these relationships were better fit with a second-order polynomial than a linear relationship. Topographic shading patterns had a wide range of values at every elevation, with low slope and low R-squared values.

4. Results

The results compare the spatial patterns of temperature as a function of number of sensors, time of year, and between years.

The first ten months of the study period (July 2009 to April 2010) compare 16 Benchmark and Reference stand temperature sensor data to 40 newly installed Bird site data, and then also to the 40 BIRD site data combined with the 16 Benchmark and Reference Stand data. The number of useable sensor data varies from 52 to 55 sensors during this time period. The twelve months from May 2010 to April 2011 use only the 40 BIRD sensors in a three-year interannual comparison. The number of sensors varies between 38 and 40. The last fourteen months of the study (May 2011 to June 2012) use the 40 original BIRD sites, 126 newly added BIRD sites, and the 16 Reference and Benchmark stand sensors. The total number of sensors varies from 153 to 179 (Table 4, Figure 6).

4.1. Overall patterns and spatial variability of temperature

Spatial variability, measured by the standard deviation of the monthly temperature, was highest in summer and lowest in winter months, for maximum and minimum temperature and temperature range. Standard deviation of temperature was not affected much when the number of sensors quadrupled starting in Mary 2011 from 40 (56) to 166 (182).

Mean maximum temperature varies from 3^{O}C to 28.1^{O}C over the three-year period from 2009 to 2012 (**Figure 6**). July and August are the warmest months in 2009 and 2010, but summer was a bit later in 2011 with August and September the warmest months. The coolest mean maximum temperature was in December in 2009, December and March in the winter of 2010-2011, but not until March in 2012 (winter of 2011-2012).

Mean minimum temperature varies from -2.2^{O}C in December 2009 to 12.9^{O}C in July 2009 (Figure 6). December, February, and March are the coldest months respectively for the three separate winters from 2009-10 to 2011-2 and the warmest summer minimums occur in July and August for 2009 and 2010, but in August and September for 2011.

Daily mean temperature range was highest in the summer and lowest in late winter through spring (Figure 6). Mean temperature range exceeded 14°C in July and August and 8°C in May through September, but was as low as 3°C in November through April. The daily temperature range depends on the dominating synoptic weather regime; high pressure is associated with large daily temperature ranges, and low pressure and moisture is associated with small daily temperature ranges.

4.2. Relationship of temperature to elevation

During the period from May 2011 to June 2012, maximum daily temperature revealed normal lapse rates (steeper than -5°C/1000 m) for April through June and an inversion or cold air pooling in December 2011 and January 2012 (a positive lapse rate of 2.5°C/1000 m and 0.2°C/1000 m) (Table 5, Figure 7). Minimum daily temperature revealed lapse rates from -3°C to -5.4°C/1000 m except for August and December; and an inversion and cold air pooling in September 2011 resulted in a positive lapse rate of 1.2°C/1000 m.

4.3. Effect of number of sensors on observed temperature patterns

As the number of sensors increased from 16 to 182 sensors, the mean elevation sampled increased from 850 to over 950 m (with 40 sensors) to just under 950 m (with 166 and 182 sensors) (Figure 8). As a result, mean maximum temperature for the whole study area decreased by as much as 3°C in the months of May to November 2011, increased by 0.5 to 1°C for March and April 2012, and was unaffected in December 2011 to February 2012 (Figure 9). The mean maximum temperature anomaly (defined as the difference of each sensor from the mean temperature for the landscape) was similarly affected (Figure 10). Increased numbers of sensors increased mean minimum temperature and minimum temperature anomaly became less negative for the study area for most months, but by less than 1°C (Figure 11, Figure 12). As a result, mean temperature range for the study area decreased by as much as 2°C in May and June of 2011, but decreased by less than 1°C for other months based on 182 compared to 16 sensors (Figure 13); temperature range in April 2012 increased by 0.5°C with 182 compared to 16 sensors.

4.3.1. Comparison of 16, 40, and 56 Sensors, July 2009 to April 2010

This comparison shows how topographic shading and cold air pooling become apparent when the number of sensors increases from 16 to 40 or 56 (Table 6, Figure 14). Overall for maximum temperature, lapse-rate patterns dominate with 16 sensors, but topographic shading effects dominate when the number of sensors increases to 40 or 56 sensors. For minimum temperature, increasing the number of sensors from 16 to 40 or 56 had no effect on the dominant temperature pattern, which was lapse-rate, but it did increase the evidence of cold air pooling as a secondary pattern (Table 6, Figure 14).

16 sensors. Based on 16 sensors, lapse rate effects dominated monthly maximum temperature patterns in all months from July 2009 to April 2010 except December, when cold air pooling was the dominant pattern. Cold air pooling was evident in September through March, but secondary to lapse rate effects, except in December. Cold air pooling was weakly expressed in maximum monthly temperature in October and March. Topographic shading effects were apparent in November and December and in March and April (Table 6, Figure 14). Based on 16 sensors, lapse rate effects also dominated monthly minimum temperature patterns in all months from July 2009 to April 2010 (Table 6, Figure 14). Cold air pooling dominated monthly minumum temperature in July, September, and December, and was evident in February, August, and November (Table 6, Figure 14).

40 sensors. Based on 40 sensors, topographic shading effects dominated monthly maximum temperature patterns in all months from July 2009 to April 2010, except December 2009, which was dominated by cold air pooling, and January 2010, which was dominated by a lapse rate pattern (Table 6, Figure 14). However, with 40 sensors, lapse rate effects dominated monthly minimum temperature patterns from July 2009 to April 2010 (Table 6, Figure 14). Cold air pooling dominated monthly minimum temperature in July 2009 and was evident in August, September, and December of 2009. Topographic shading influences were evident in October 2009 and February 2010 (Table 6, Figure 14).

56 sensors. Based on 56 sensors, topographic shading effects dominated monthly maximum temperature patterns over all months from July 2009 to April 2010 (Table 6, Figure 14). Cold air pooling dominated in December 2009 and was evident in October 2009, and lapse rate effects were apparent in January and February 2010. With 56 sensors, lapse rate effects dominated monthly minimum temperature patterns from July 2009 to April 2010 (Table 6, Figure 14); Topographic shading influences were evident in October and February.

4.3.2. Comparison of 40, 166, and 182 Sensors, May 2011 to June 2012

This comparison shows how cold air pooling became more apparent when the number of sensors increases from 40 to 166 or 182. Maximum temperature patterns were not affected by increasing the number of sensors from 40 to 182, but minimum temperature patterns revealed much more cold air pooling with 166 or 182 sensors compared to 40 sensors (Table 7, Figure 15, Figure 16).

4.3.2.1. Maximum temperature by month

January maximum monthly temperature was dominated by cold air pooling with 40 sensors, but a topographic shading influence became apparent with 166 and 182 sensors (Table 7, Figure 15, Figure 16). In February, the pattern was dominated by topographic shading for 40, 166 and 182 sensors. March maximum monthly temperature was dominated by a lapse-rate pattern with 40 sensors, and topographic shading effects became apparent with 166 and 182 sensors. April maximum temperature was predominantly a lapse-rate pattern, but topographic shading effects became more pronounced as sensor number increased from 40 to 166 to 182 sensors. With 40 sensors, May had a lapse-rate dominated pattern in 2011 and a topographic shading influenced pattern in 2012. With 166 and 182 sensors, lapse-rate and topographic shading effects are apparent. In June 2011 and June 2012 topographic shading was the predominant pattern with 40 sensors. With 166 and 182 sensors, lapse rate influences predominated. Maximum monthly temperature in July 2011 was dominated by topographic shading effects with 40, 166, and 182 sensors). In August maximum monthly temperature was topographic shading influenced with 40, 166 and 182 sensors. September was principally topographic shading influenced with 40, 166, and 182 sensors. With 40 sensors, October and November maximum temperature was dominated by topographic shading effects; with 166 and 182 sensors, lapse rate effects were also apparent. With 40 sensors, December had a topographic shading dominated temperature pattern, but cold air-pooling became more apparent with 166 and 182 sensors (Table 7, Figure 15, Figure 16).

4.3.2.2. Minimum temperature by month.

With 40 sensors January minimum monthly temperature was lapse-rate dominated, but cold air pooling became dominant with more sensors (Table 7, Figure 15, Figure 16). Minimum monthly temperature in February was lapse-rate dominated, but cold air pooling became more apparent with 166 and 182 sensors. March and April both show a predominant lapse-rate pattern but topographic shading and cold air pooling influences were more apparent with 166 and 182 sensors. Minimum monthly temperature in May, June, and July was lapse-rate dominated, but topographic shading and cold air pooling were more apparent with 166 and 182 sensors. With 40 sensors, August 2011 mean minimum temperature was lapse-rate dominated but cold air pooling became dominant with 166 and 182 sensors. September mean temperature was strongly influenced by cold-air pooling with 40 sensors, and it became more pronounced with 166 and 182 sensors. October and November reverted to a lapse rate-oriented temperature regime with cold air pooling effects when 166 and 182 sensors were used. With 40 sensors, December minimum temperature was a mixture of topographic shading and lapse-rate effects, but with more sensors (166 and 182) cold air pooling became dominant (Table 7, Figure 15, Figure 16).

4.4. Inter-annual consistency of temperature patterns

4.4.1. Maximum temperature

Maximum monthly temperature in January 2010 was dominated by topographic shading effects (Table 8, Figure 15, Figure 17). By 2011, signs of cold air pooling appeared, and in 2012, the cold air pooling pattern was most obvious, with some topographic shading. In 2010, 2011, and

2012, February had a predominantly topographic shading temperature pattern, with very small signs of a lapse-rate pattern. March, April, and May of 2010, 2011, and 2012 had both lapse-rate and topographic shading influenced temperature patterns. Maximum monthly temperature in June, July, and August was dominated by topographic shading in 2010, 2011, and 2012. September, October, and November also were principally influenced by a topographic shading temperature pattern in 2009, 2010, and 2011. Both cold air pooling and topographic patterns are evident in December of 2009, 2010, and 2011 (Table 8, Figure 15, Figure 17).

4.4.2 Minimum temperature

In 2010, January mean minimum temperature was principally a lapse-rate pattern with signs of topographic shading influence (Table 8, Figure 15, Figure 17). In 2011, the pattern shows a strong cold air pooling component, with signs of topographic shading. January 2012 was mostly lapse-rate dominated, with signs of both topographic shading influence and cold air pooling.

February through June of all three years was characterized by a lapse-rate dominated temperature pattern with some topographic shading influence (Table 8, Figure 15, Figure 17). May of 2012 and June of 2011 are the only exception with a more significant lapse-rate dominated temperature pattern.

July through December of all years had a dominating lapse-rate temperature pattern, but July through September of all years also showed signs of cool-air pooling except for September 2010. October and November of all three years were lapse-rate dominated, and December of 2009 and 2011 have distinct cold air pooling, while December 2010 stays completely lapse-rate oriented.

5. Discussion

5.1. Types of temperature patterns in the Andrews Forest

Three main types of temperature patterns in the Andrews Forest were evident in temperature maps: dominated by (1) lapse-rate, (2) topographic shading, and (3) cold air drainage or pooling (Figure 1). Lapse-rate dominated temperature patterns are broad-scale, whereas topographic shading and cold air pooling effects are fine scale.

Lapse rate is often used to model temperature patterns in mountainous terrain, but for short temporal periods it is a poor indicator of spatial temperature because it omits synoptic-scale weather and topographic shading influences (Cayan, 2004). In the Andrews Forest, spring and summer lapse rates are close to the mean of -6.5^{O}C/km, but fall and winter lapse rates are sometimes positive, highly connected to synoptic weather (Daly and Conklin, 2010). Lapse rate values are on the order of +3.5^{O}C/km during anti-cyclonic high pressure periods to -4^{O}C/km during strong Jetstream events when the air is well mixed (Daly, 2009).

Researchers typically use environmental lapse rates of 6.0-6.5^{O} C to represent variation in temperature with elevation (Dodson, 1997). However, measured lapse rates on the western slope of the Washington Cascades showed rates on the windward side between -3.9^{O} C and -5.2^{O} C / km (Minder et al 2010). Lapse rates for late summer minimum temperature may be as low as -2.5 to -3.5^{O}C/km and late spring lapse rates may be as steep as -6.5 to -7.5^{O}C (Minder et al 2010).

In this study in the western Cascades, we found mean monthly minimum lapse rates as high as 2.5^{O}C/km in the winter and as low as -8.9^{O}C/km in late spring. Mean monthly maximum lapse rates varied from 1.2^{O}C/km in fall to -5.4^{O}C/km in late spring. Lapse rates were the dominant mean maximum temperature pattern in spring with 166/182 sensors, and present only in winter with 40 sensors. The lapse rate pattern was present in minimum temperature for nearly all months in this study, and it dominated the temperature pattern in all months except late summer and early winter (Tables E, F, G).

Aspect and gradient values are critical to snowpack in the southern North American Rocky Mountains, also influenced by low precipitation, warm temperature, evaporation, transpiration, soil moisture and stream flow (Broxton, 2010). Fridley (2008) also notes topographic shading influences on mean maximum temperature; landscape positions do not account for temperature regimes across seasons, and closeness of sensor sites to streams decouples sensors from regional temperature, leading to warmer winter readings and cooler summer values.

Our study found that topographic shading influences were present in 13 of 14 months between May 2011 and June 2012 for maximum temperature, but only 4 of 14 months for minimum temperature. Topographic shading influences were dominant in middle to late summer and early fall maximum temperature with 166/182 sensors, and in mid-winter maximum temperature with 40 sensors. Topographic shading did not dominate minimum temperature with 166/182 sensors (Tables E, F, G).

Small-scale micrometeorological phenomena are much more likely to be decoupled from the synoptic weather pattern, giving these areas more chance to preserve temperature even with climatic change (Daly et al 2010). Microrefugia are sites that tend toward local climate regimes rather than unfavorable synoptic climates (Dobrowski, et al., 2013). They allow small populations of species to persevere outside of their normal habitat. There is no consensus on where these refuges will occur in a landscape, but evidence points toward mountain valley environments.

Other studies performed at HJ Andrews observed strong katabatic (down-valley) winds occurring primarily in the warmer months from late spring to early fall in steep watersheds (Unsworth, et al., 2004; Pypker et al., 2007). Significant breezes up to approximately 0.7 m/s occur near streams with maximum speeds around 3-5 meters above the stream surface. Up-valley flows occur until about mid-afternoon, and are then replaced very quickly by downslope airflows which persist through the night until sunrise. Cold air drainage affects temperature sensors close to streams, where air is much cooler in the day and warmer at night than sensors away from the stream's influence.

The frequency of cold air pooling events is dependent on the frequency of synoptic weather patterns characterized by high-pressure, light winds and clear skies (Lundquist, et al., 2008). Climatic trends show these patterns may be increasing in some mid-latitude locations across the globe. Other studies have found that night-time temperature across the globe is increasing faster than daytime temperature (Karl, et al., 1993). Cold-tolerant species may migrate to cold air pooling locations, which may prove to be linked to biological refuges during global warming.

Our study found mean monthly patterns dominated by cold air pooling were apparent in winter mean monthly maximum and summer and winter minimum temperature. Cold air pooling was the dominant pattern in early winter maximum temperature and in late summer and early winter minimum temperature (Tables E,F,G).

5.2. Effect of number of sensors on apparent temperature patterns

There is little to no published research describing the effect of the number of sensors on fine-scale micrometeorological conditions measured in a complex terrain. There have been many studies examining spatial and temporal patterns in complex topography, but this study has the highest density of sensors in any study of mountain meteorology.

Holden et al., (2011) dispersed 175 sensors in short transects in a 45000 km^2 area in the Bitterroot National Forest in Montana, but only 140 sensors produced usable data.

A separate study was performed in the Andrews Forest with 33/45 sensors in 2003 to determine a better sense of small-scale temperature influences using just the month of July in two separate years (Lookingbill and Urban 2003). While these results are helpful in distinguishing overall complexities within the landscape of a complex forest, they lack the robustness necessary to fully understand the annual variation encompassing temporal and spatial complexities in near-surface temperature patterns.

We found that as the number of sensors increases for a given month and type of temperature readings (both maximum and minimum) increases, the spatial variability of temperature also increases, so that more detailed processes become apparent. Once the number of sensors exceeds 56, there is little change in the apparent spatial pattern of maximum temperature. However, as the number of sensors increases from 40 to 166 or 182, cold air pooling in minimum temperature becomes increasingly apparent.

5.3. Interannual, seasonal temperature patterns in the Andrews Forest

Jonathan Smith (2002) successfully completed a Master's defense encompassing the mapping of spatial and temporal patterns for monthly mean temperature in the entirety of HJ Andrews using long-term and short-term data from sensors throughout the watershed. He used 43 sites with 13 of the sites longer than 22.5 years and 30 sites with less than 22.5 years of data. With the help of Chris Daly's PRISM interpolation method (Daly, 2002), he mapped long-term average temperature maps of the entire Andrew's basin.

Daly (2009) has extensively studied the Andrews Forest seeking better comprehension of topographic shading and especially cold air drainage processes that are such an influential variable in complex terrain. Unsworth (2004) and Pypker (2007) have studied many of the processes associated with carbon exchange along the cold air drainage basin of Watershed 1 at H.J. Andrews.

We found that spatial patterns of temperature tend to be dominated by lapse-rate processes during spring mean monthly maximum temperature. Mixed air was especially enhanced in the transitional spring and fall seasons. Topographic shading effects are apparent principally in mid-summer to late fall and in late winter, and cold air drainage/pooling effects are apparent in late summer and early winter.

5.4. Implications of this work

Possible outcomes from this research are a better understanding of how species may migrate toward these small areas of cooler or less variable micro-climates where animals may seek refuge from a warming synoptic climate.

Incorporation of a more detailed and smaller layout of sensors may be necessary to truly grasp the infinite detail of small-scale temperature patterns in such a complex environment.

6. Conclusions

This study compared temperature patterns detected using 0.25, 0.6. 0.88, 2.6, and 2.8 sensors per km^2 (16, 40, 56, and 166 or 182 sensors in a 64 km^2 landscape). The sensors were systematically distributed, but some parts of the landscape were not sampled. There were no sensors on Lookout Mountain, except along the top N-S ridge. There also were no sensors in upper McRae Creek, especially along the NW-facing slope.

As the number of sensors increases, the type of temperature pattern changed, and increasingly fine scale variability was detected in the landscape. The lapse rate dominated pattern was easiest to detect with a few sensors. With an intermediate number of sensors the effect of topographic shading became apparent, and if cold air pooling was present it was detected only with the highest density of sensors.

Topographic shading produced warm night-time minimum temperature and cool daytime maximum temperature relative to surrounding areas, on steep N-facing slopes. It was apparent year-round in maximum daytime temperature but rare in minimum nighttime temperature.

Cold air pooling was associated with cool night-time minimum temperature and occasionally cool daytime maximum temperature in broad valleys relative to adjacent hillslopes. It was apparent in maximum daytime temperature in winter and in minimum nighttime temperature throughout the year.

7. Acknowledgements

Data collection was supported by the Andrews Forest LTER6 grant, NSF NSF 0823380.

Dr. Julia Jones was instrumental to the entire content of this paper, from the inception to the very end. She gave hundreds of hours of her time over the course of the four years working on the data, content, text, figures, instrumentation, data retrieval and analysis, and funding through Graduate Teaching Assistantships in addition to the LTER6 grant.

Candice Michelle Weems contributed immensely to the GIS work performed for the mapping section of my paper, always making herself available as I struggled through countless GIS "ghosts" changing my output around and bringing me misery.

Evan Miles was instrumental in the data collection and analysis, and the intense Matlab coding that went into the parsing of the Excel files into a form that could be easily worked with.

Sarah Hadley/Frey made certain that I got a thorough workout at Andrews when I helped with the sensor-data-retrieval on a very wet day in July – though I have to give some credit to Evan for this as well – I think they were trying to kill me.

And of course, generous thanks to my family; Therisa, Jake, Ashton, Mom and Dad, Samantha, and Aspen, for not killing me.

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9. List of Tables

Table 1. Number of sensors used in each analysis and the temporal period of the analysis.

	Analysis type		
	Effect of number of sensors		Interannual comparison
TIme period	July 2009 – April 2010	May 2011 – June 2012	July 2009 – June 2012
Benchmark met stations	6	6	--
Reference stand stations	10	10	--
BIRD sensors	40	166	40
Total	56	182	40

Table 2. Average error of sensors measured in calibration test, July 21, 2011.

	# Sensors Tested	Average Measurement Error	Standard Deviation	Standard Error
Ambient	41	-0.83	0.06	0.01
Cold (Ice Bath)	41	0.21	0.10	0.02
Warm (30 C)	41	-1.26	0.08	0.01

Table 3. Percentage of Values Lying Outside Plus or Minus Two and Three Standard Deviations (s), by month, May 2011-June 2012, for 166 BIRD sensors and 182 total sensors.

		Percent of sensors with values outside of ±2s					Percent of sensors with values outside of ±3s				
Month	Year	Max	MaxAnom	Min	MinAnom	Range	Max	MaxAnom	Min	MinAnom	Range
May	2011	6.5	6.5	2.6	2.6	6.6	3.3	3.3	0.0	0.0	2.6
June	2011	2.8	2.8	5.1	5.1	4.0	0.6	0.6	0.6	0.6	1.1
July	2011	3.9	3.9	3.4	3.4	4.5	0.6	0.6	1.1	1.1	1.7
August	2011	6.2	6.2	3.4	3.9	5.1	1.1	1.1	0.6	0.6	1.1
September	2011	5.1	5.1	1.7	1.7	4.5	0.6	0.6	0.6	0.6	0.0
October	2011	3.4	3.4	2.8	2.8	5.1	1.1	1.1	1.1	1.1	2.2
November	2011	2.8	2.8	5.6	5.6	5.0	0.6	0.6	0.6	0.6	2.2
December	2011	4.0	4.0	2.3	2.3	4.5	1.7	1.7	0.0	0.0	2.3
January	2012	3.0	3.0	5.4	5.4	4.2	1.8	1.8	1.2	1.2	3.0
February	2012	4.3	4.3	4.9	4.9	4.9	1.2	1.2	0.0	0.0	3.0
March	2012	5.5	5.5	4.3	4.3	6.7	0.6	0.6	0.0	0.0	1.8
April	2012	6.1	6.1	2.5	2.5	7.4	0.0	0.0	0.0	0.0	0.0

Month	Year	Max 2sd	MaxAnom	Min	MinAnom	Range	Max 3sd	MaxAnom	Min	MinAnom	Range
May	2011	6.5	6.5	1.4	1.4	6.6	3.6	3.6	0.0	0.0	2.9
June	2011	2.5	2.5	5.5	5.5	3.1	0.6	0.6	0.6	0.6	1.2
July	2011	4.3	4.3	3.7	3.7	5.6	0.6	0.6	1.2	1.2	0.6
August	2011	6.7	6.7	3.7	3.7	5.6	1.2	1.2	1.2	1.2	0.6
September	2011	4.9	4.9	2.5	2.5	4.3	0.6	0.6	0.6	0.6	0.6
October	2011	3.1	3.1	3.1	3.1	4.9	1.2	1.2	1.2	1.2	2.5
November	2011	2.5	2.5	5.6	5.6	4.9	0.6	0.6	0.6	0.6	1.9
December	2011	5.5	5.5	3.1	3.1	4.3	1.8	1.8	0.0	0.0	2.5
January	2012	3.1	3.1	5.6	5.6	3.1	1.8	1.8	1.2	1.2	3.1
February	2012	4.3	4.3	5.0	5.0	3.8	1.2	1.2	0.0	0.0	2.5
March	2012	5.0	5.0	4.4	4.4	5.6	1.2	1.2	0.0	0.0	1.3
April	2012	5.6	5.6	2.5	2.5	6.3	0.0	0.0	0.0	0.0	0.6
May	2012	4.3	4.3	5.6	5.6	3.8	0.6	0.6	0.0	0.0	0.6
June	2012	2.5	2.5	3.1	3.1	3.7	0.0	0.0	0.0	0.0	1.2

Table 4. Numbers of sensors and spatial variability of maximum T, minimum T, and T range, by month, May 2011-June 2012.

Month	no of sensors	mean max	stdev of max	mean min	stdev of min	range	stdev range
Jul-09	54	28.1	2.9	12.9	1.1	15.2	3.6
Aug-09	55	24.6	2.8	11.6	1	12.8	3.3
Sep-09	55	21.4	2.7	9.9	1.1	11.3	3.1
Oct-09	55	10.8	1.6	4.1	1.1	6.5	1.7
Nov-09	54	5.9	1.4	0.8	0.8	4.8	1.3
Dec-09	53	3	1.6	-2.2	0.9	4.8	1.4
Jan-10	54	6.4	1.1	2	1	4.3	0.9
Feb-10	53	6.8	1.6	1.1	1	5.6	1.6
Mar-10	53	7.5	2.1	0	1	7.3	2.3
Apr-10	52	8.8	3	0.5	1.2	8.1	3.1
May-10	38	11.8	2.5	3	1.4	8.5	2.3
Jun-10	40	16.9	2	7.3	1.3	9.5	2.1
Jul-10	40	26	3	11.4	1.1	14.6	3.6
Aug-10	40	24.4	2.9	11.1	1.2	13.3	3.4
Sep-10	40	18	2.4	9.5	1	8.4	2.7
Oct-10	40	12.9	1.9	5.7	1	7.1	2.2
Nov-10	40	5.4	1.3	1	1.2	4.2	1.3
Dec-10	39	3.1	1	-0.6	0.9	3.6	1
Jan-11	40	4.7	1.6	0.3	0.6	4.4	1.5
Feb-11	39	3.4	1.7	-1.9	1	5.1	1.5
Mar-11	39	3.1	2.1	-0.1	0.7	3.1	2
Apr-11	38	4.5	3.4	0.1	1	4.4	3
May-11	153	10.2	3.1	3.1	1.5	7.2	2.1
Jun-11	177	16.6	2.6	6.9	1.6	9.7	1.8
Jul-11	178	21.4	2.1	9.9	1	11.5	2.1
Aug-11	178	24	2.4	11.8	1	12.2	2.6
Sep-11	178	22.8	2.4	11.4	1.3	11.4	2.8
Oct-11	178	12.1	1.8	5.8	1.2	6.2	1.6
Nov-11	179	5.1	1.5	0.5	1.1	4.5	1.1
Dec-11	176	5.5	1.7	-0.3	0.8	5.8	1.7
Jan-12	166	4.6	1.5	-0.3	0.8	5	1.5
Feb-12	164	4.2	1.6	-0.7	1.1	4.9	1.6
Mar-12	163	3.8	1.6	-1	0.9	4.8	1.7
Apr-12	163	8.9	3	2.3	1.2	6.6	2.2
May-12	161	15	2.3	4.4	1.1	10.6	1.9
Jun-12	163	15.7	1.8	6.7	1.2	8.9	1.4

Table 5. Lapse rates estimated from regression of temperature vs. elevation (n = 166 sensors), for the period May 2011 to June 2012.

	Maximum T		Mininum T	
Month	slope (°C/1000m)	R - Squared	slope (°C/1000m)	R - Squared
May-11	-8.9	0.52	-5.4	0.76
Jun-11	-7.2	0.59	-4.9	0.70
Jul-11	-4.1	0.29	-2.3	0.33
Aug-11	-3.7	0.17	-0.7	0.04
Sep-11	-2.5	0.08	1.2	0.06
Oct-11	-2.8	0.18	-2.8	0.40
Nov-11	-3.0	0.30	-3.4	0.68
Dec-11	2.5	0.16	-0.4	0.01
Jan-12	0.2	0.00	-2.0	0.43
Feb-12	-2.4	0.16	-3.7	0.77
Mar-12	-2.6	0.18	-2.9	0.70
Apr-12	-7.7	0.48	-3.6	0.62
May-12	-5.8	0.46	-3.2	0.56
Jun-12	-5.2	0.57	-3.9	0.76
average	-3.8		-2.7	

Table 6. Dominant Temperature Patterns by Month, Maximum and Minimum temperature, 16, 40, and 56 sensors, for ten months, July 2009 to April 2010. T = Topographically Influenced Temperature Pattern; L = Lapse-Rate Dominated Temperature Pattern; C = Cold-Air Drainage Dominant Temperature Pattern.

	Maximum temperature Number of sensors			Minimum temperature Number of sensors		
Month	16	40	56	16	40	56
2009_Jul	L	T	T	C/L	C/L	C/L
2009_Aug	L	T	T	L/C	L/C	L/C
2009_Sep	L/C	T	T/C	C/L	L/C	L/C
2009_Oct	L	T	T	L	L/T	L/T
2009_Nov	L/C/T	T/C	T/C	L/C	L/T/C	L/T/C
2009_Dec	C/T	C/T	C/T	C/L	L/C	L/C
2010_Jan	L/C	L/T	L/T	L	L/C	L/C
2010_Feb	L/C	T/L	T/L	L/C	L/T/C	L/T/C
2010_Mar	L/T/C	T	T	L	L/T/C	L/T/C
2010_Apr	L/T	T	T	L	L/T	L/T
Dominant						
L	9	1	1	7	9	9
T	0	8	8	0	0	0
C	1	1	1	3	1	1
Present						
L	9	2	2	10	10	10
T	4	10	10	1	5	5
C	6	2	3	6	8	8

Table 7. Dominant Temperature Patterns by Month, Maximum and Minimum temperature, 166 and 182 sensors, for fourteen months, May 2011 to June 2012. T = Topographically Influenced Temperature Pattern; L = Lapse-Rate Dominated Temperature Pattern; C = Cold-Air Drainage Dominant Temperature Pattern.

	Maximum temperature Number of sensors			Minimum temperature Number of sensors		
Month	40	166	182	40	166	182
2011_May	L	L/T	L/T	L	L/T	L/T
2011_Jun	T	L	L/T	L	L	L/T
2011_Jul	T	T/L	T/L	L	L/C	L/C
2011_Aug	T	T	T	L/C	C	C
2011_Sep	T	T	T	C	C	C
2011_Oct	T	T/L	T/L	L	L/C	L/C
2011_Nov	T	T/L	T/L	L	L/C	L/C
2011_Dec	T	C/T	C/T	T/L	C	C
2012_Jan	C	T/C	T/C	L/T	C/L	C/L
2012_Feb	T/L	T/L	T/L	L	L/C	L/C
2012_Mar	L/T	T/L	T/L	L/T	L/T/C	L/T/C
2012_Apr	L	L/T	L/T	L/T	L/T/C	L/T/C
2012_May	T	L/T	L/T	L	L/T/C	L/T/C
2012_Jun	T	L/T	L/T	L	L/C	L/C
Dominant						
L	3	5	5	12	10	1
T	10	8	8	1	0	0
C	1	1	1	1	4	4
Present						
L	4	10	10	13	11	11
T	11	13	13	4	4	4
C	2	2	2	2	12	12

Table 8. Dominant Temperature Patterns by Month, Maximum and Minimum temperature, 40 sensors, July 2009 to June 2012. T = Topographically Influenced Temperature Pattern; L = Lapse-Rate Dominated Temperature Pattern; C = Cold-Air Drainage Dominant Temperature Pattern.

Month	Maximum T				Minimum T			
	2009	2010	2011	2012	2009	2010	2011	2012
Jan		L/T	L/C/T	C/T		L/C	C/T	L/T
Feb		T/L	T	T/L		L/T/C	T/L	L/T
Mar		T	L	L		L/T/C	L	L
Apr		T	L	L		L/T	L/T	L/T
May		T	L	T/L		L/T	L/T	L/T
Jun		T	T	T		L	L	L
Jul	T	T	T		C/L	L/C	L	
Aug	T	T	T		L/C	L/C	L/C	
Sep	T	T	T		L/C	L	L/C	
Oct	T	T	T		L/T	L	L	
Nov	T/C	T	T		L/T/C	L	L/T	
Dec	C/T	T	T/C		L/C	L	T	
Dominant								
L	0	1	4	2	0	0	9	0
T	6	11	8	2	6	12	2	6
C	0	0	0	1	0	0	1	0

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Figure 17. Comparison of spatial pattern of maximum T, minimum T, and T range, by month, among years (2009-2012). Inferences about interannual differences in patterns are made based on precipitation from McKenzie Bridge Ranger Station climate station.

Figure 1. Conceptual diagram of three temperature pattern types in the Andrews Forest.

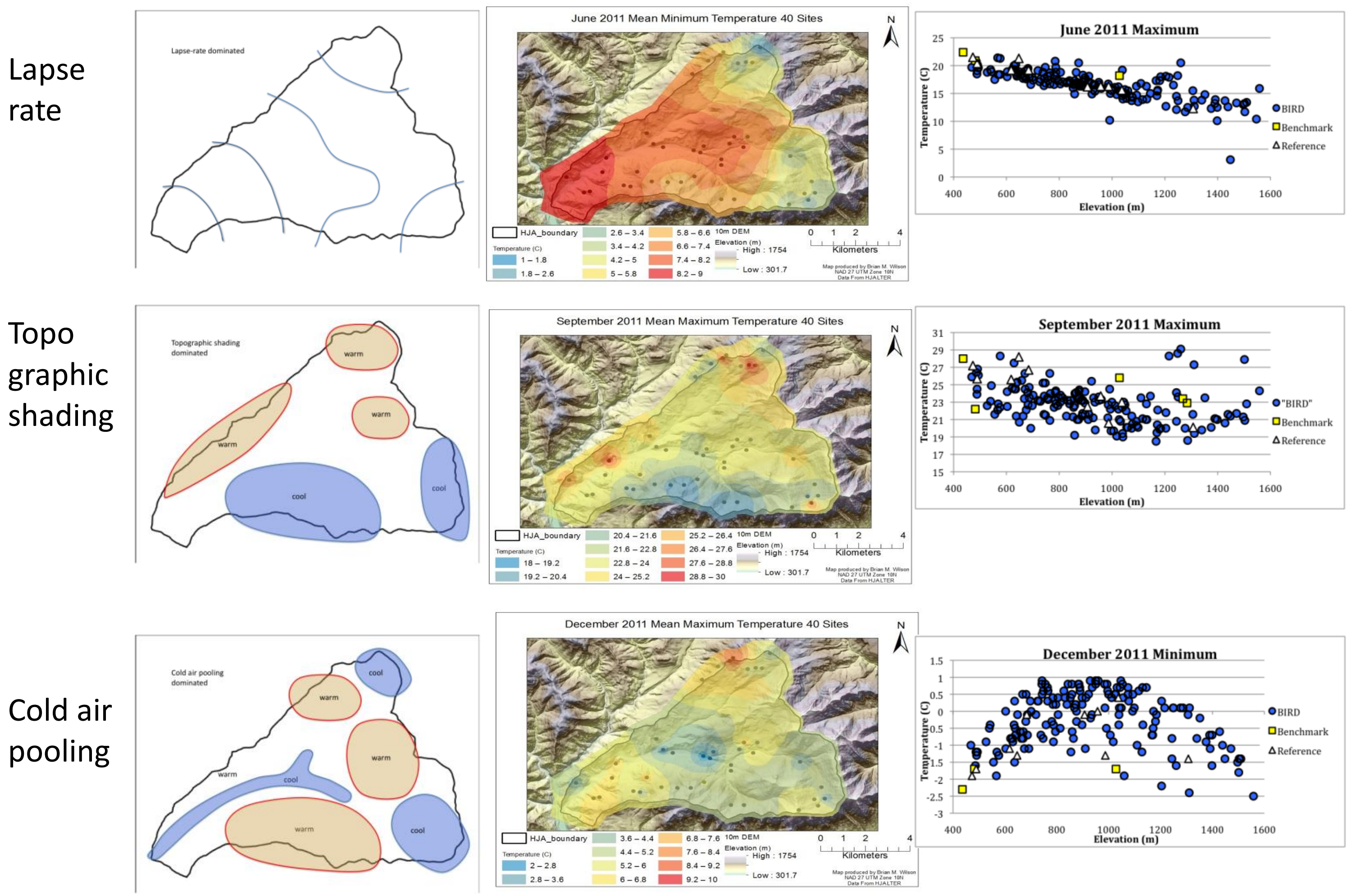


Figure 2. Location of benchmark met stations, forest clearcuts/plantations, roads, and streams, with elevation contour lines, in the Andrews Forest.

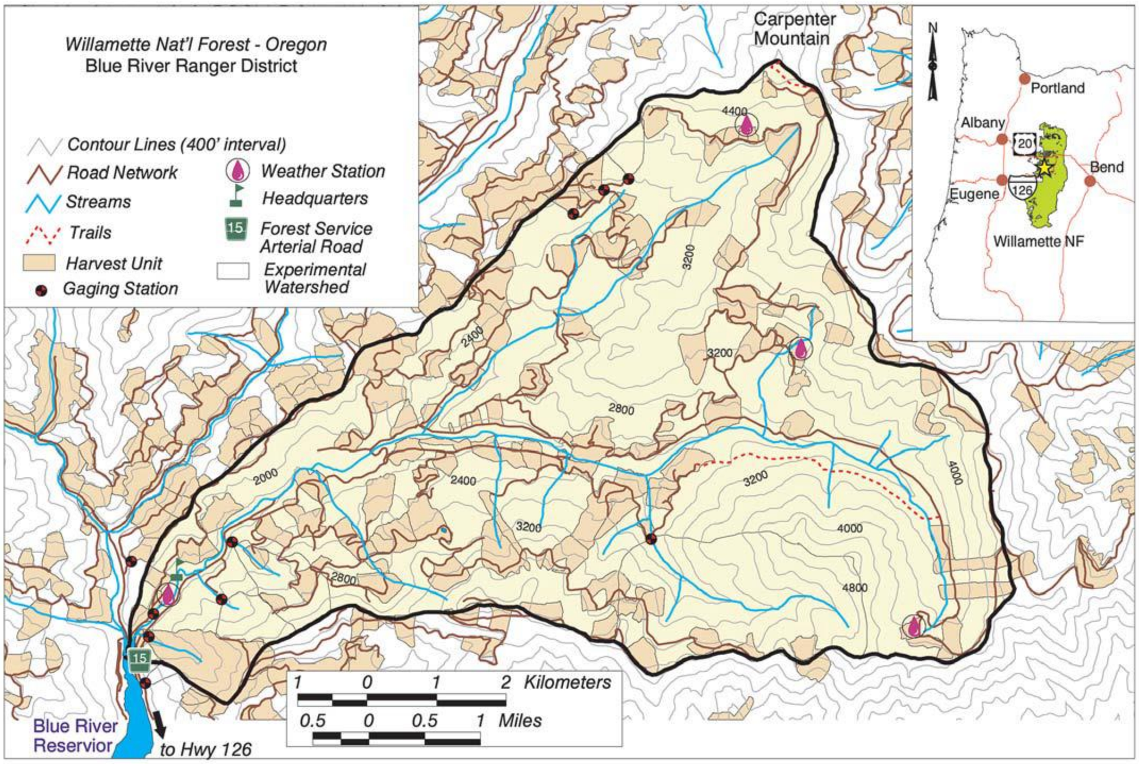


Figure 3. Location of six benchmark met stations, and ten reference sites in the Andrews Forest.

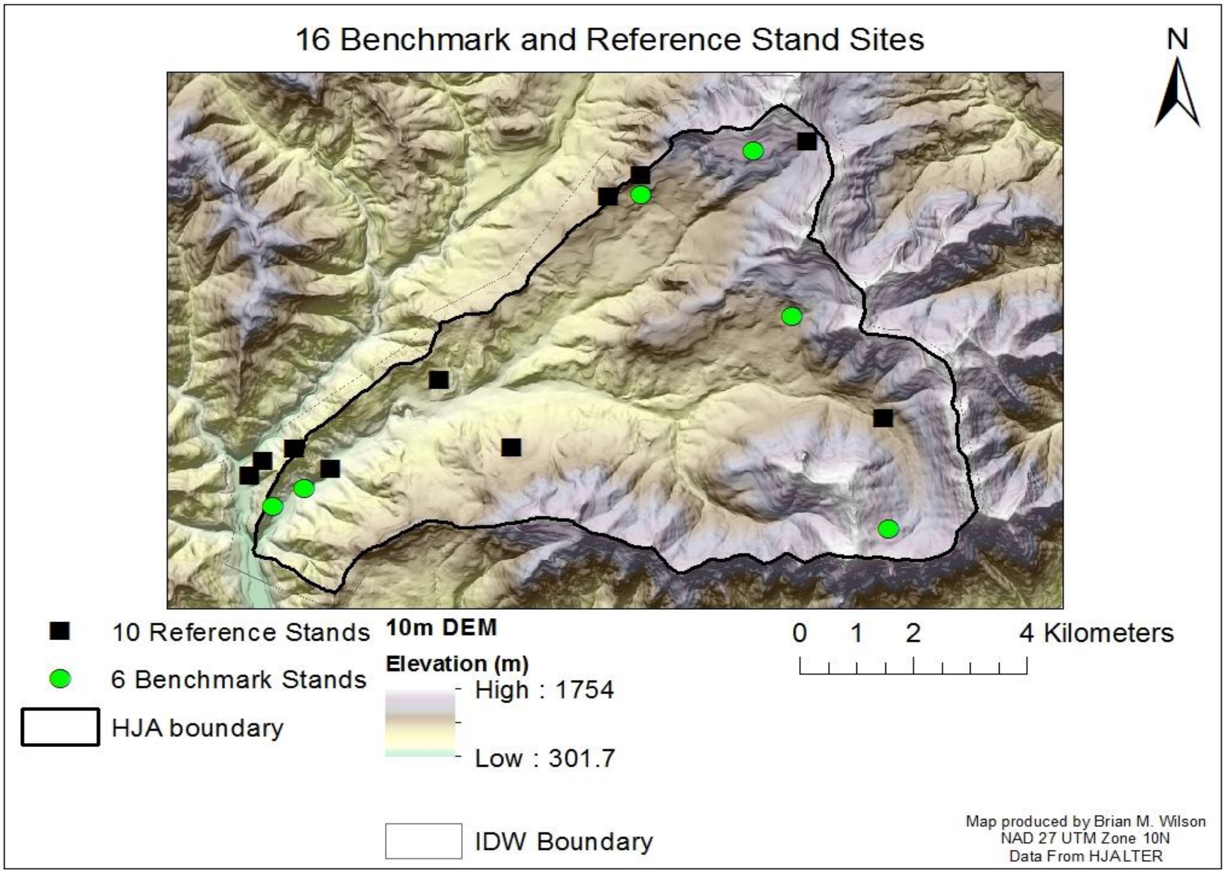


Figure 4. Locations of 166 BIRD sensor locations, as well as six benchmark sites and ten reference stand sites.

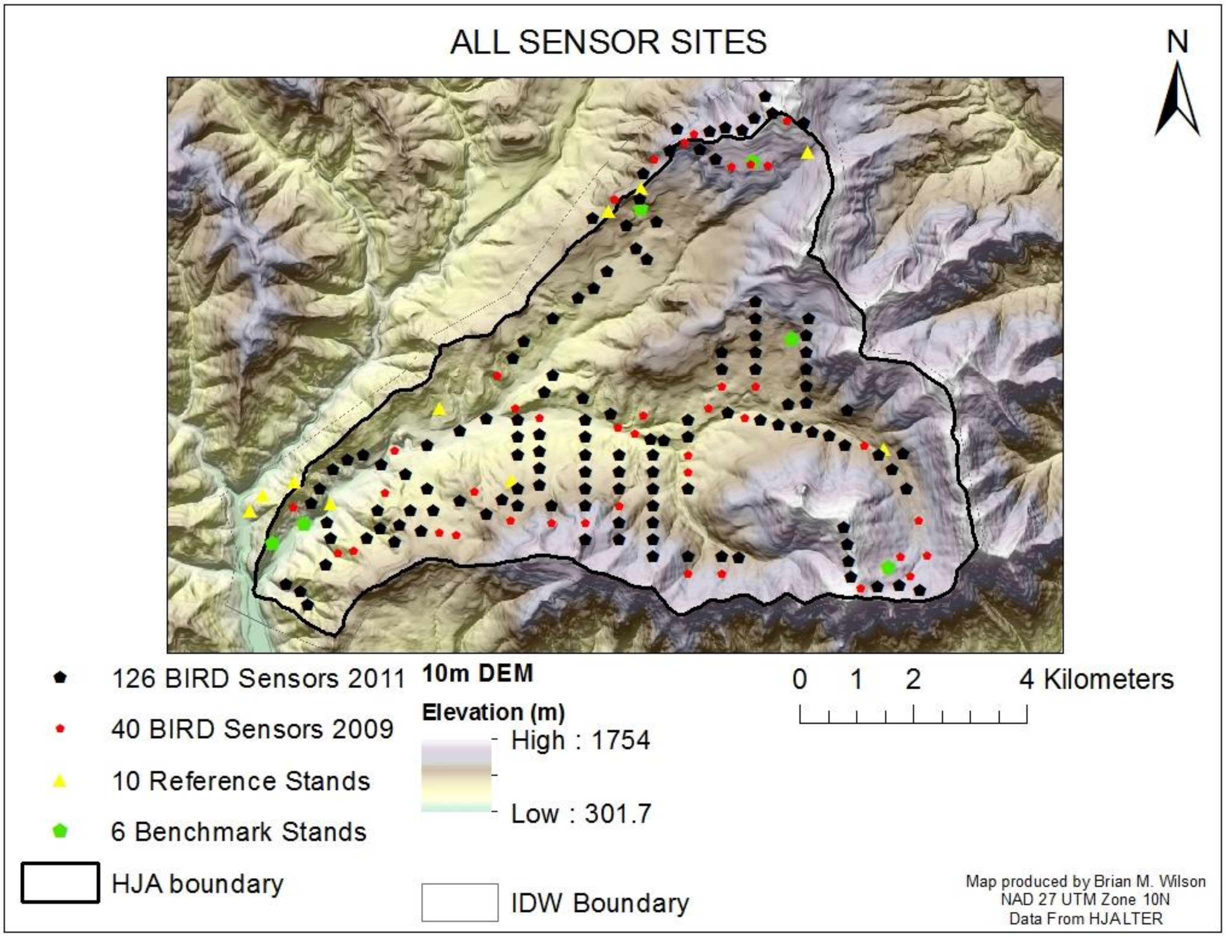
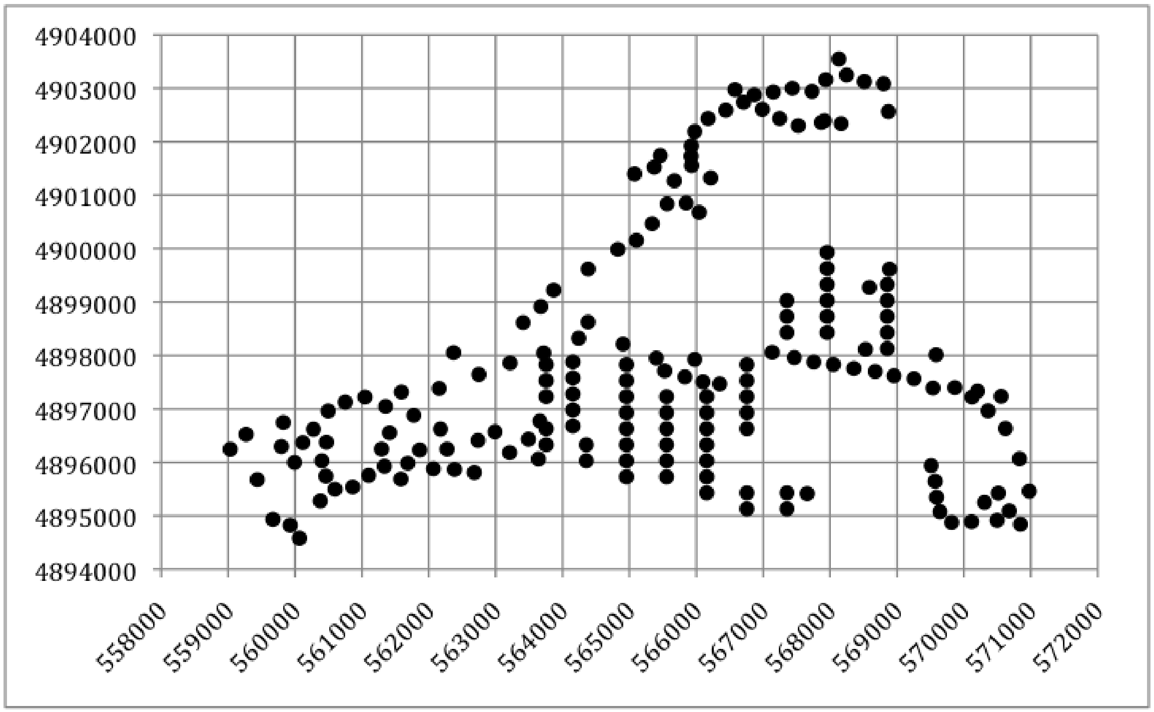
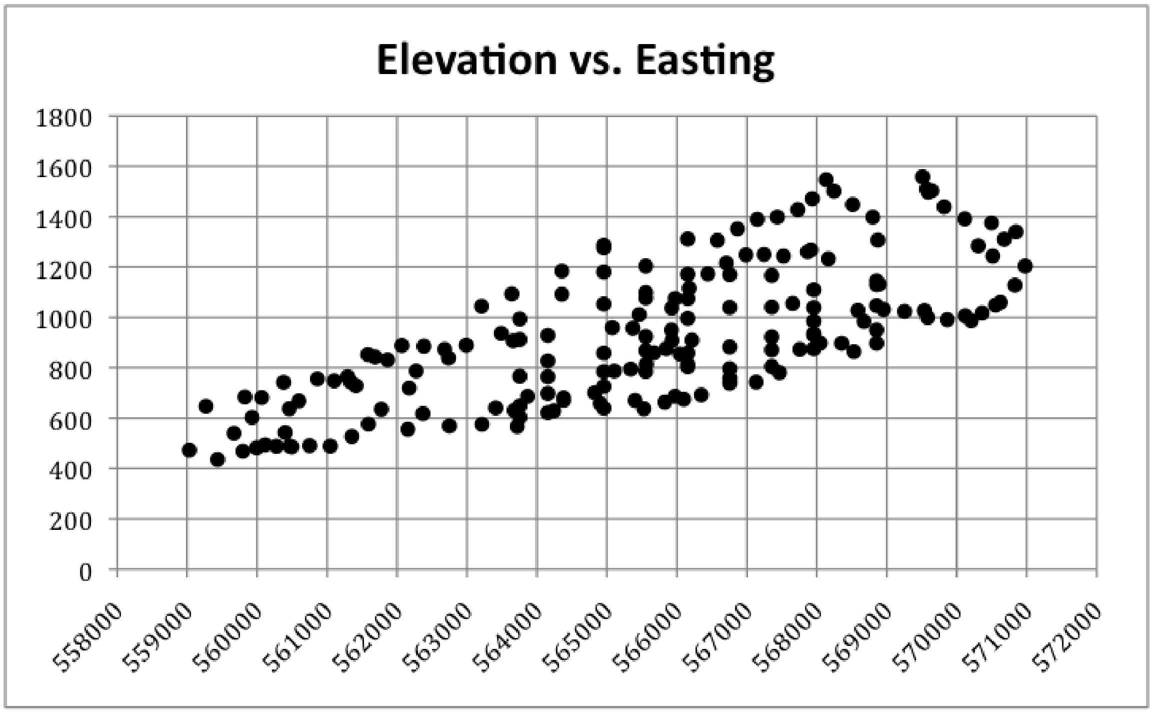


Figure 5. Spatial distribution of BIRD temperature sampling sites (a) x,y coordinates, (b) elevation by easting, (c) elevation by northing.

(a)



(b)


Elevation vs. Easting
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1600
1400
1200
1000
800
600
400
200
0
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559000
560000
561000
562000
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564000
565000
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569000
570000
571000
572000

(c)

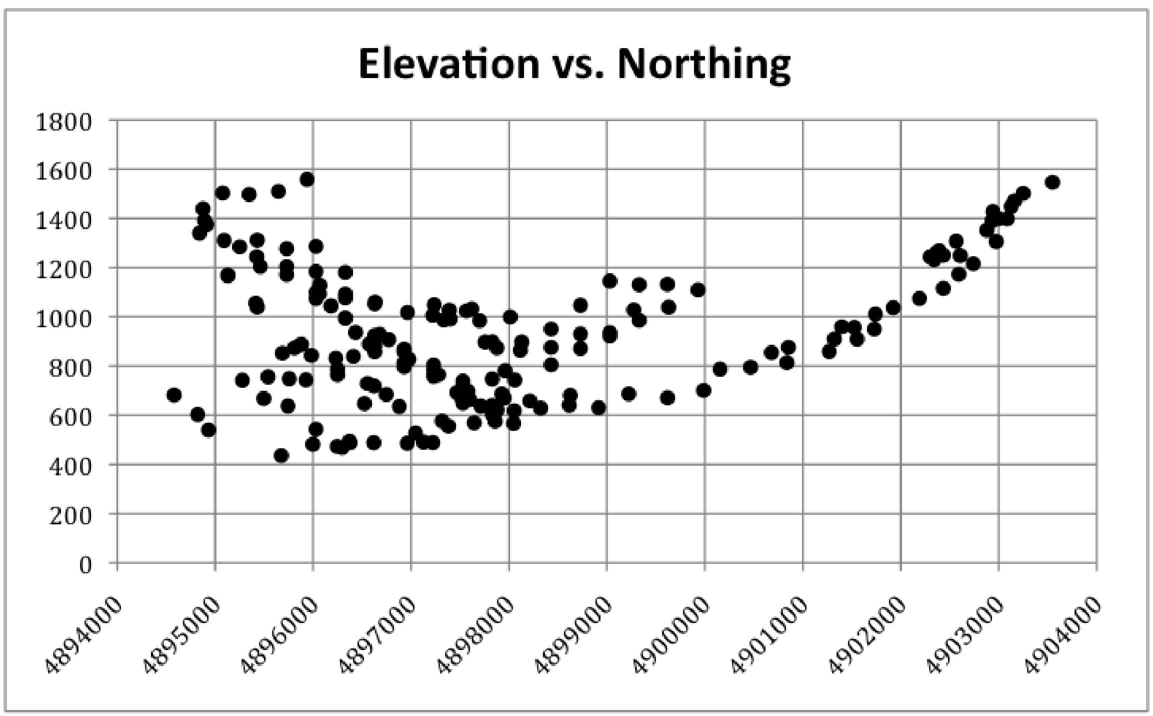
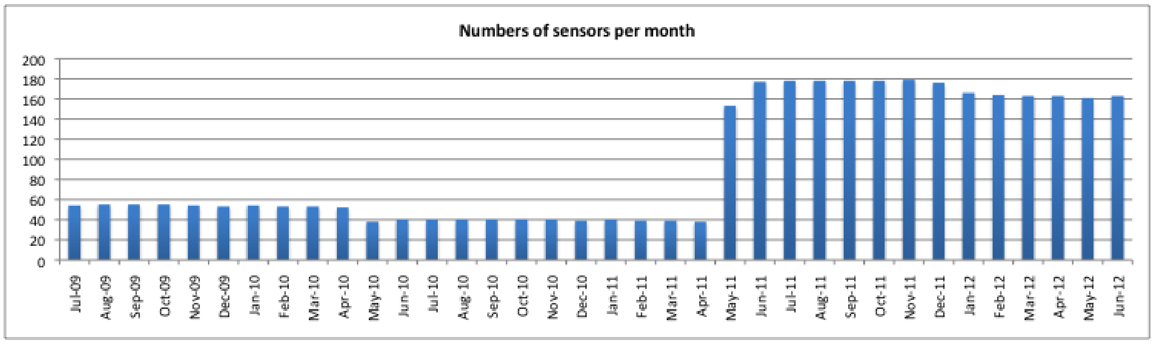
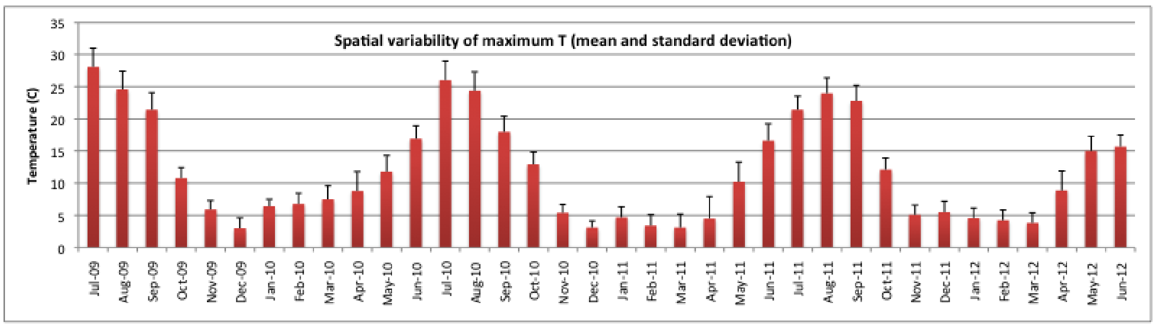
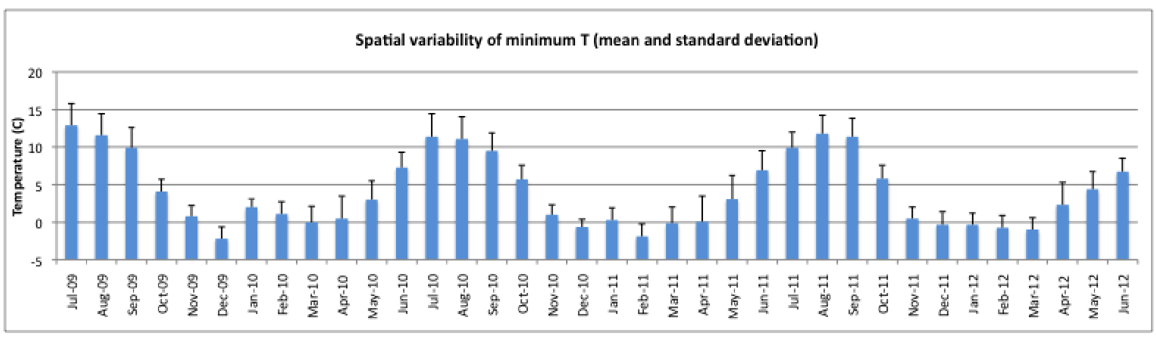

Elevation vs. Northing
1800
1600
1400
1200
1000
800
600
400
200
0
4894000
4895000
4896000
4897000
4898000
4899000
4900000
4901000
4902000
4903000
4904000

Figure 6. Numbers of sensors and spatial variability (mean and standard deviation) of maximum T, minimum T, and T range, by month, April 2009 to June 2012.







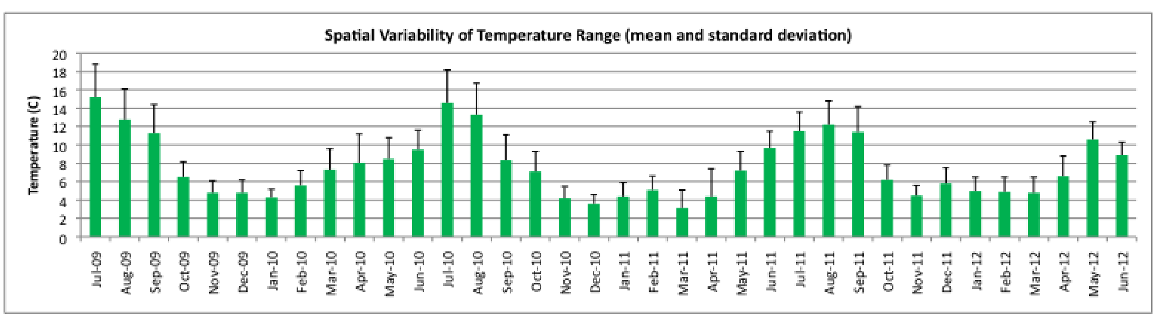
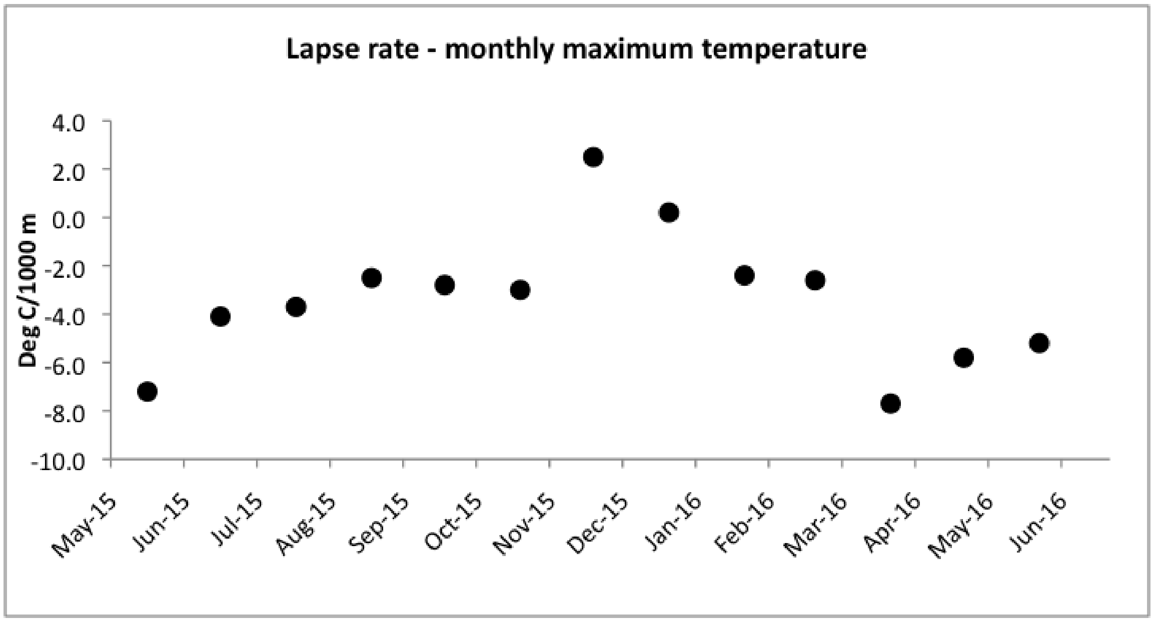


Figure 7. Plots of lapse rate (change in T per 1000 m elevation) by month, May 2011-June 2012.



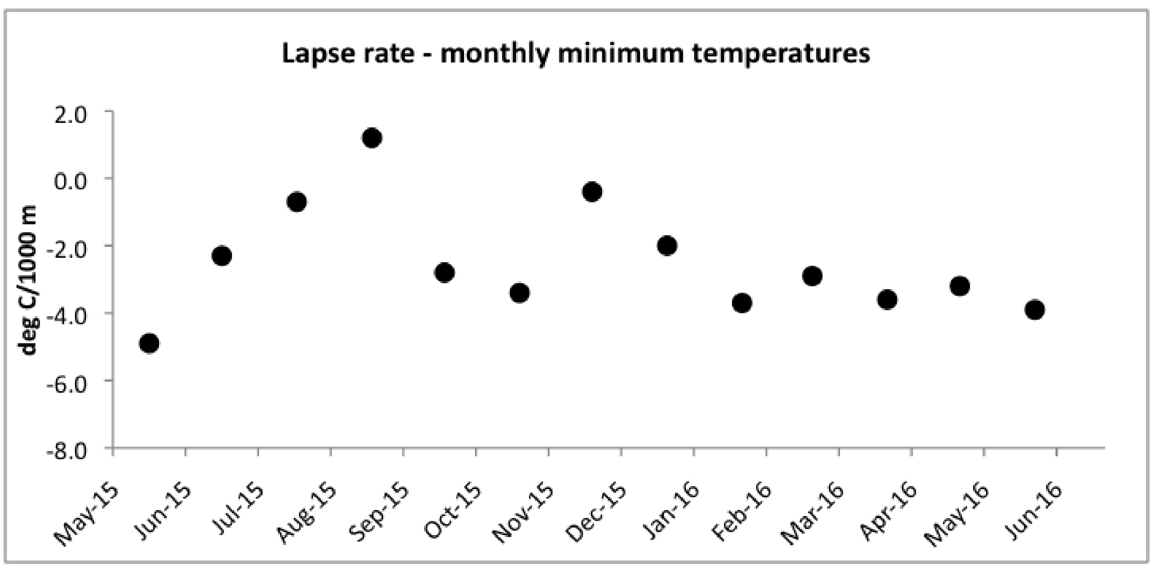


Figure 8. Relationship of number of sensors to mean elevation sampled, May 2011 to June 2012.

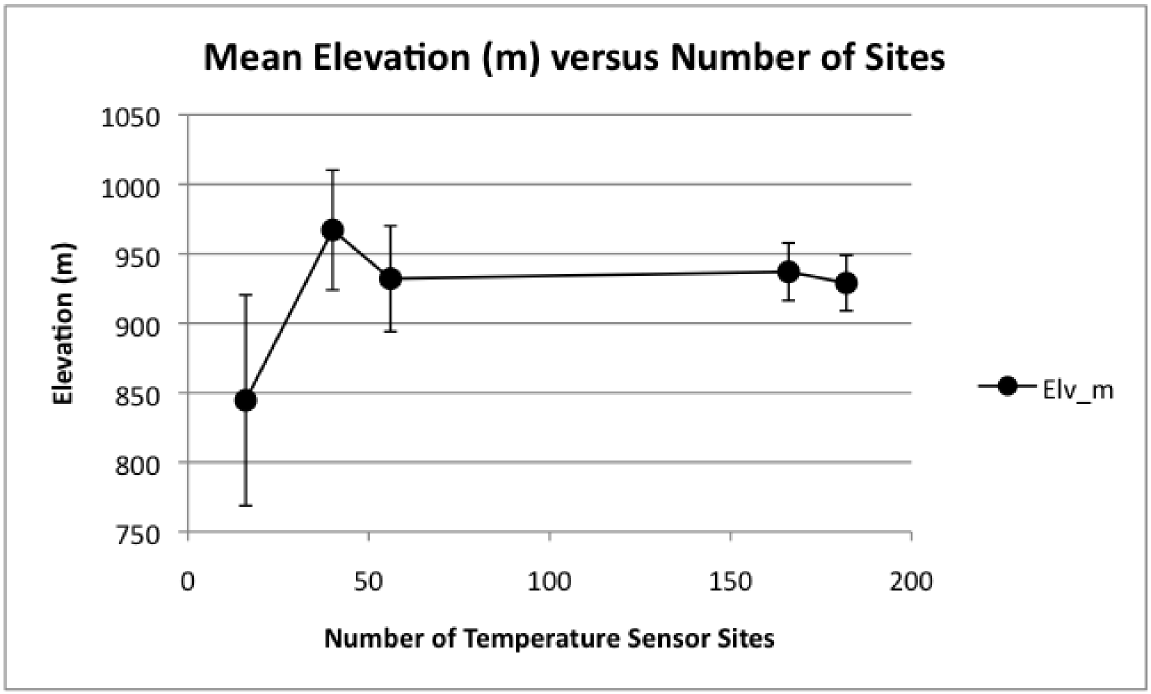
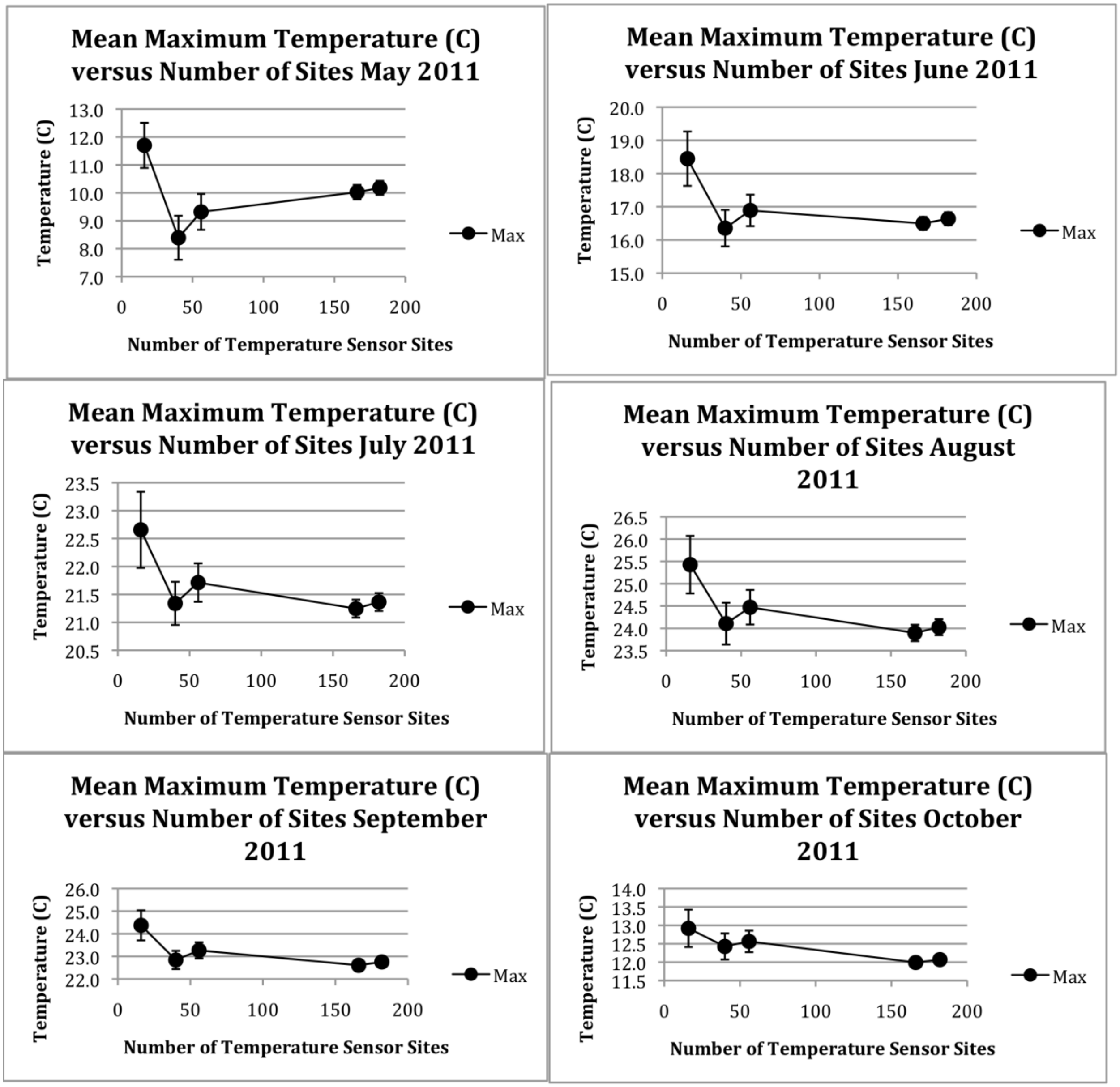
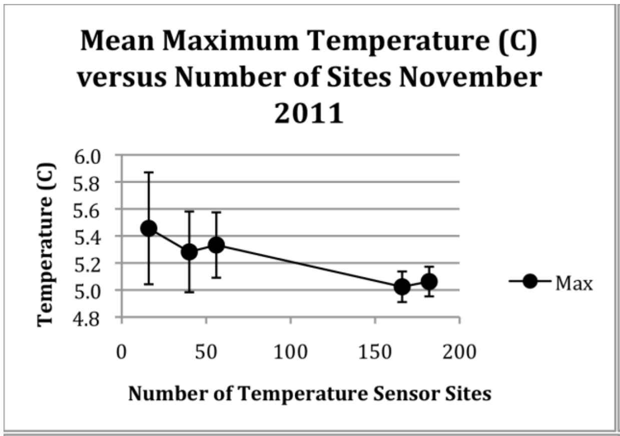
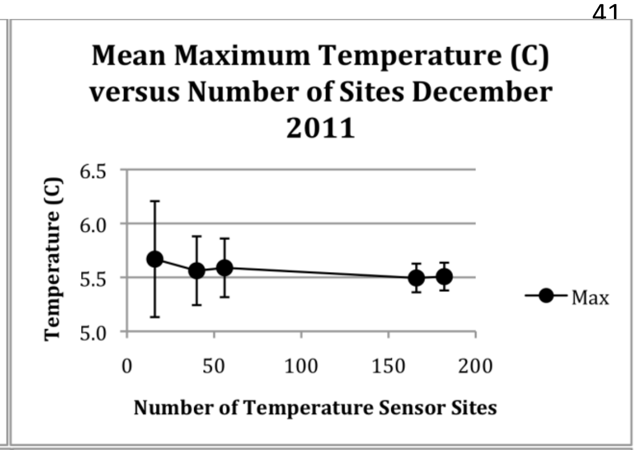
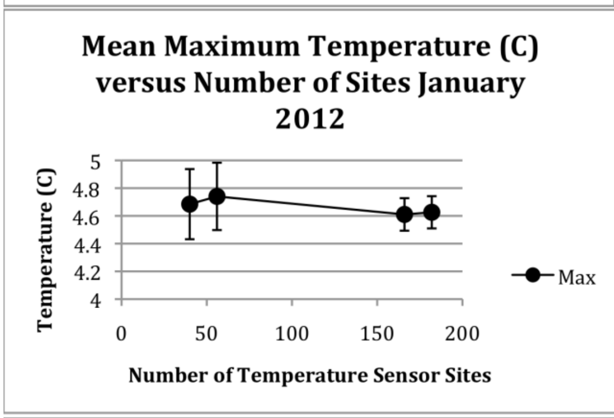


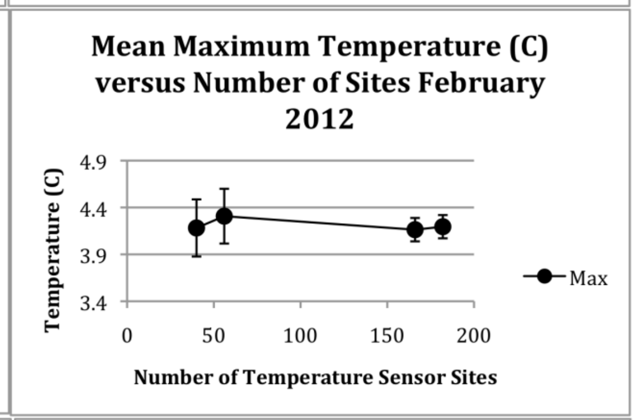
Figure 9. Effect of number of sensors on maximum T (with standard errors), May 2011 to June 2012.

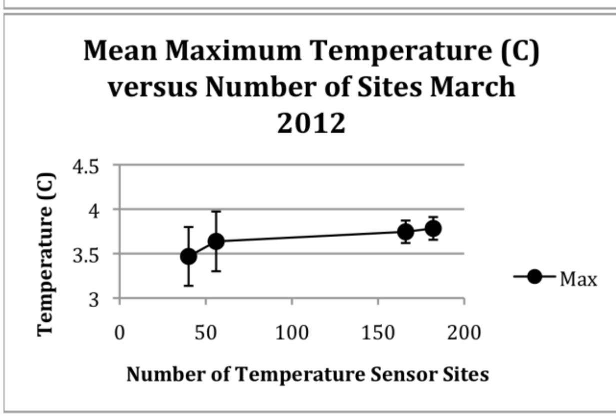


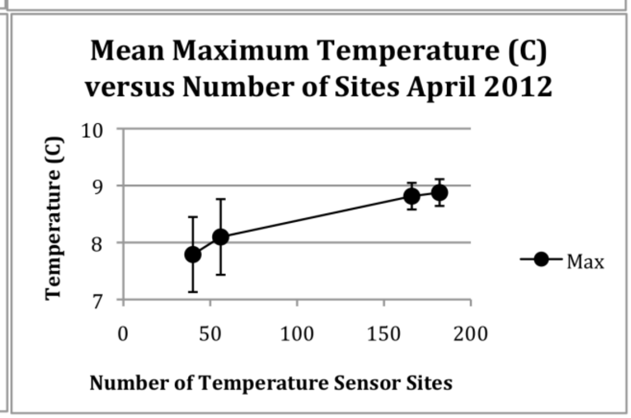

Mean Maximum Temperature (C) versus Number of Sites November 2011
Temperature (C)
6.0
5.8
5.6
5.4
5.2
5.0
4.8
0
50
100
150
200
Number of Temperature Sensor Sites
Max

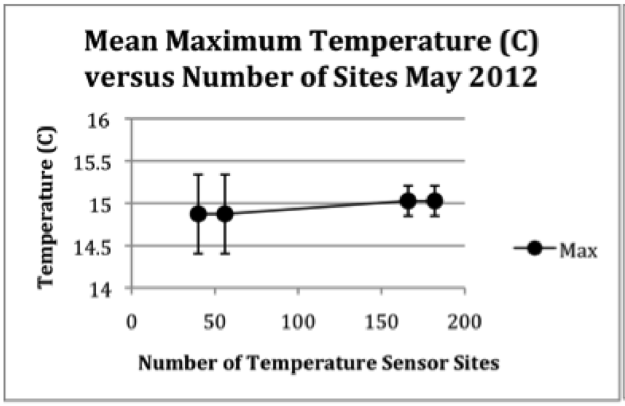

Mean Maximum Temperature (C) versus Number of Sites December 2011
Temperature (C)
6.5
6.0
5.5
5.0
0
50
100
150
200
Number of Temperature Sensor Sites
Max


Mean Maximum Temperature (C) versus Number of Sites January 2012
Temperature (C)
5
4.8
4.6
4.4
4.2
4
0
50
100
150
200
Number of Temperature Sensor Sites
Max


Mean Maximum Temperature (C) versus Number of Sites February 2012
Temperature (C)
4.9
4.4
3.9
3.4
0
50
100
150
200
Number of Temperature Sensor Sites
Max


Mean Maximum Temperature (C) versus Number of Sites March 2012
Temperature (C)
4.5
4
3.5
3
0
50
100
150
200
Number of Temperature Sensor Sites
Max


Mean Maximum Temperature (C) versus Number of Sites April 2012
Temperature (C)
10
9
8
7
0
50
100
150
200
Number of Temperature Sensor Sites
Max


Mean Maximum Temperature (C) versus Number of Sites May 2012
Temperature (C)
16
15.5
15
14.5
14
0
50
100
150
200
Number of Temperature Sensor Sites
Max

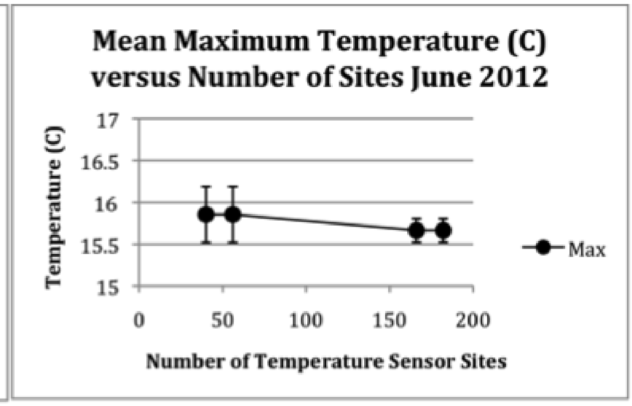
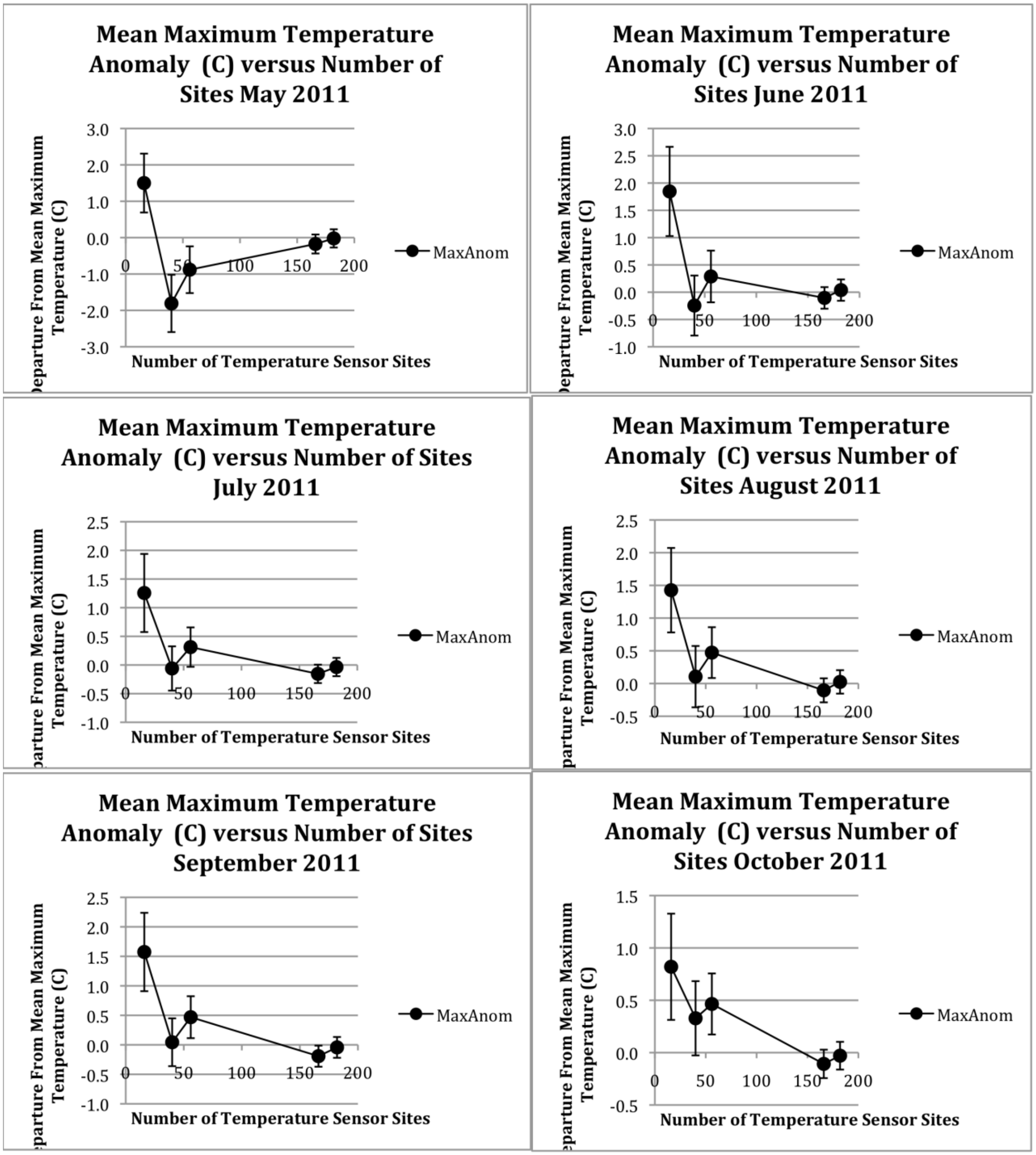
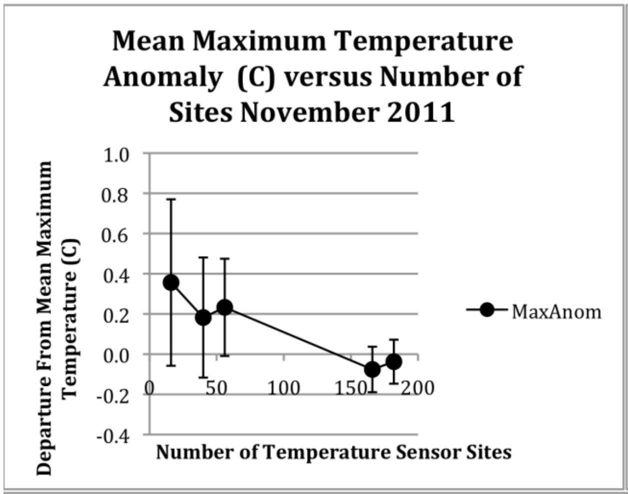
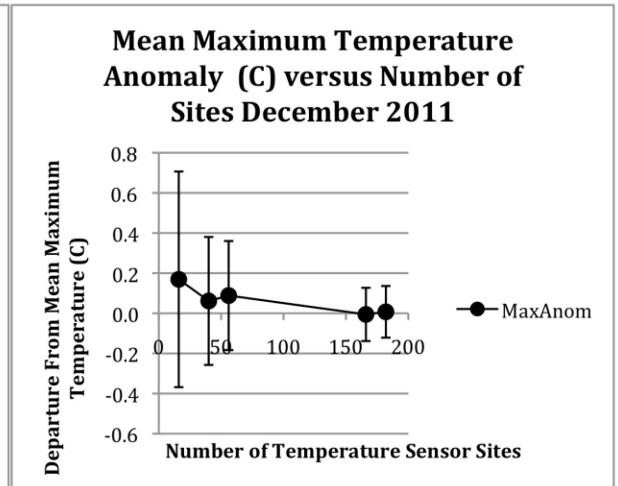
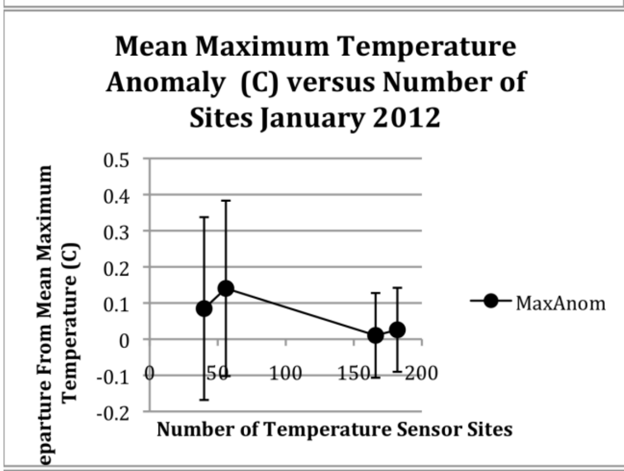

Mean Maximum Temperature (C) versus Number of Sites June 2012
Temperature (C)
17
16.5
16
15.5
15
0
50
100
150
200
Number of Temperature Sensor Sites
Max

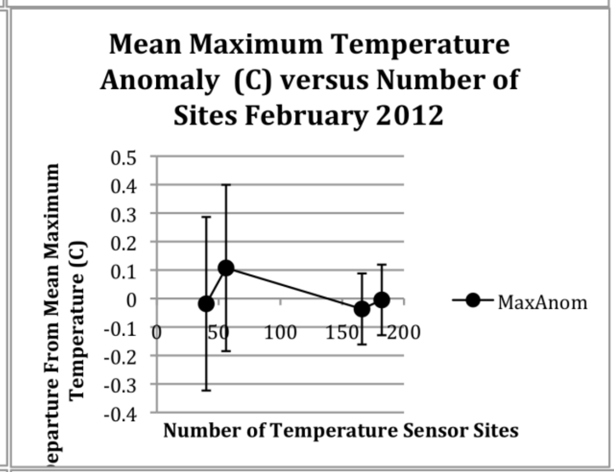
Figure 10. Effect of number of sensors on max T anomaly, May 2011-June 2012.

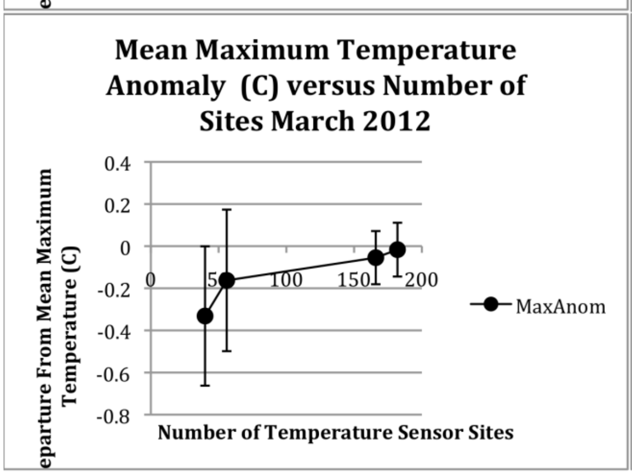


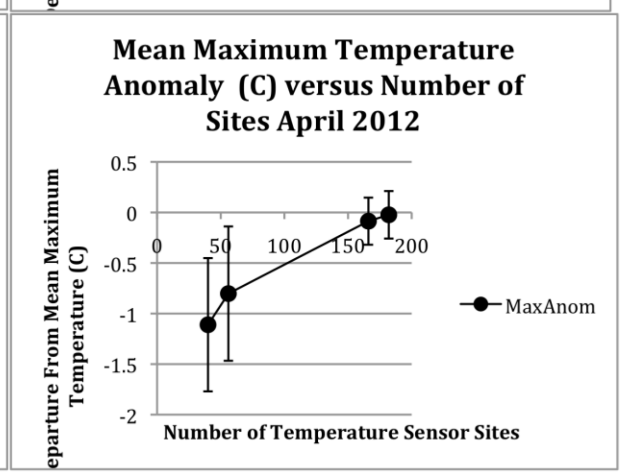

Mean Maximum Temperature Anomaly (C) versus Number of Sites November 2011
Departure From Mean Maximum Temperature (C)
Number of Temperature Sensor Sites
MaxAnom
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
50
100
150
200

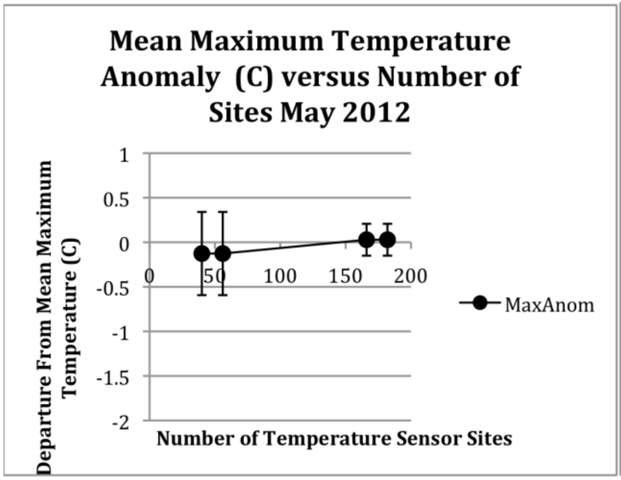

Mean Maximum Temperature Anomaly (C) versus Number of Sites December 2011
Departure From Mean Maximum Temperature (C)
Number of Temperature Sensor Sites
MaxAnom
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
50
100
150
200


Mean Maximum Temperature Anomaly (C) versus Number of Sites January 2012
eparture From Mean Maximum Temperature (C)
Number of Temperature Sensor Sites
MaxAnom
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
50
100
150
200

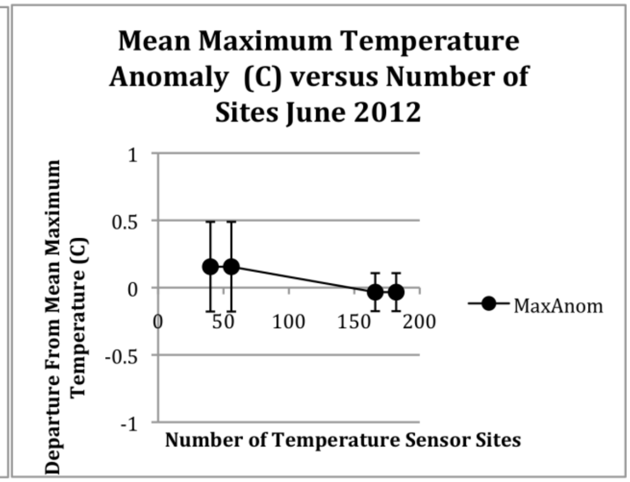

Mean Maximum Temperature Anomaly (C) versus Number of Sites February 2012
eparture From Mean Maximum Temperature (C)
Number of Temperature Sensor Sites
MaxAnom
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
50
100
150
200


Mean Maximum Temperature Anomaly (C) versus Number of Sites March 2012
eparture From Mean Maximum Temperature (C)
Number of Temperature Sensor Sites
MaxAnom
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
50
100
150
200


Mean Maximum Temperature Anomaly (C) versus Number of Sites April 2012
eparture From Mean Maximum Temperature (C)
Number of Temperature Sensor Sites
MaxAnom
0.5
0
-0.5
-1
-1.5
-2
0
50
100
150
200

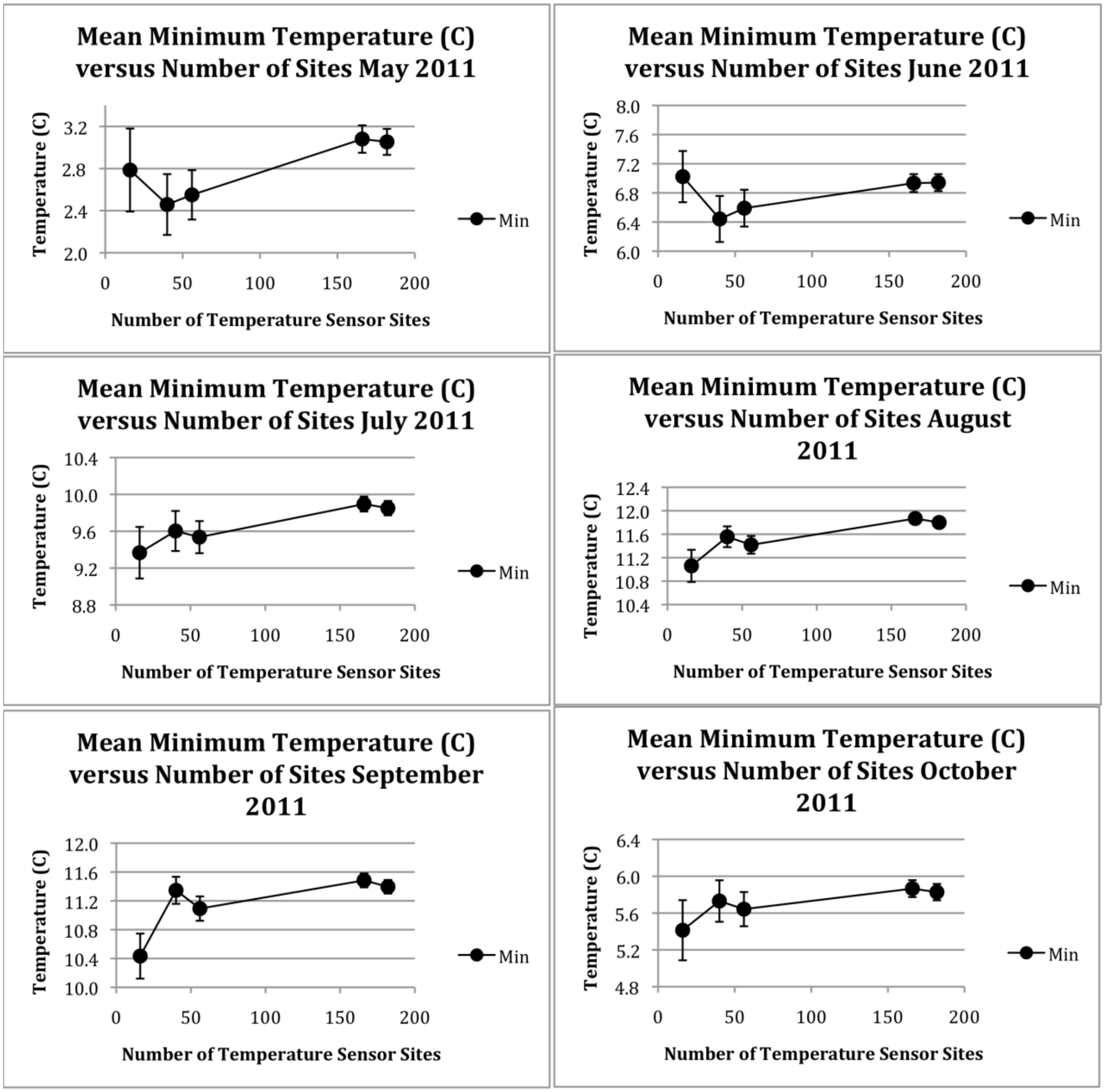


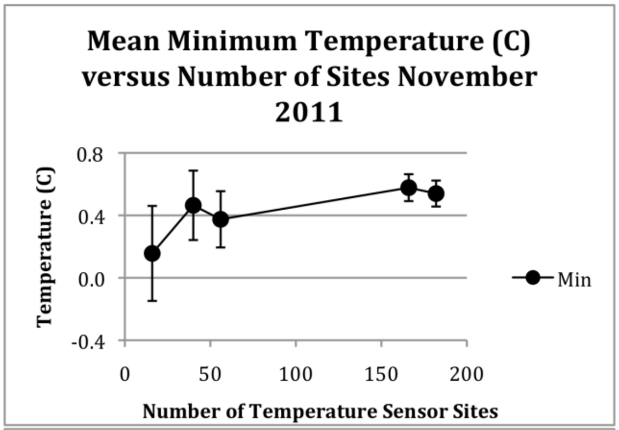
Mean Maximum Temperature Anomaly (C) versus Number of Sites May 2012
Departure From Mean Maximum Temperature (C)
1
0.5
0
-0.5
-1
-1.5
-2
0
50
100
150
200
MaxAnom
Number of Temperature Sensor Sites

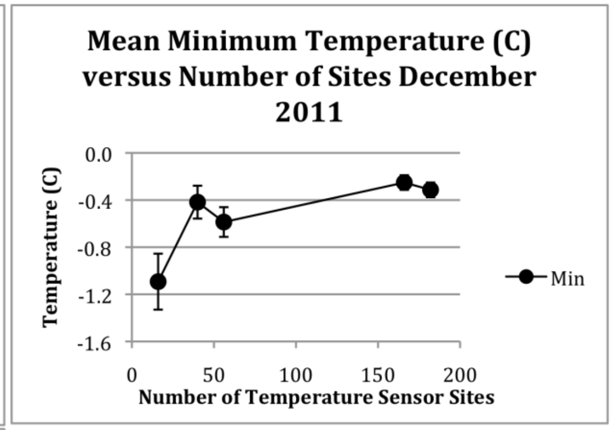


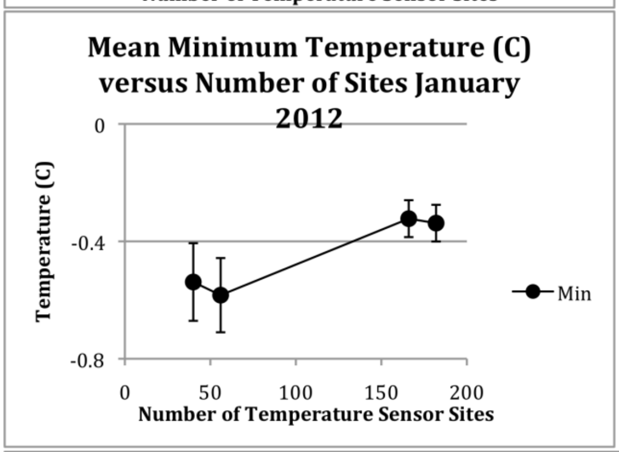
Mean Maximum Temperature Anomaly (C) versus Number of Sites June 2012
Departure From Mean Maximum Temperature (C)
1
0.5
0
-0.5
-1
0
50
100
150
200
MaxAnom
Number of Temperature Sensor Sites

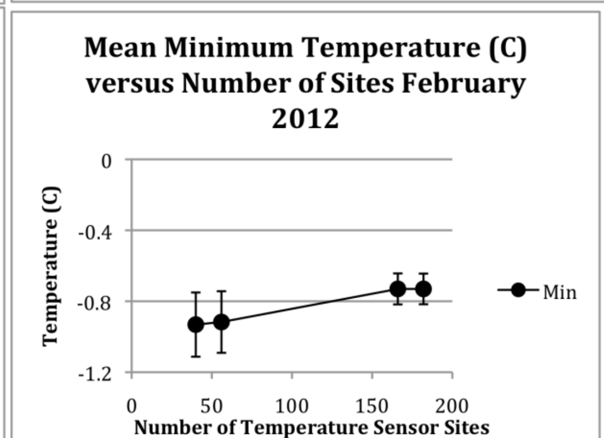
Figure 11. Effect of number of sensors on minimum T, May 2011 to June 2012.

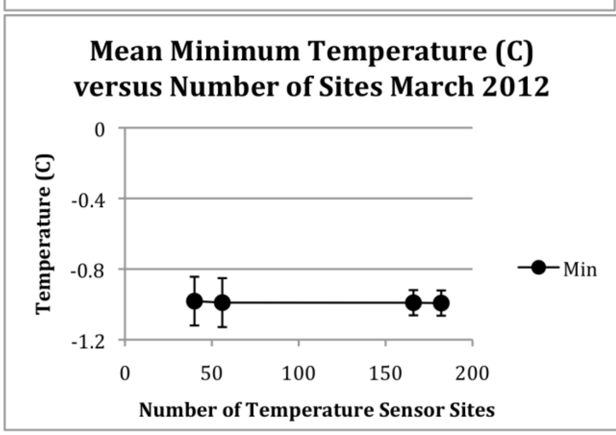


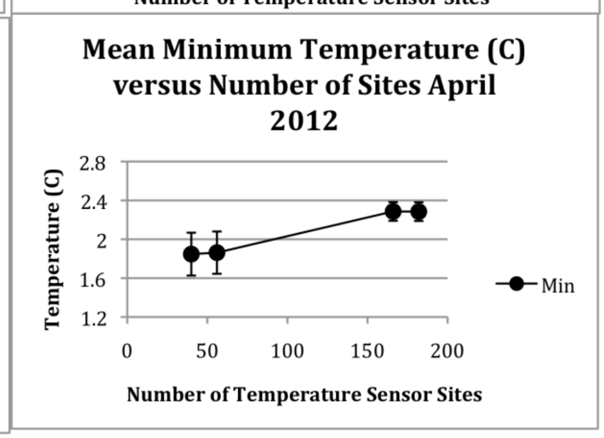

Mean Minimum Temperature (C) versus Number of Sites November 2011
Temperature (C)
0.8
0.4
0.0
-0.4
0
50
100
150
200
Number of Temperature Sensor Sites
Min

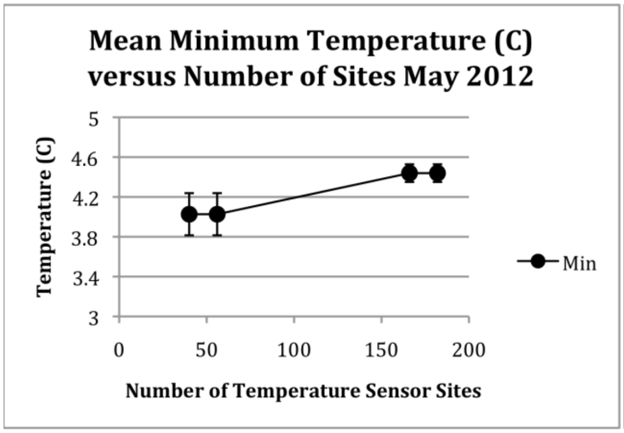

Mean Minimum Temperature (C) versus Number of Sites December 2011
Temperature (C)
0.0
-0.4
-0.8
-1.2
-1.6
0
50
100
150
200
Number of Temperature Sensor Sites
Min


Mean Minimum Temperature (C) versus Number of Sites January 2012
Temperature (C)
0
-0.4
-0.8
0
50
100
150
200
Number of Temperature Sensor Sites
Min

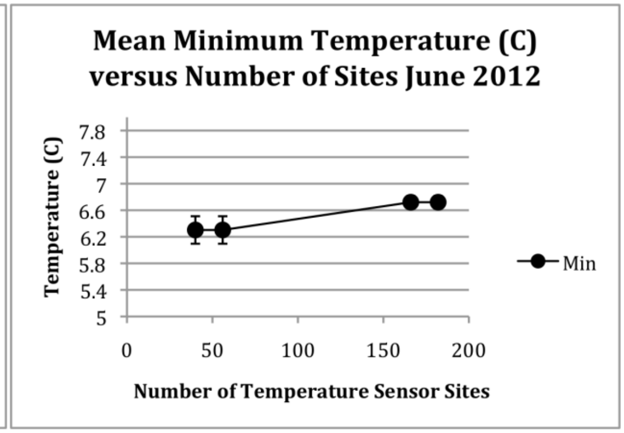

Mean Minimum Temperature (C) versus Number of Sites February 2012
Temperature (C)
0
-0.4
-0.8
-1.2
0
50
100
150
200
Number of Temperature Sensor Sites
Min


Mean Minimum Temperature (C) versus Number of Sites March 2012
Temperature (C)
0
-0.4
-0.8
-1.2
0
50
100
150
200
Number of Temperature Sensor Sites
Min


Mean Minimum Temperature (C) versus Number of Sites April 2012
Temperature (C)
2.8
2.4
2
1.6
1.2
0
50
100
150
200
Number of Temperature Sensor Sites
Min

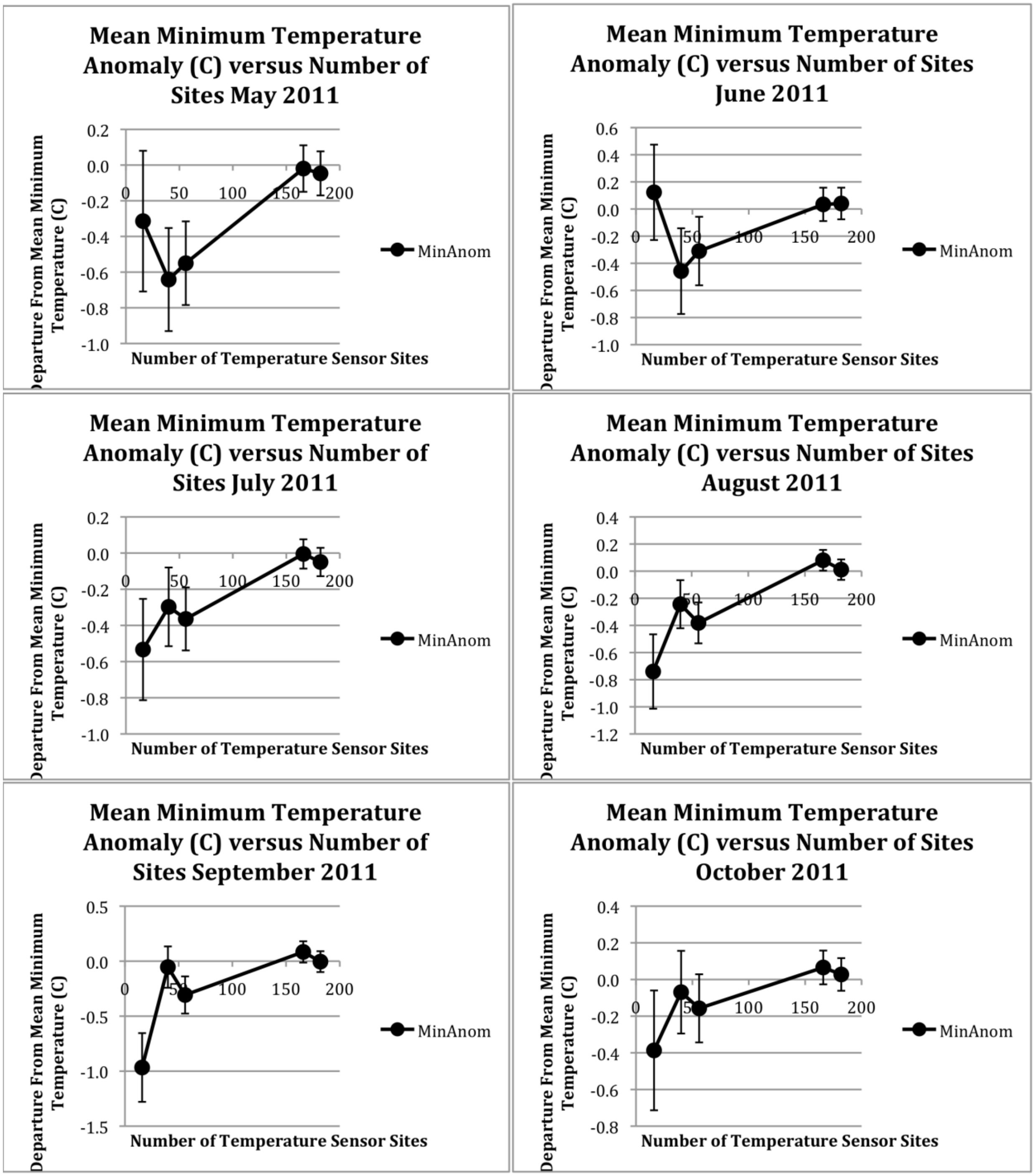


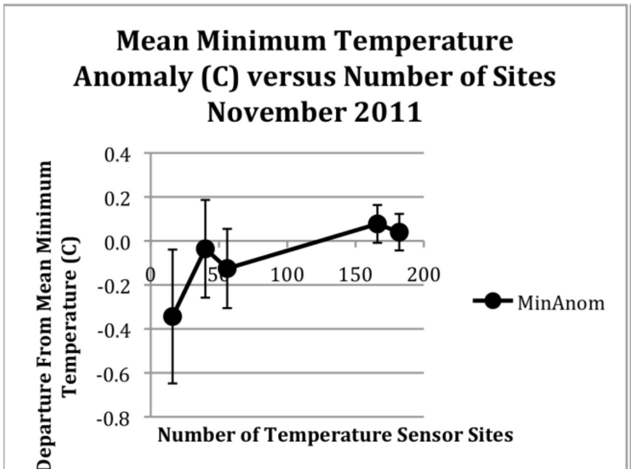
Mean Minimum Temperature (C) versus Number of Sites May 2012
Temperature (C)
5
4.6
4.2
3.8
3.4
3
0
50
100
150
200
Number of Temperature Sensor Sites
Min

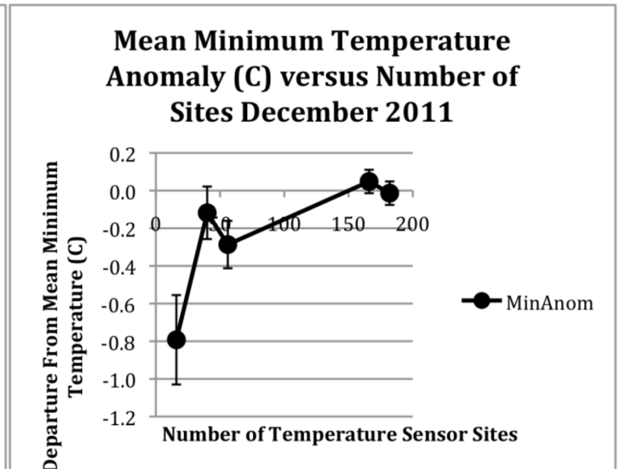


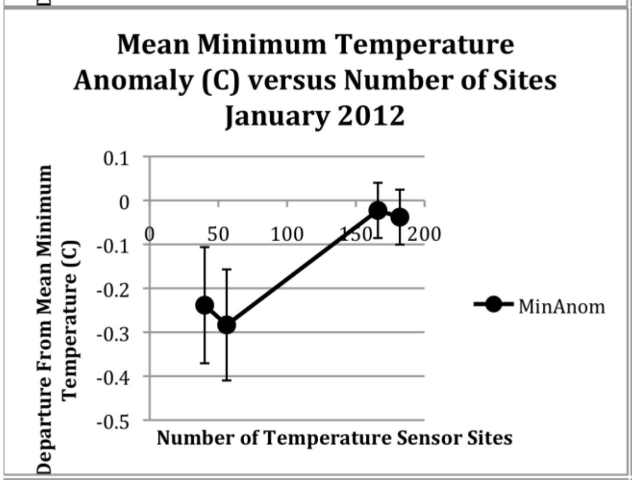
Mean Minimum Temperature (C) versus Number of Sites June 2012
Temperature (C)
7.8
7.4
7
6.6
6.2
5.8
5.4
5
0
50
100
150
200
Number of Temperature Sensor Sites
Min

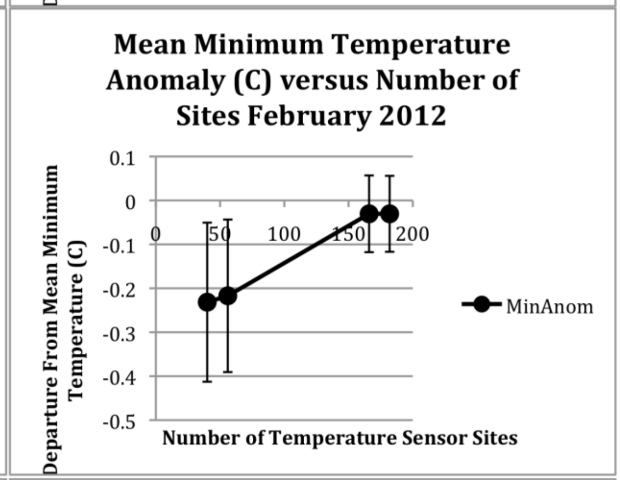
Figure 12. Effect of number of sensors on minumum T anomaly (with standard errors), May 2011 to June 2012.

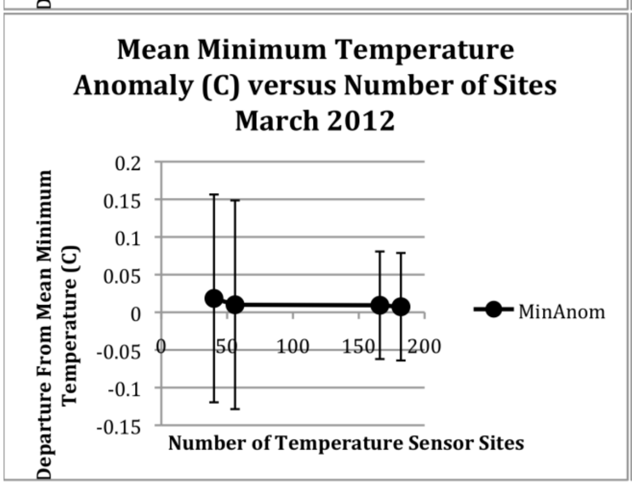


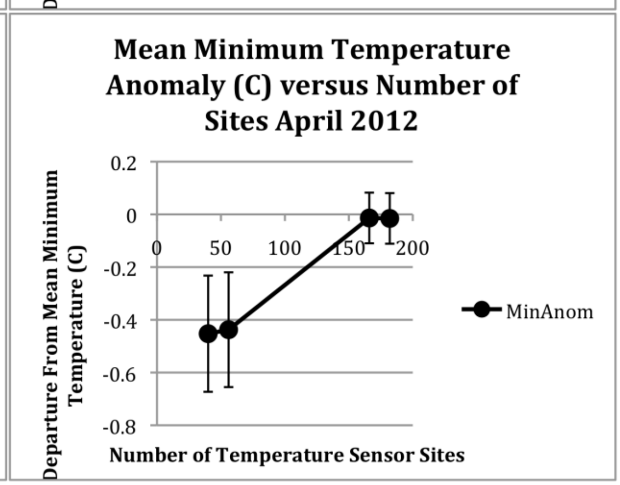

Mean Minimum Temperature Anomaly (C) versus Number of Sites November 2011
Departure From Mean Minimum Temperature (C)
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
50
100
150
200
Number of Temperature Sensor Sites
MinAnom

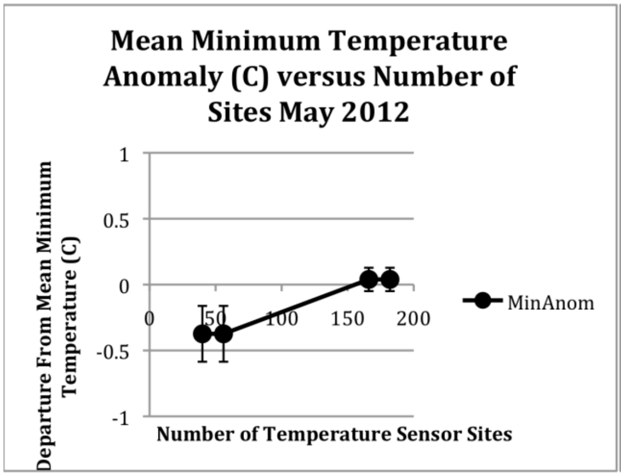

Mean Minimum Temperature Anomaly (C) versus Number of Sites December 2011
Departure From Mean Minimum Temperature (C)
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
100
150
200
Number of Temperature Sensor Sites
MinAnom


Mean Minimum Temperature Anomaly (C) versus Number of Sites January 2012
Departure From Mean Minimum Temperature (C)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
50
100
150
200
Number of Temperature Sensor Sites
MinAnom


Mean Minimum Temperature Anomaly (C) versus Number of Sites February 2012
Departure From Mean Minimum Temperature (C)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
50
100
150
200
Number of Temperature Sensor Sites
MinAnom


Mean Minimum Temperature Anomaly (C) versus Number of Sites March 2012
Departure From Mean Minimum Temperature (C)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
50
100
150
200
Number of Temperature Sensor Sites
MinAnom


Mean Minimum Temperature Anomaly (C) versus Number of Sites April 2012
Departure From Mean Minimum Temperature (C)
0.2
0
-0.2
-0.4
-0.6
-0.8
0
50
100
150
200
Number of Temperature Sensor Sites
MinAnom


Mean Minimum Temperature Anomaly (C) versus Number of Sites May 2012
Departure From Mean Minimum Temperature (C)
1
0.5
0
-0.5
-1
0
50
100
150
200
Number of Temperature Sensor Sites
MinAnom

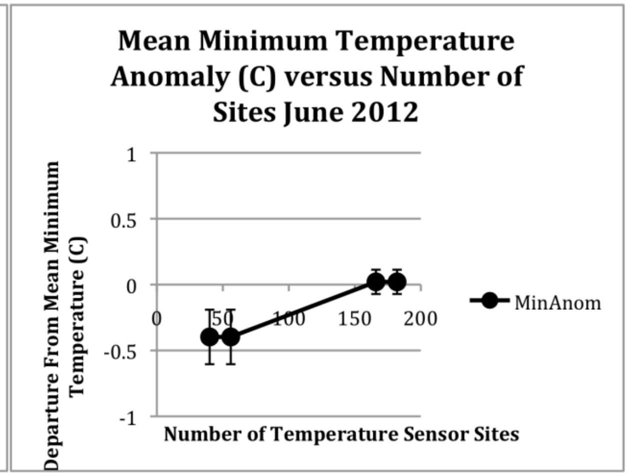
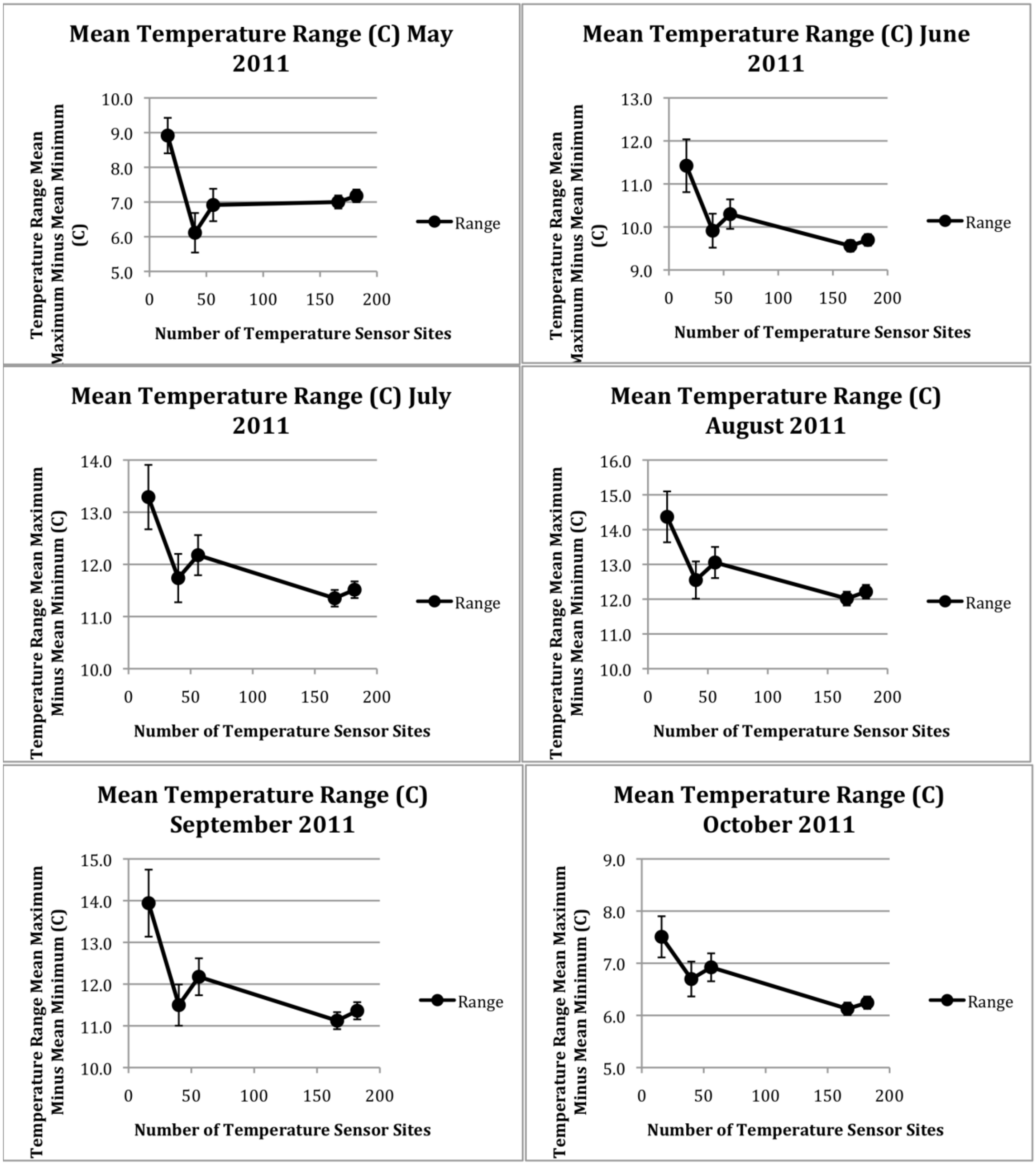
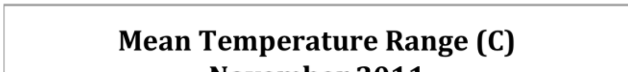
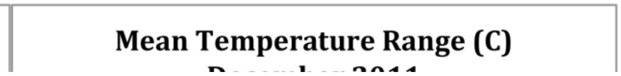
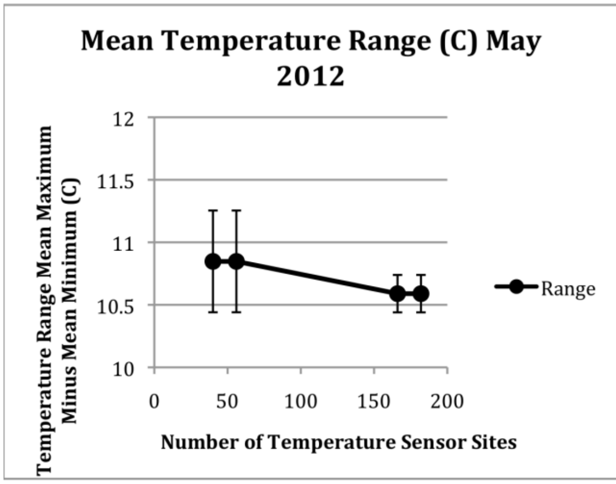

Mean Minimum Temperature Anomaly (C) versus Number of Sites June 2012
Departure From Mean Minimum Temperature (C)
1
0.5
0
-0.5
-1
0
50
100
150
200
Number of Temperature Sensor Sites
MinAnom

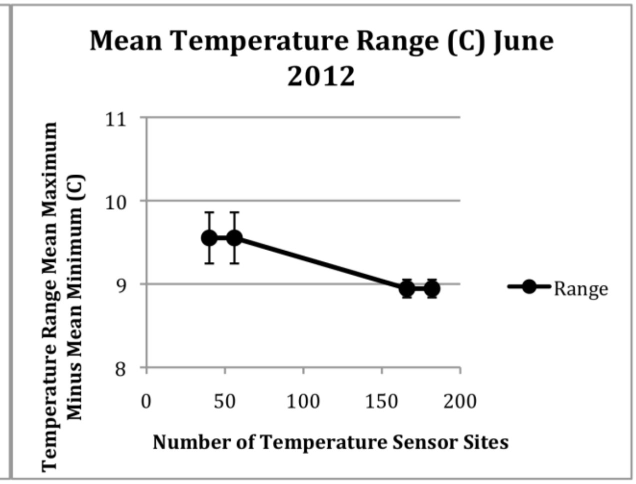
Figure 13. Effect of number of sensors on temperature range, May 2011 to June 2012.

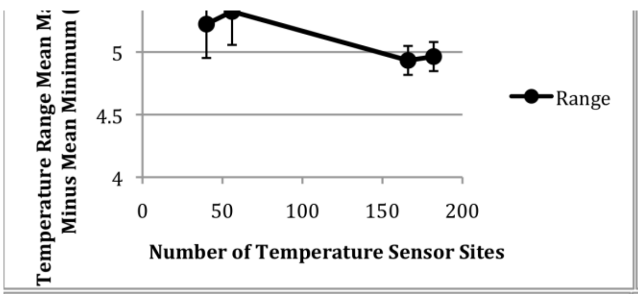


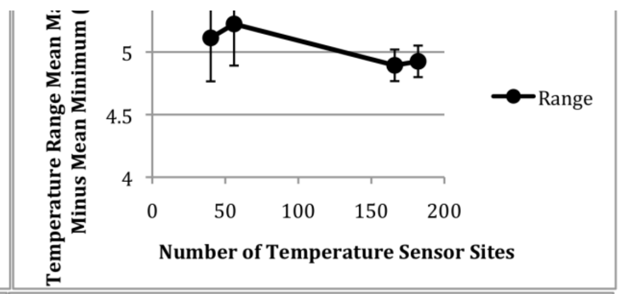

Mean Temperature Range (C)

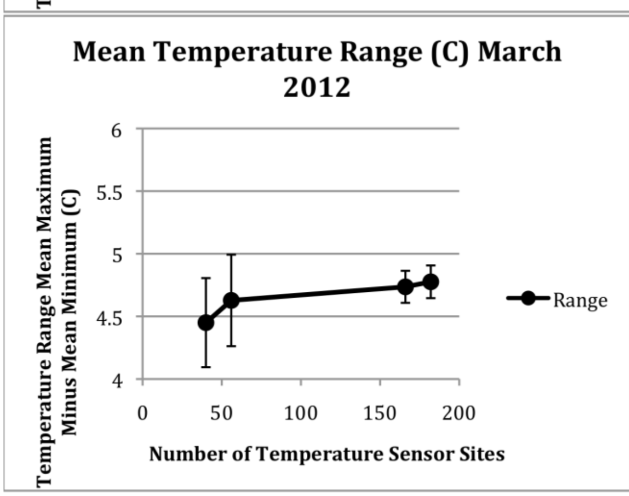

Mean Temperature Range (C)


Mean Temperature Range (C) May 2012
Temperature Range Mean Maximum Minus Mean Minimum (C)
12
11.5
11
10.5
10
0
50
100
150
200
Number of Temperature Sensor Sites
Range


Mean Temperature Range (C) June 2012
Temperature Range Mean Maximum Minus Mean Minimum (C)
11
10
9
8
0
50
100
150
200
Number of Temperature Sensor Sites
Range


Temperature Range Mean M
Minus Mean Minimum (
5
4.5
4
0
50
100
150
200
Number of Temperature Sensor Sites
Range


Temperature Range Mean M
Minus Mean Minimum (
5
4.5
4
0
50
100
150
200
Number of Temperature Sensor Sites
Range


Mean Temperature Range (C) March 2012
Temperature Range Mean Maximum Minus Mean Minimum (C)
6
5.5
5
4.5
4
0
50
100
150
200
Number of Temperature Sensor Sites
Range

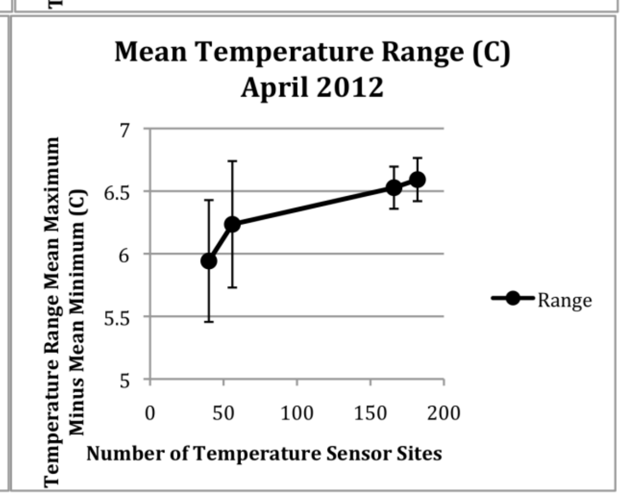
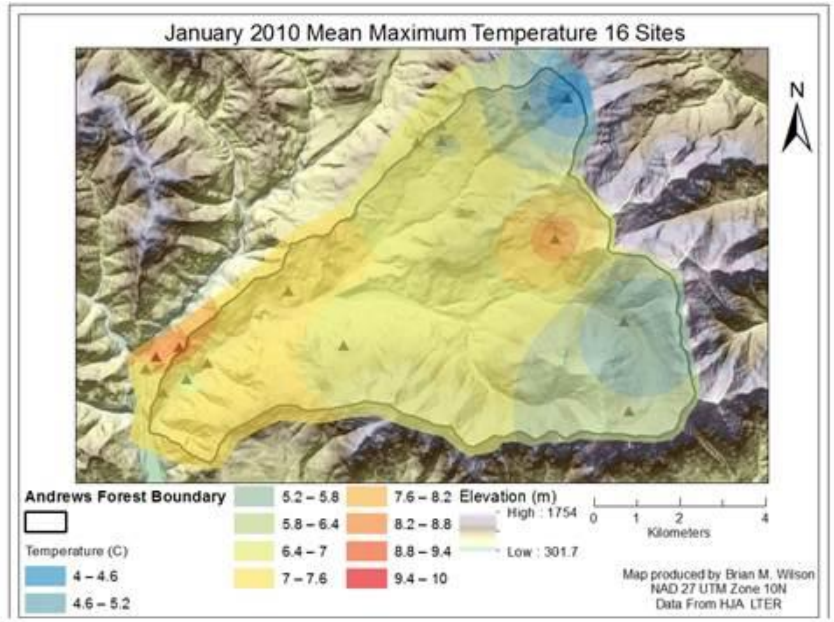
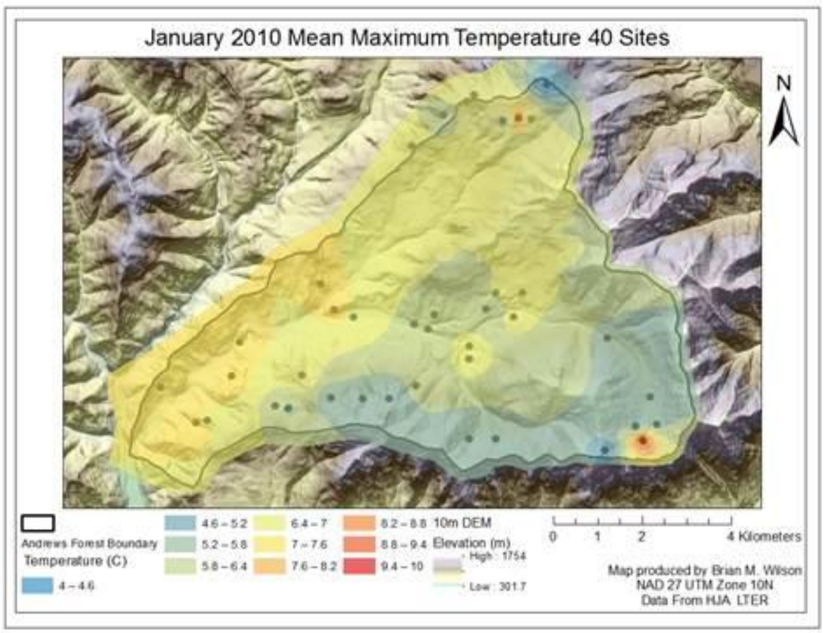
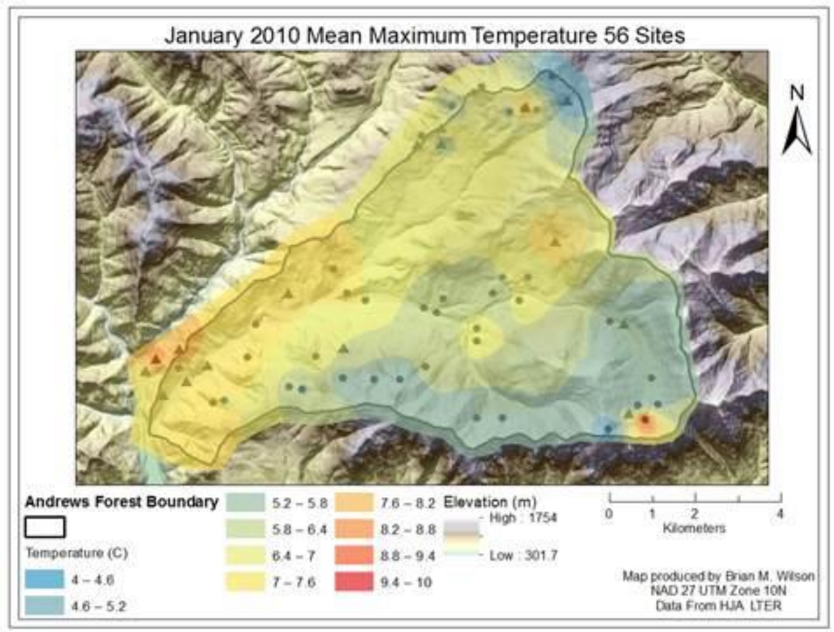

Mean Temperature Range (C) April 2012
Temperature Range Mean Maximum Minus Mean Minimum (C)
7
6.5
6
5.5
5
0
50
100
150
200
Number of Temperature Sensor Sites
Range

Figure 14. Effect of number of sensors on spatial pattern of maximum and minimum T, by month, July 2009 to April 2010: 16 vs. 40 vs. 56.

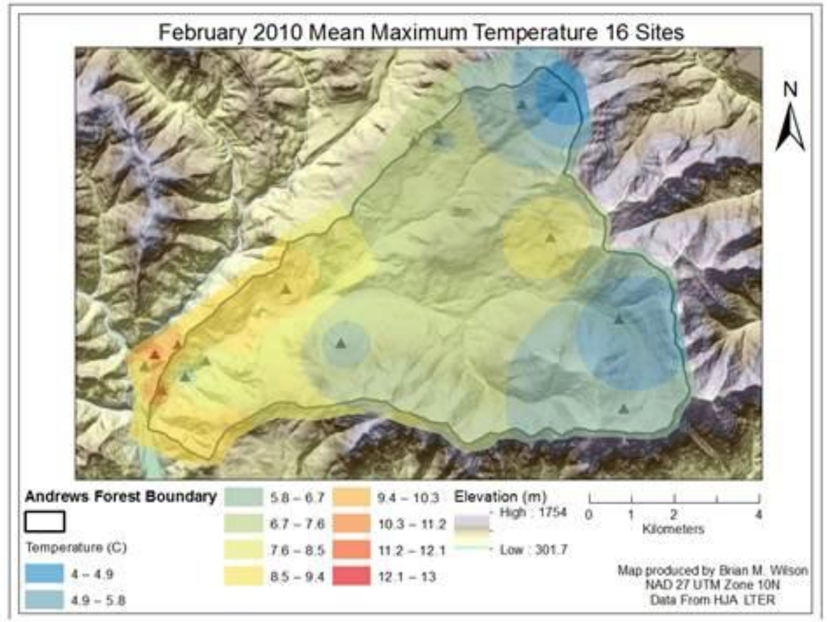
Maximum mean monthly temperature January 2010 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

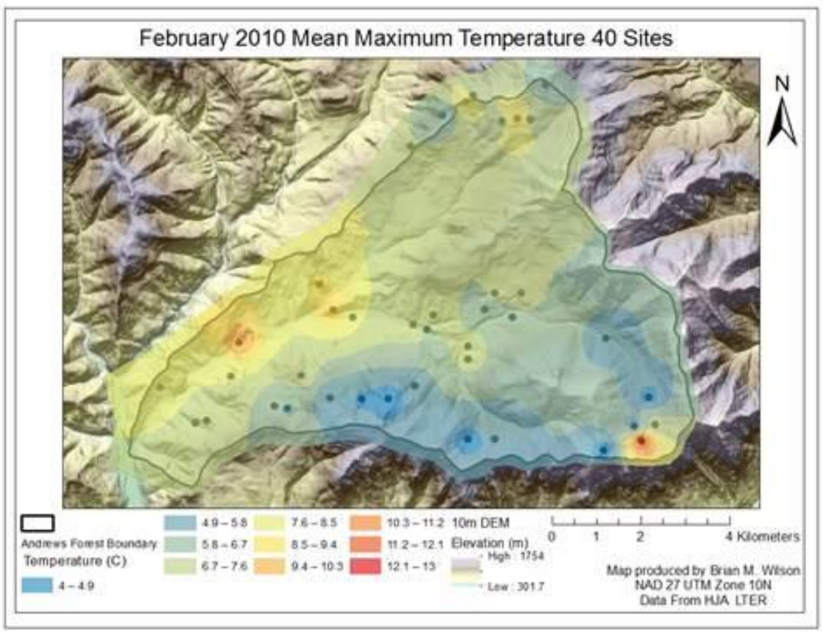


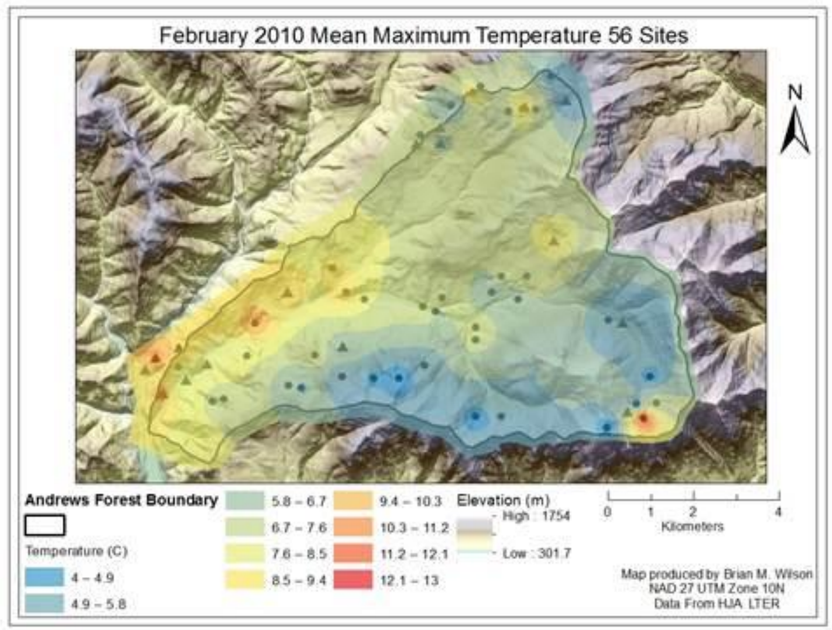




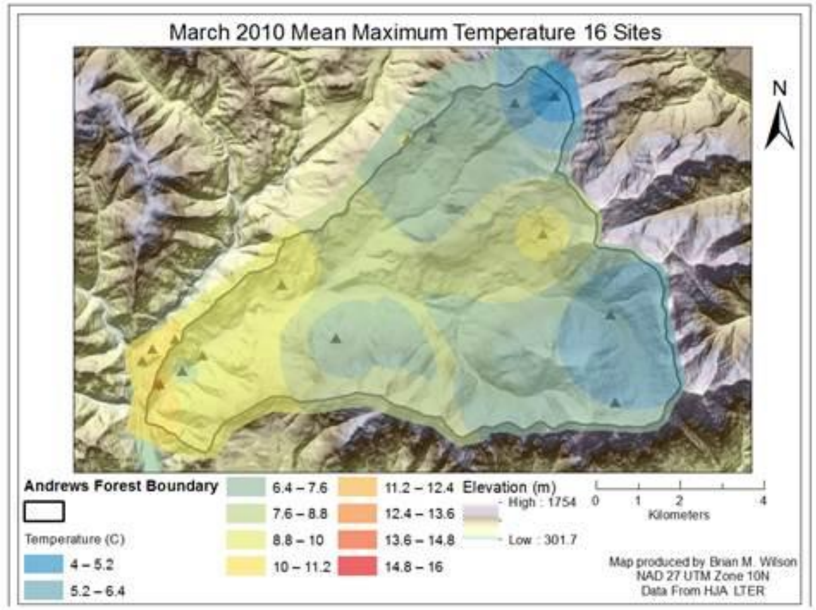
Maximum mean monthly temperature February 2010 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

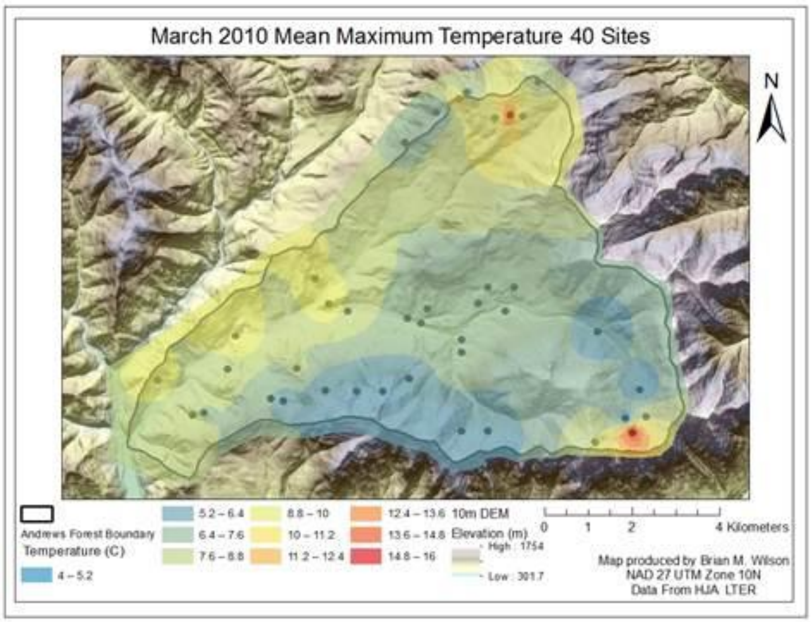


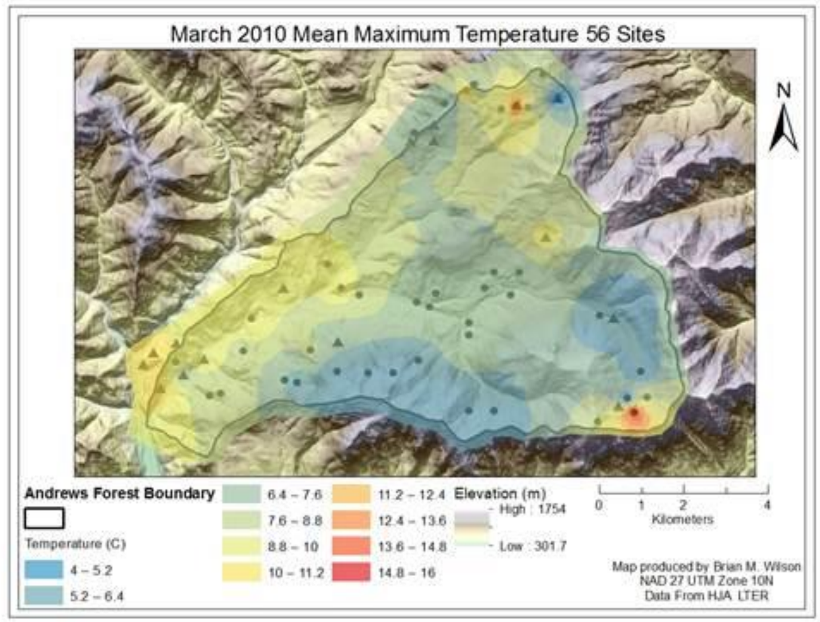




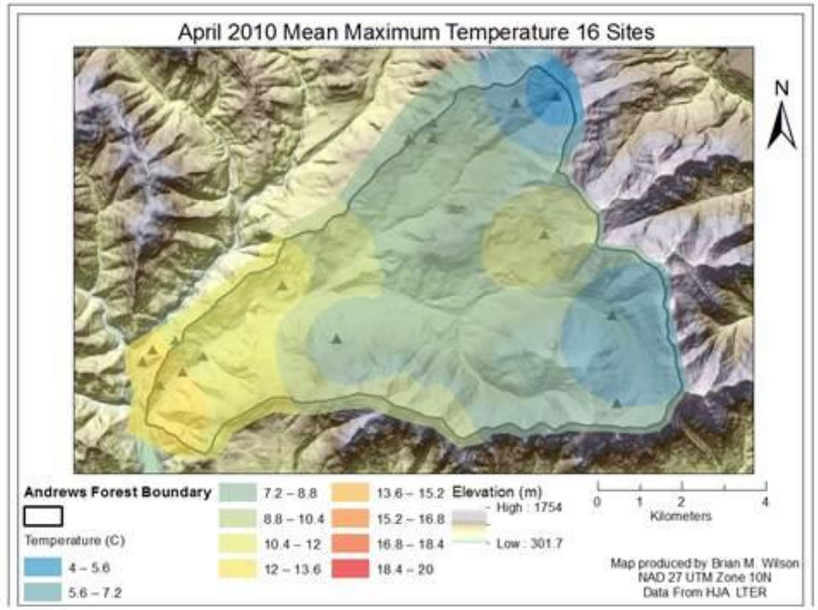
Maximum mean monthly temperature March 2010 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

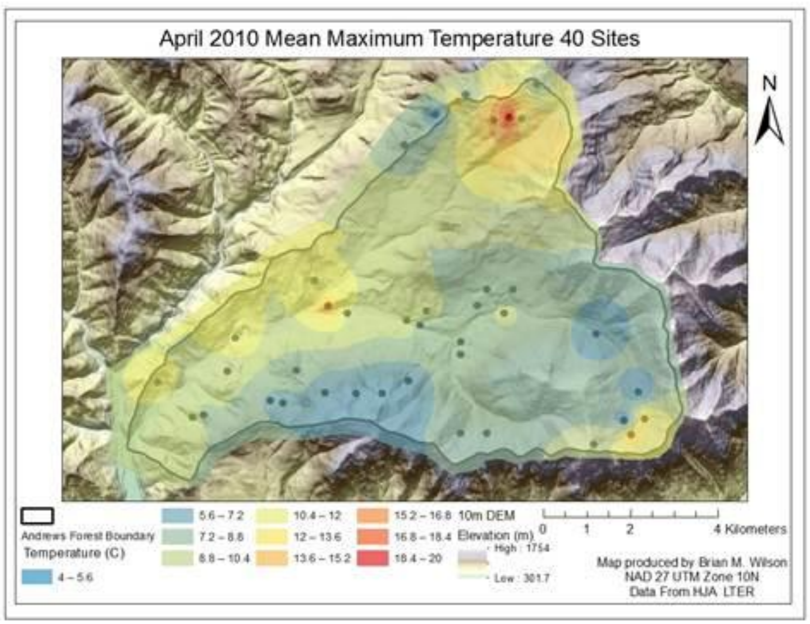


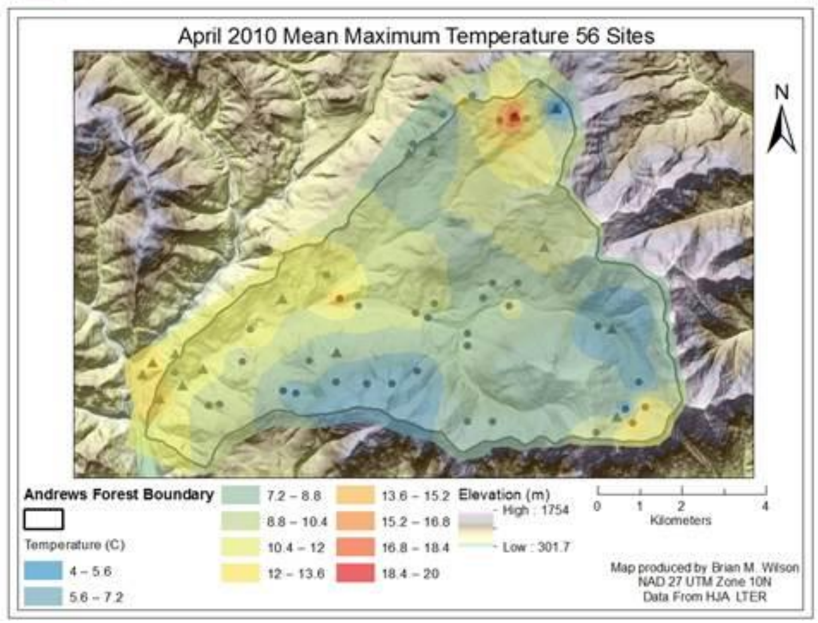


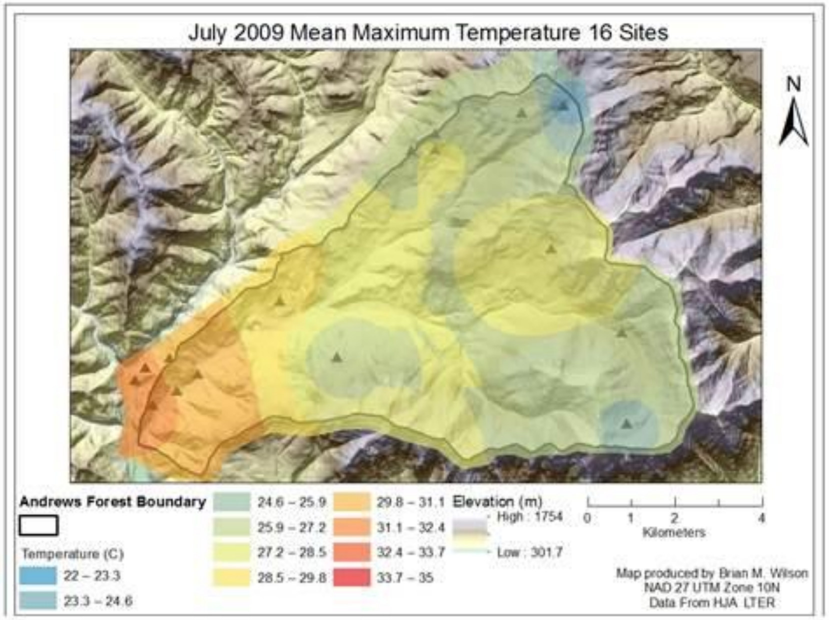


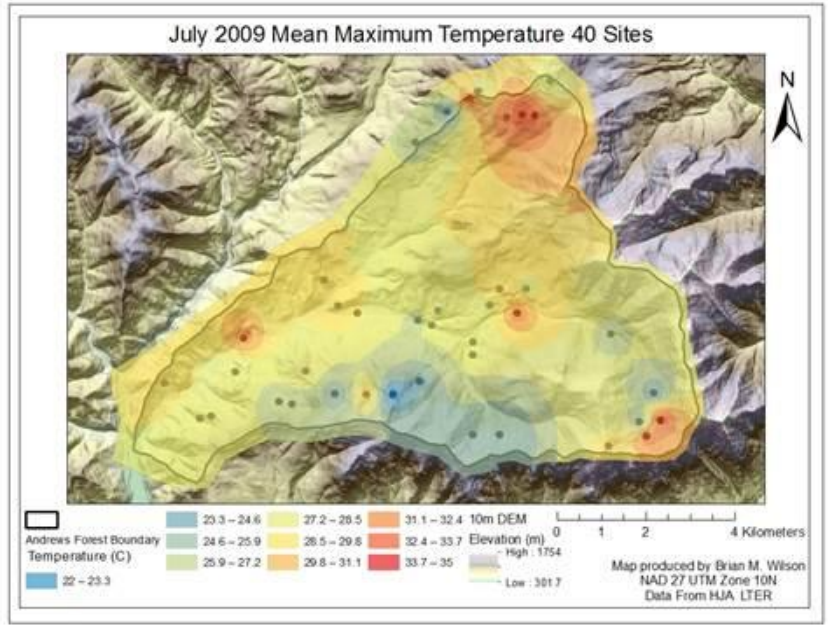
Maximum mean monthly temperature April 2010 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

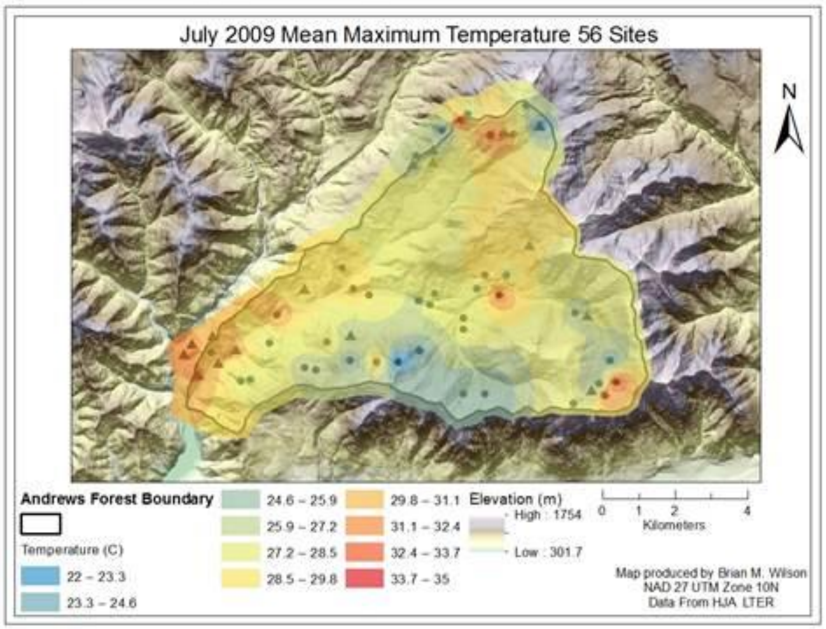




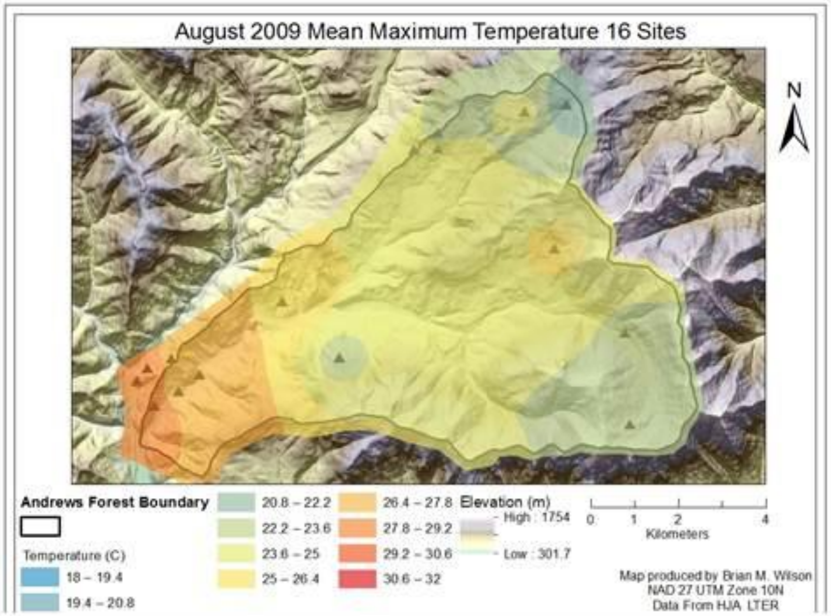


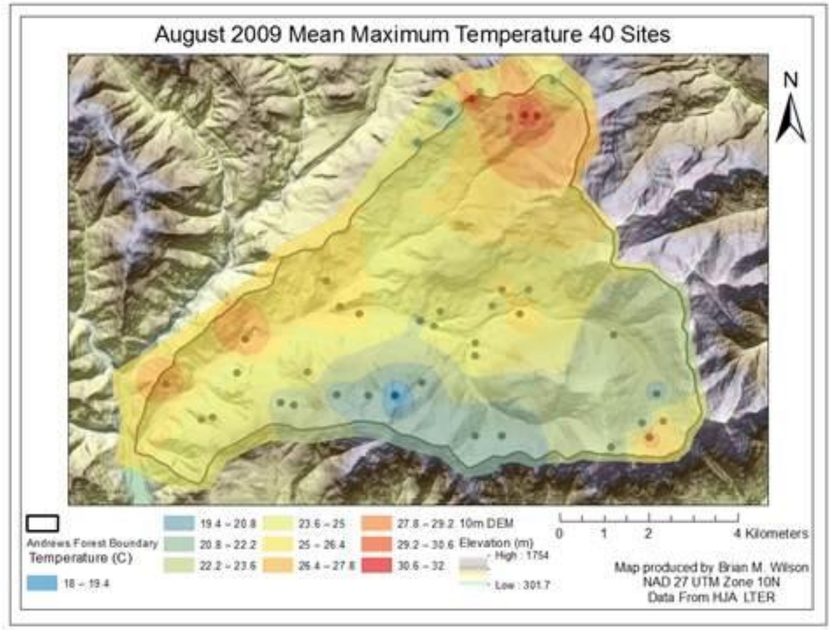


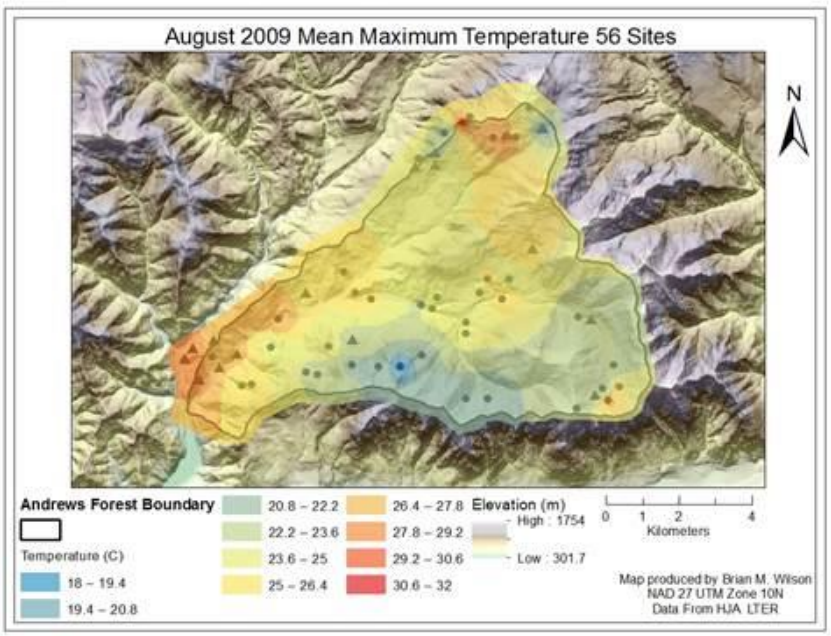




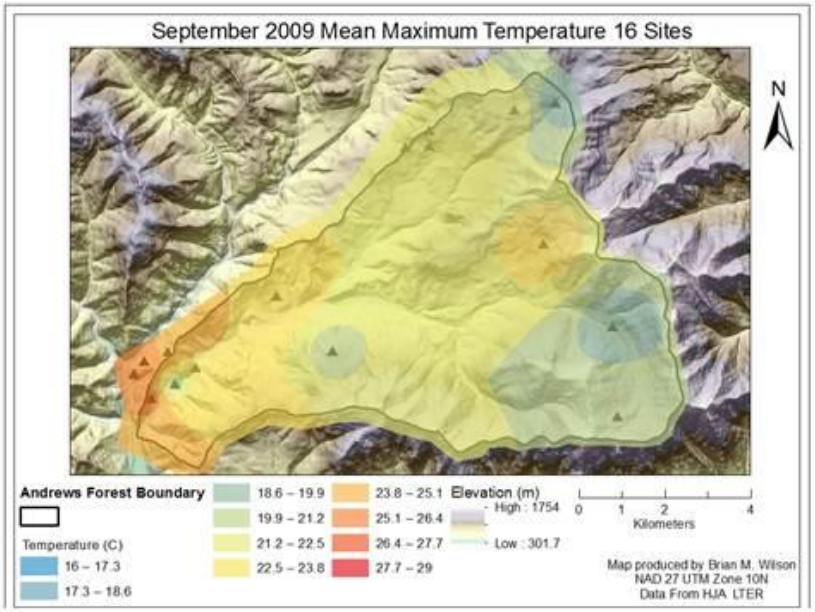
Maximum mean monthly temperature July 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

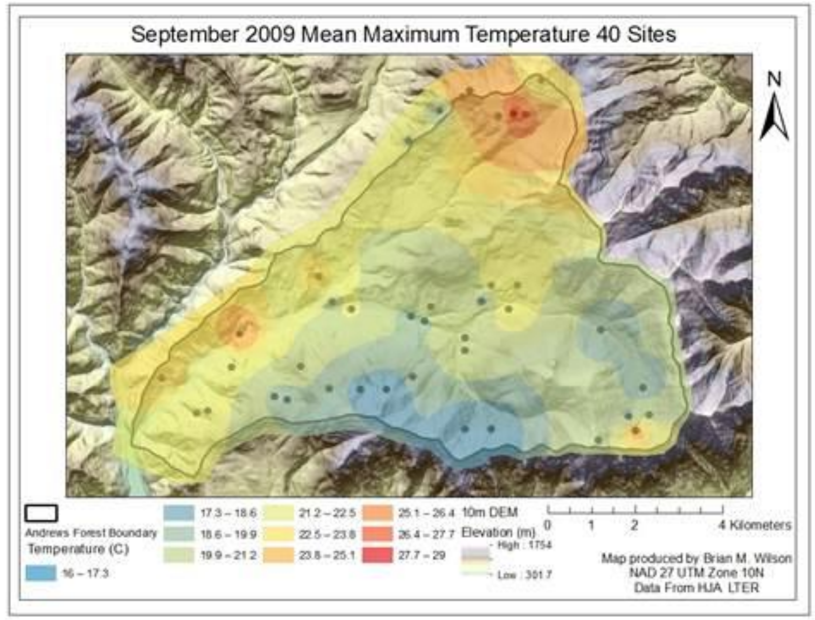


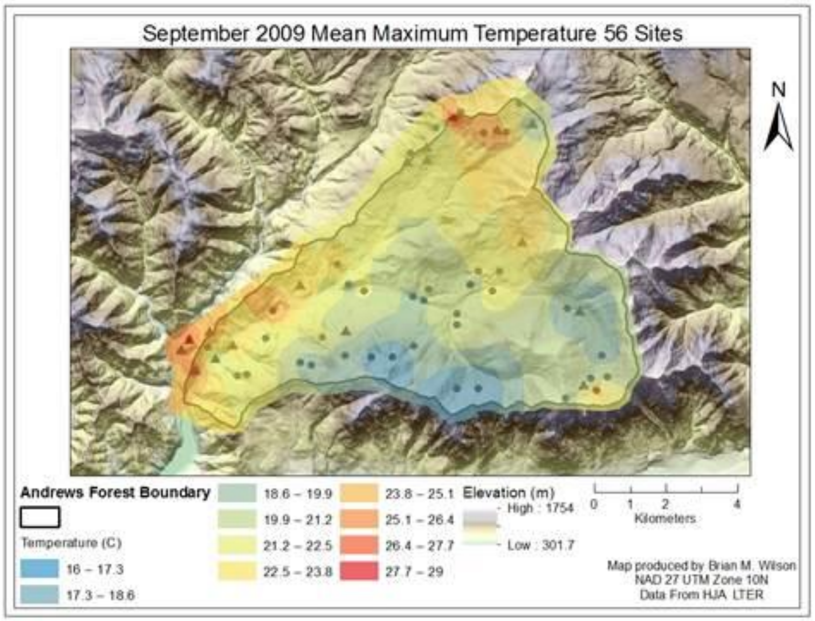




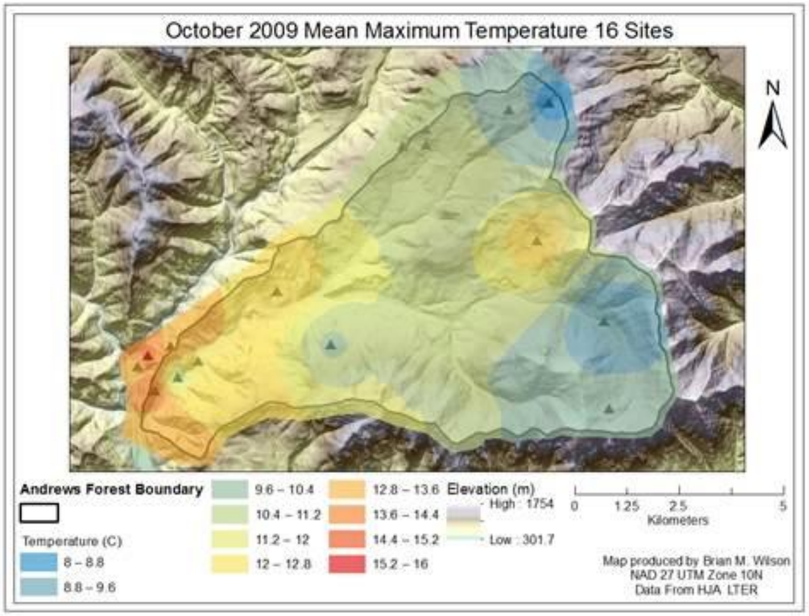
Maximum mean monthly temperature August 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

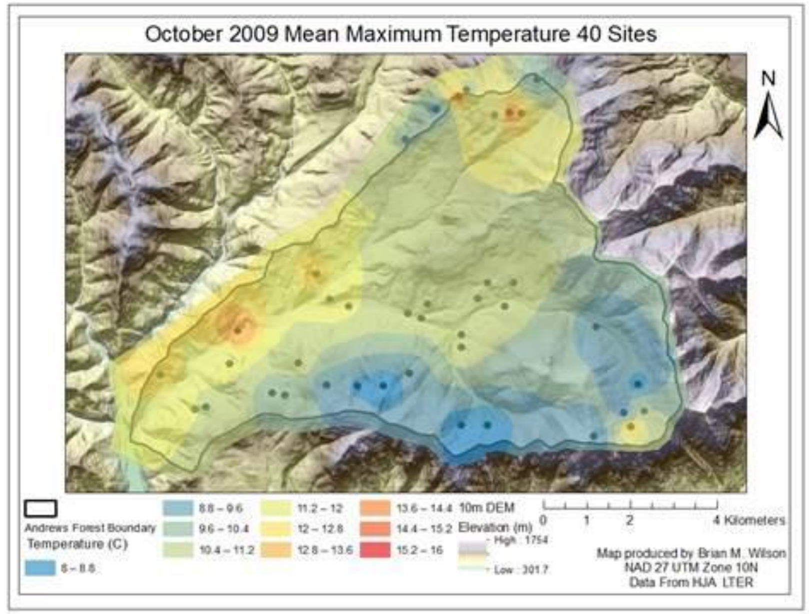


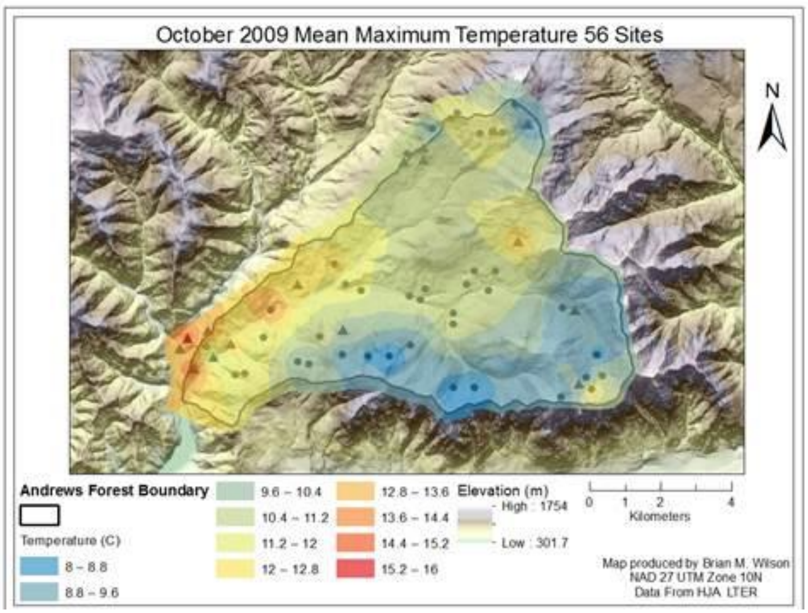




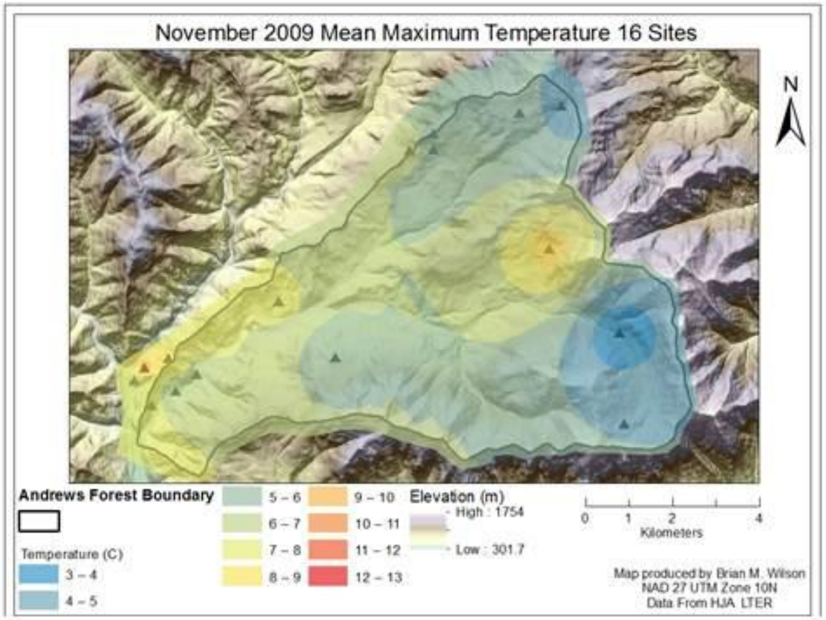
Maximum mean monthly temperature September 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

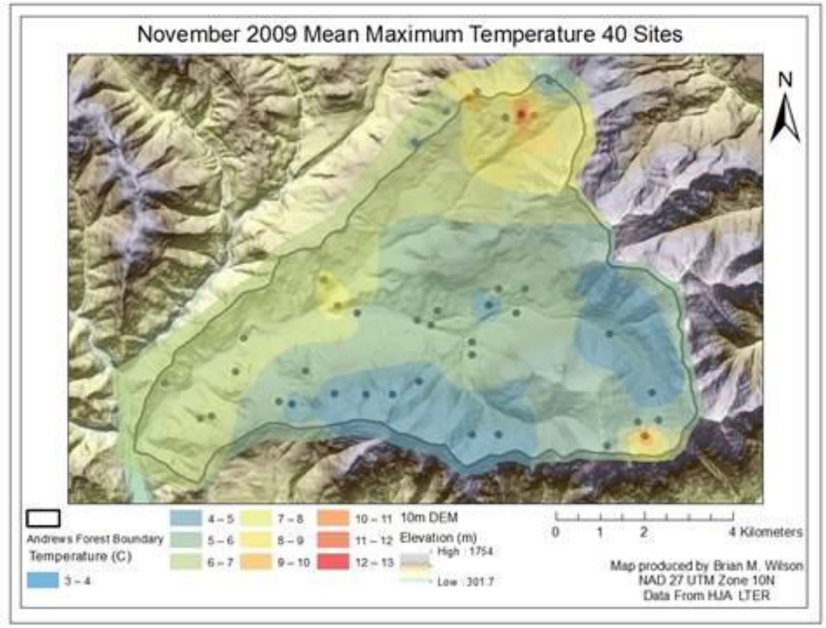


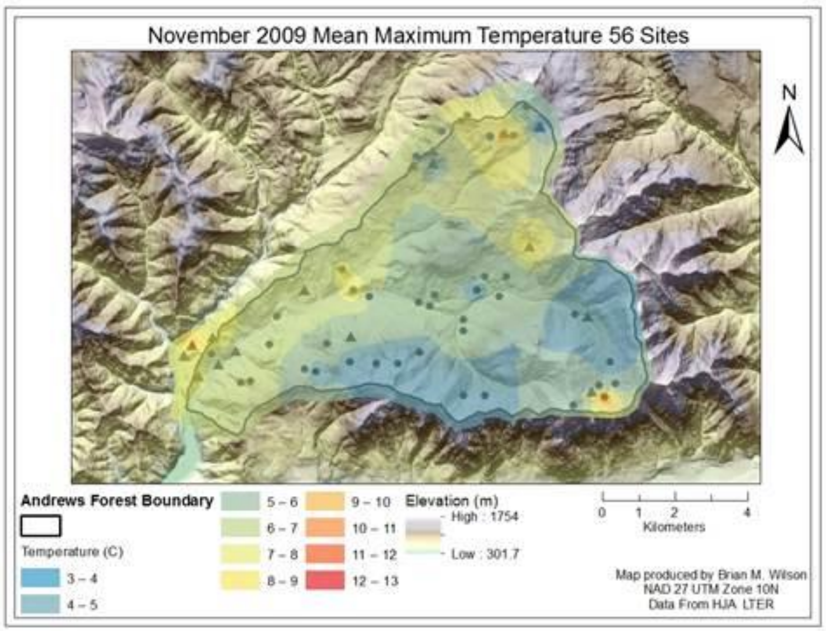




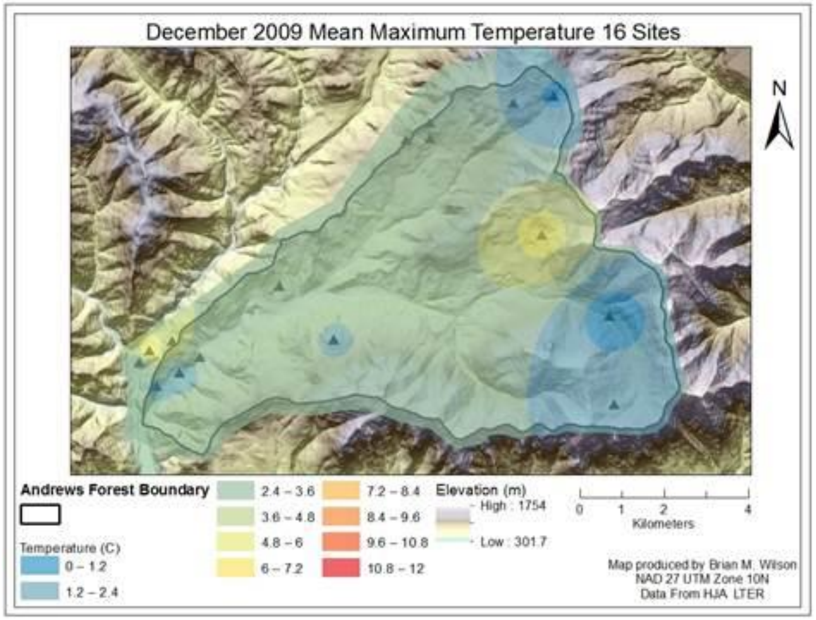
Maximum mean monthly temperature October 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

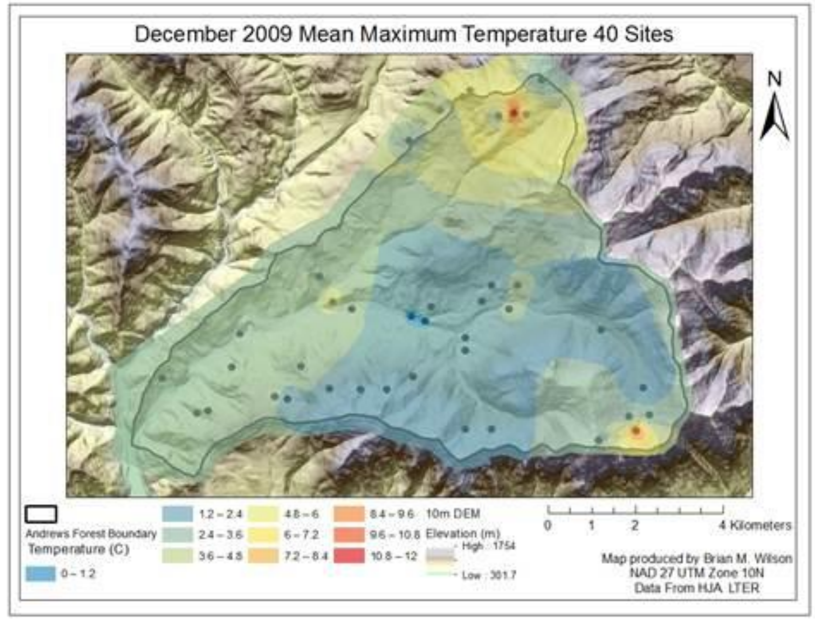


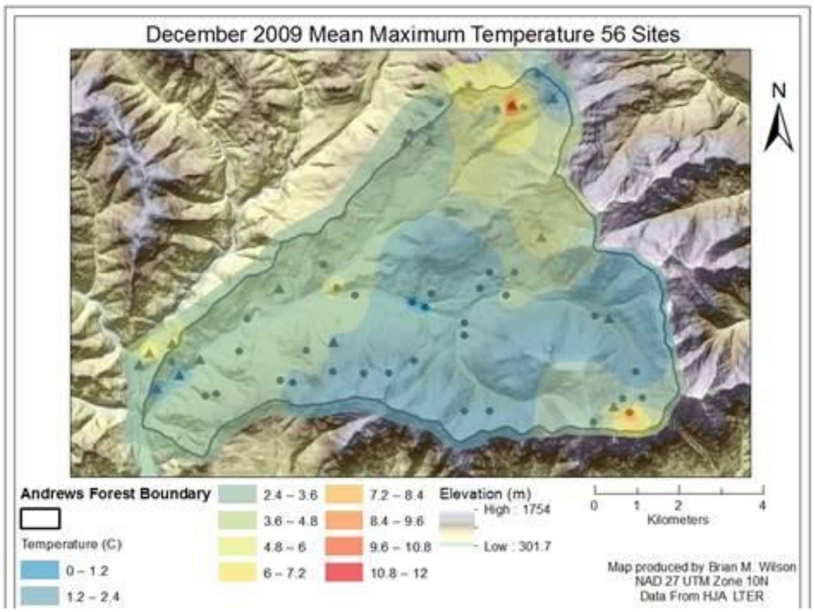




Maximum mean monthly temperature November 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

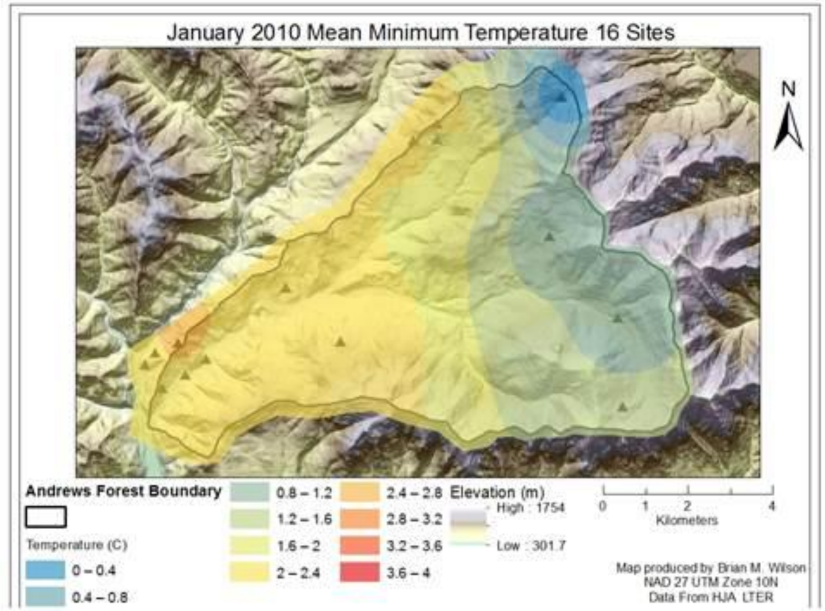


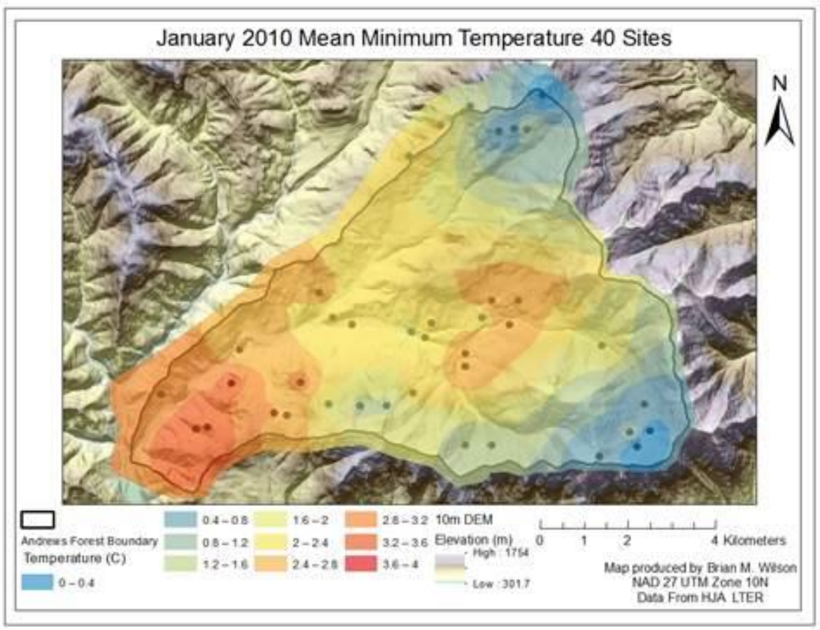


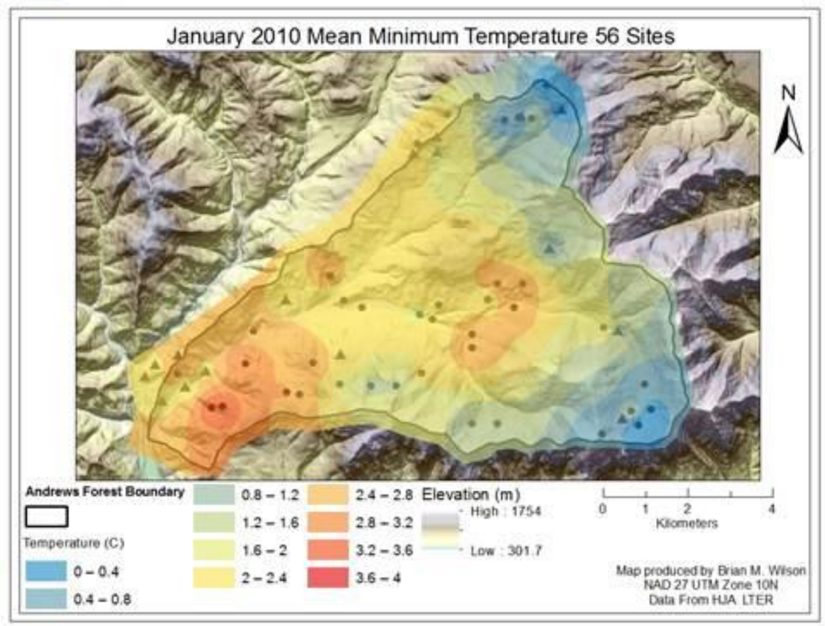


Maximum mean monthly temperature December 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

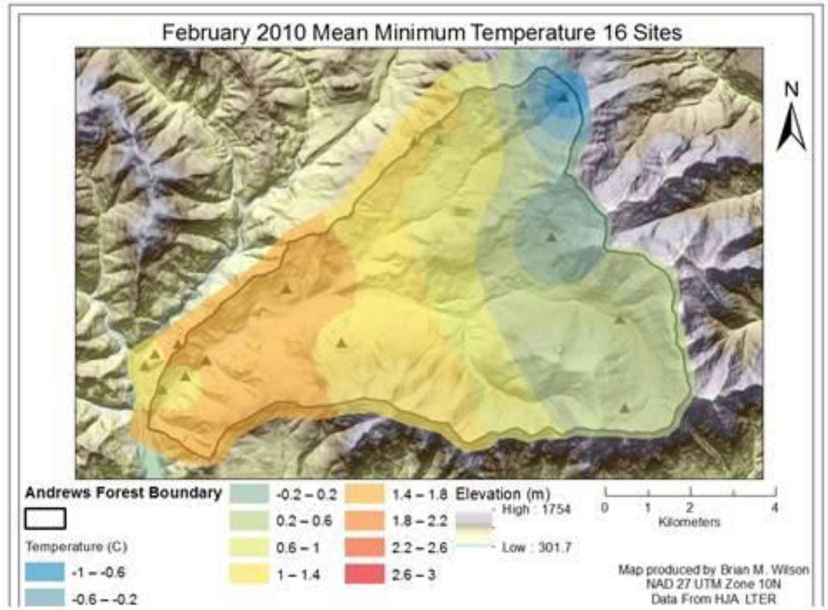
Minimum mean monthly temperature January 2010 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

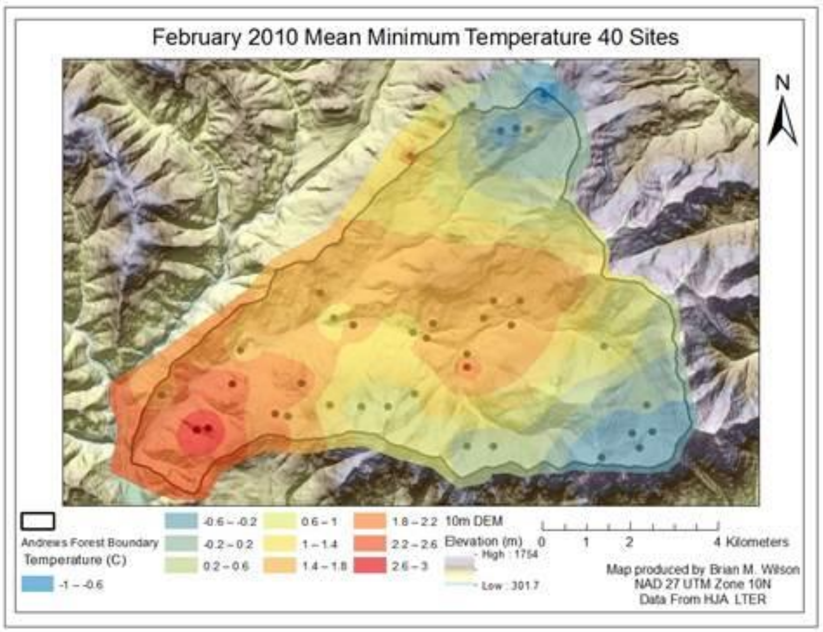


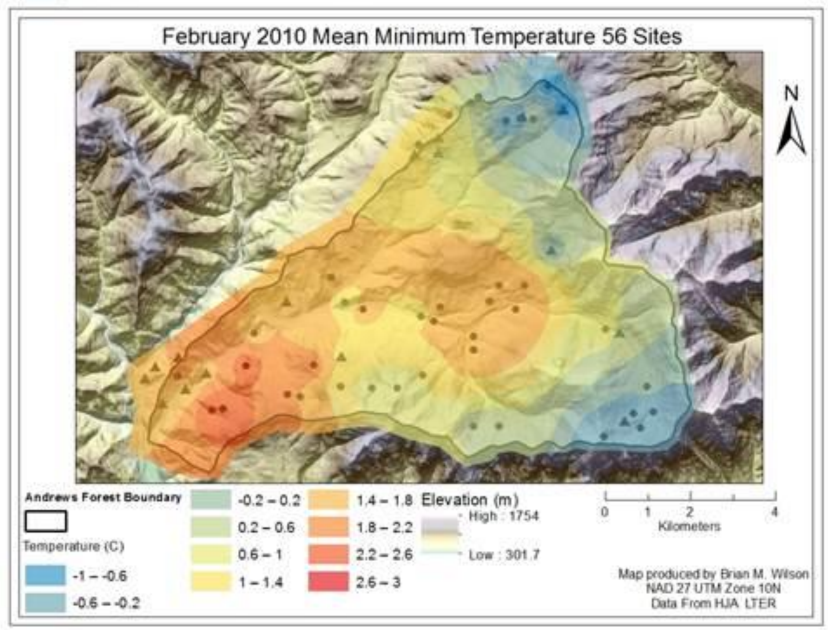




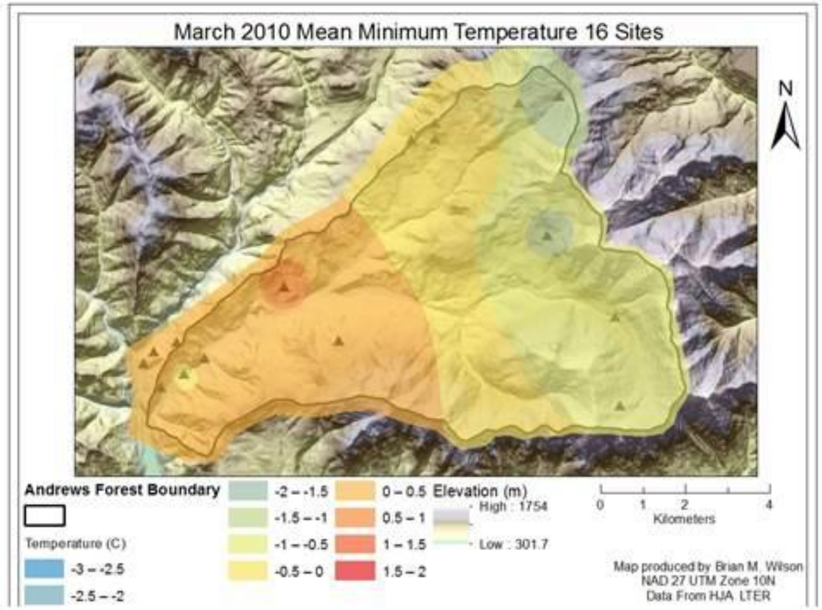
Minimum mean monthly temperature February 2010 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

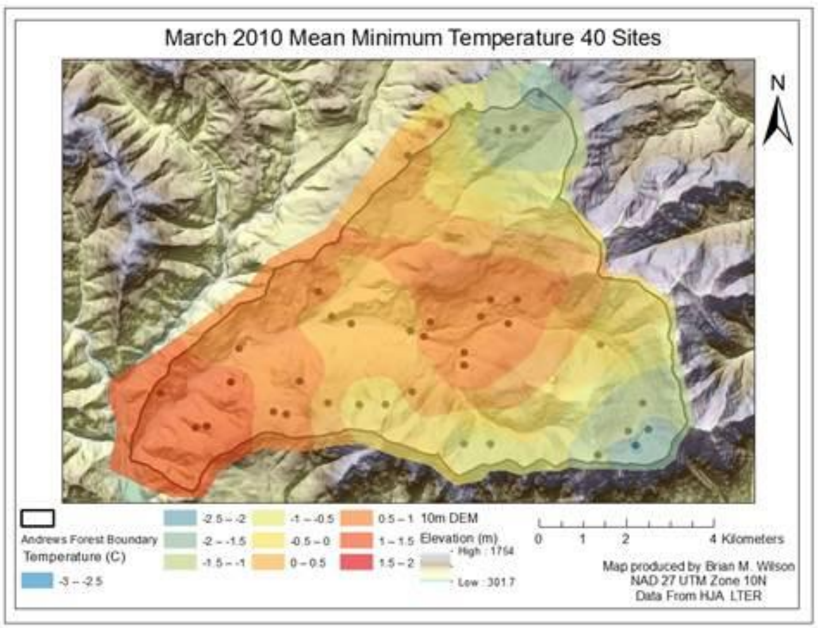


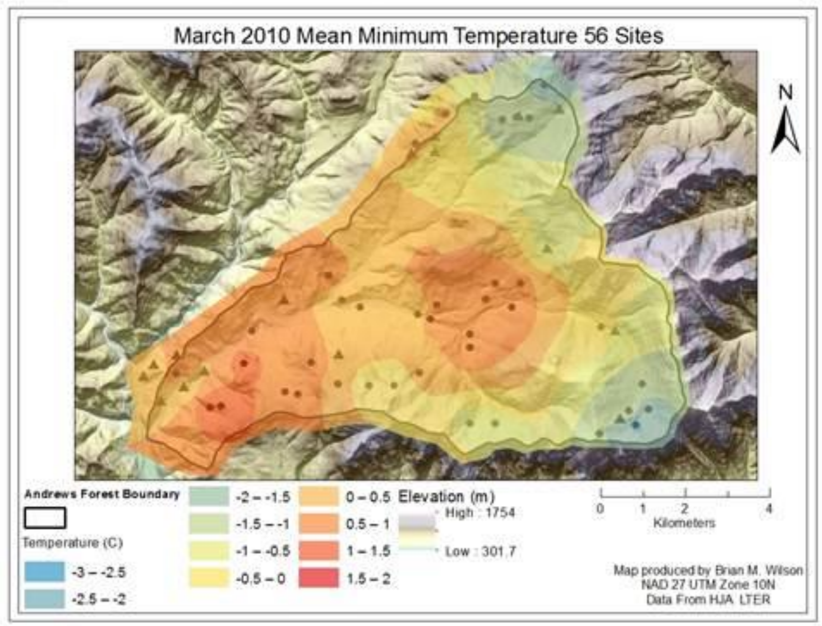




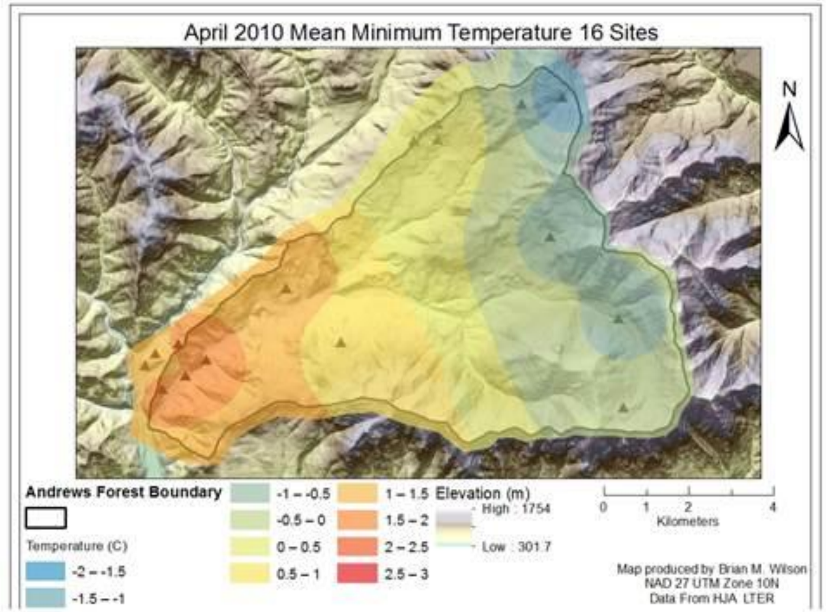
Minimum mean monthly temperature March 2010 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

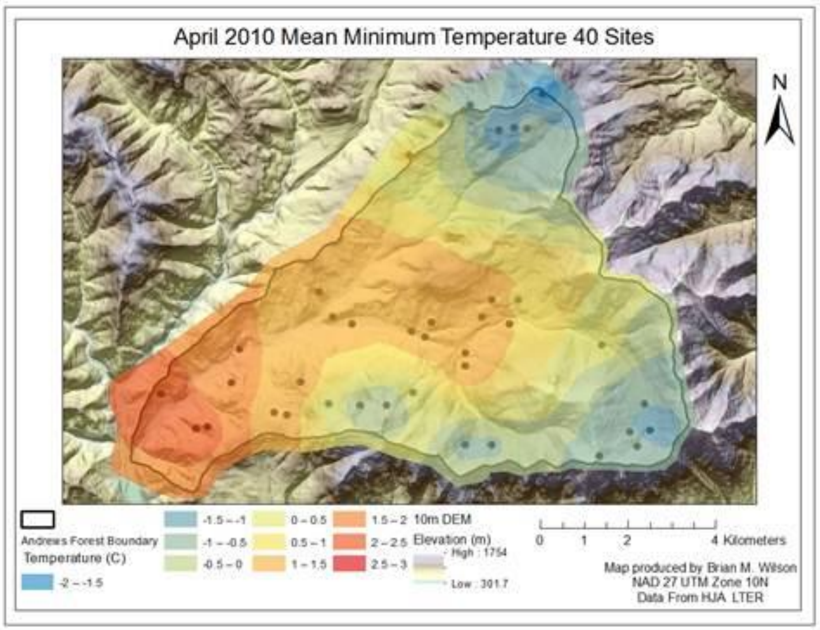


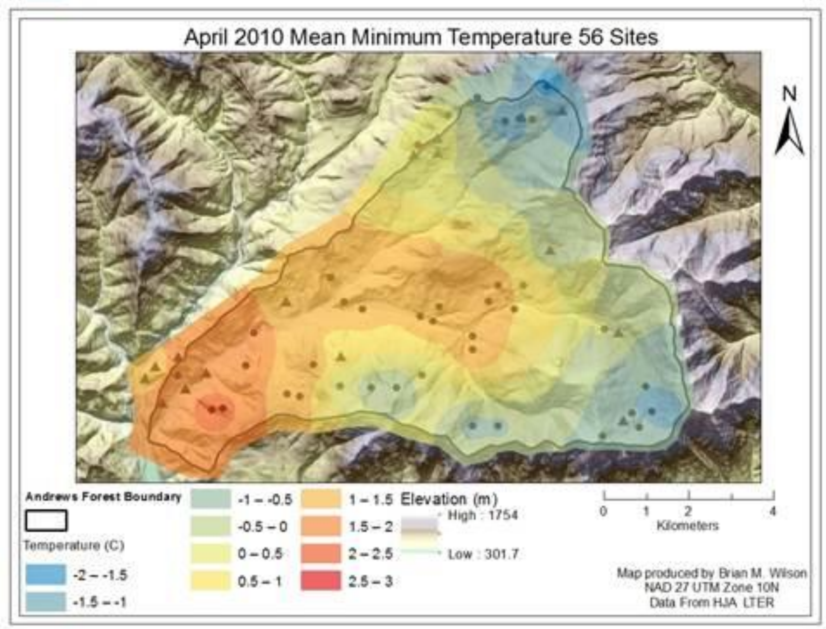


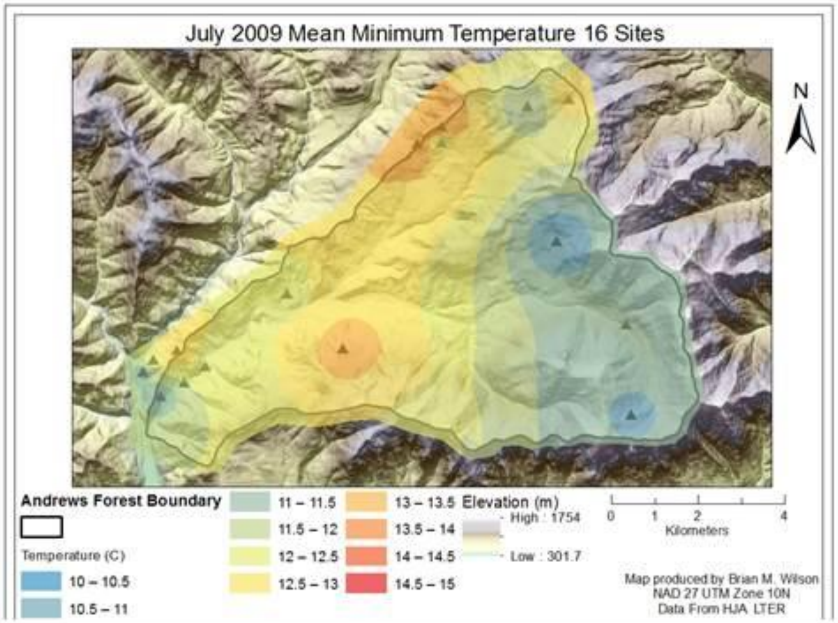


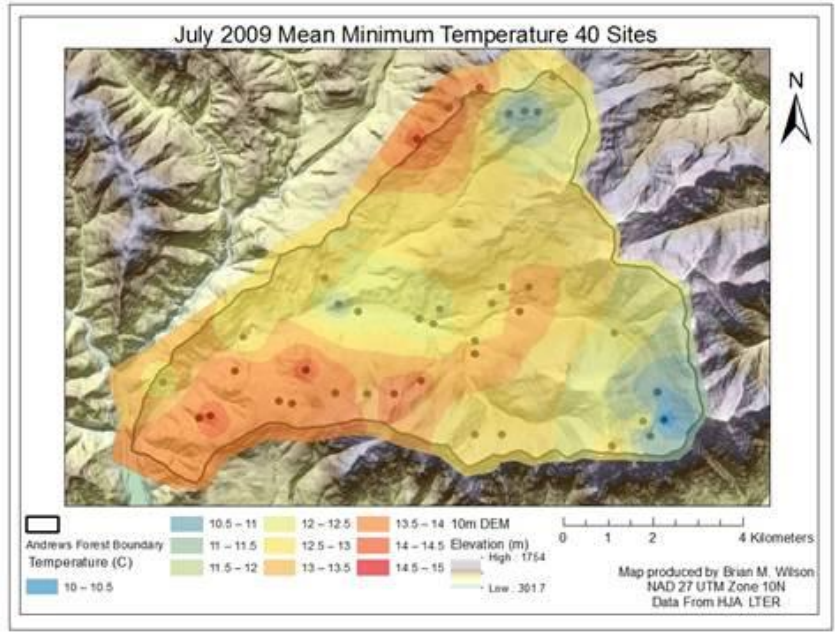
Minimum mean monthly temperature April 2010 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

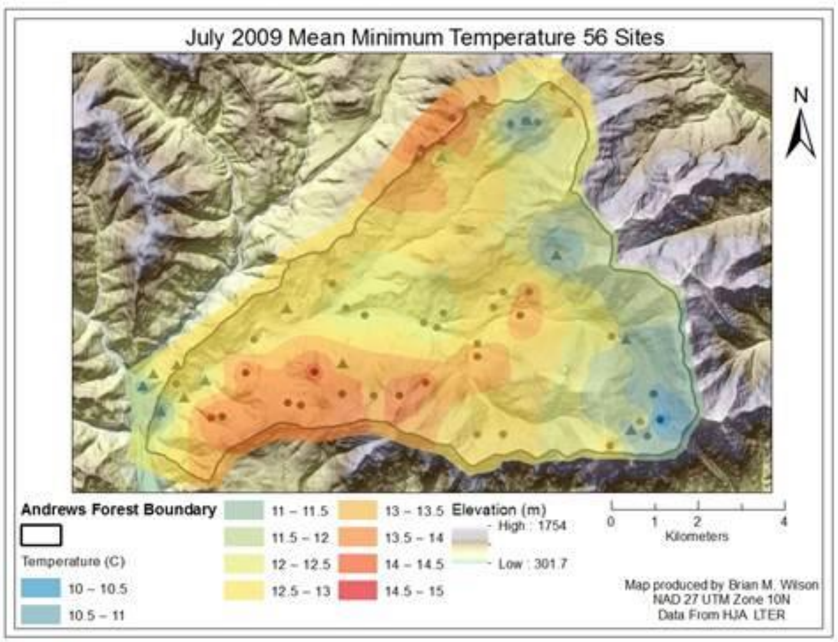




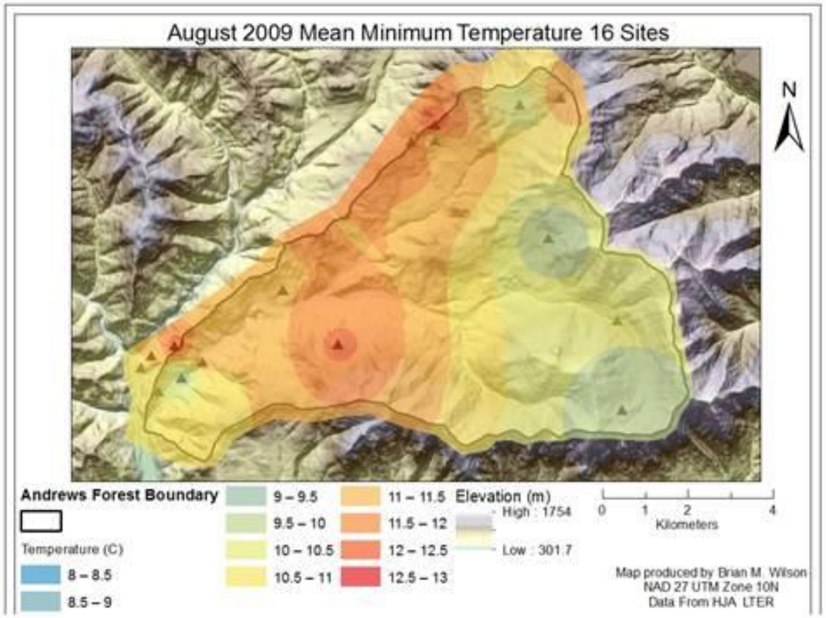


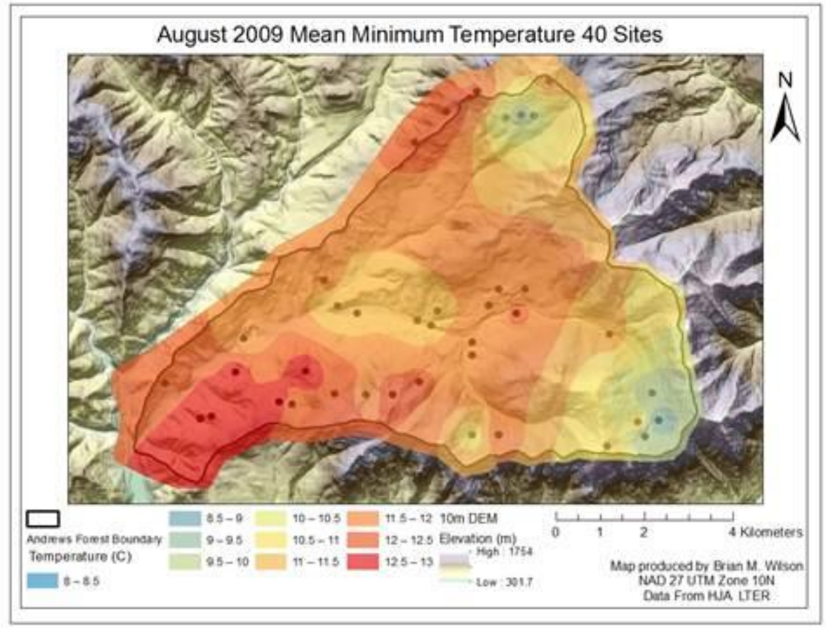


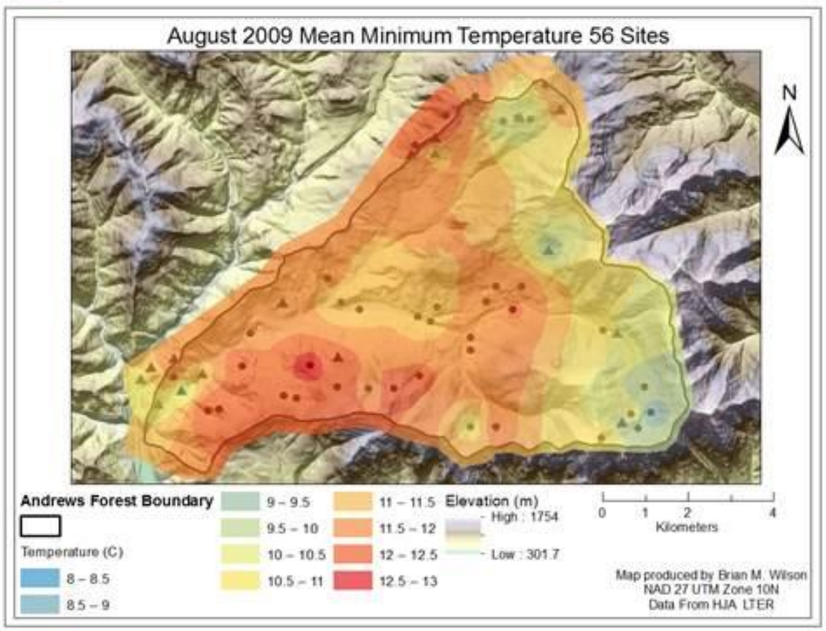




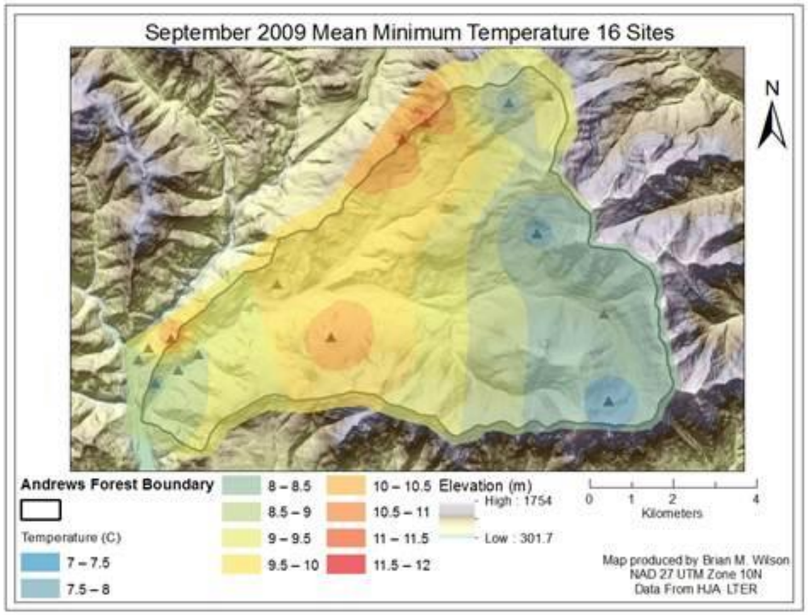
Minimum mean monthly temperature July 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

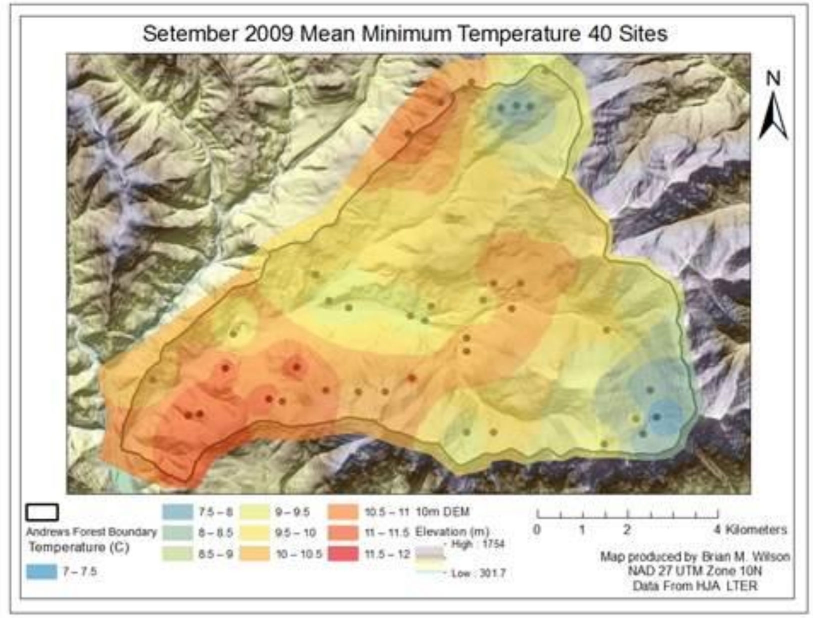


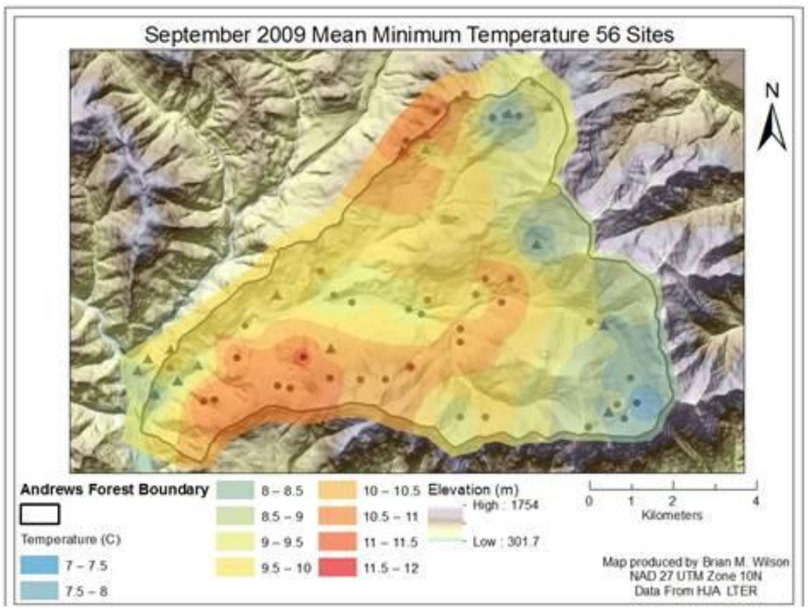




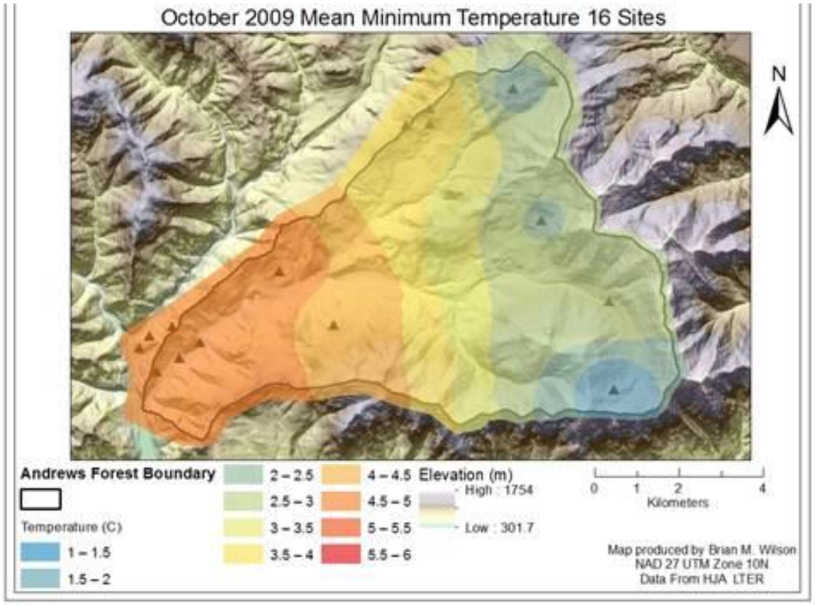
Minimum mean monthly temperature August 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

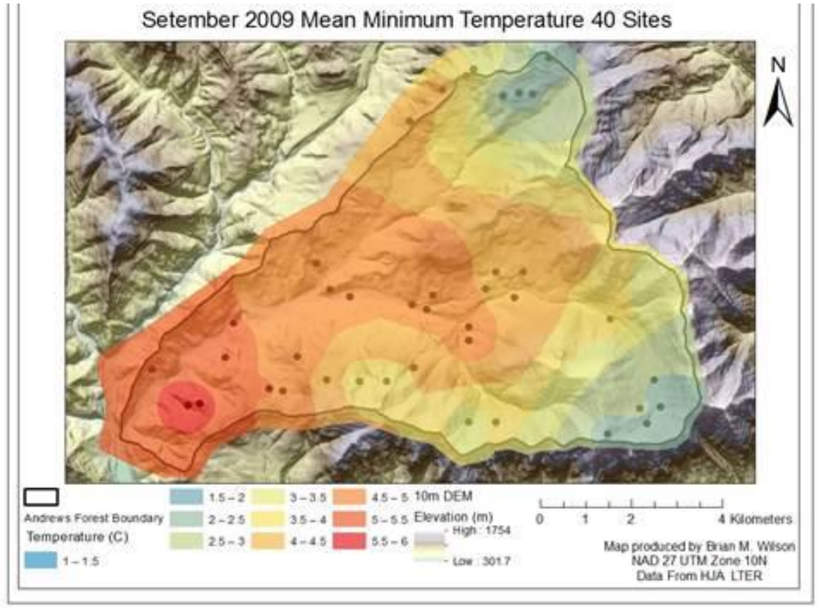


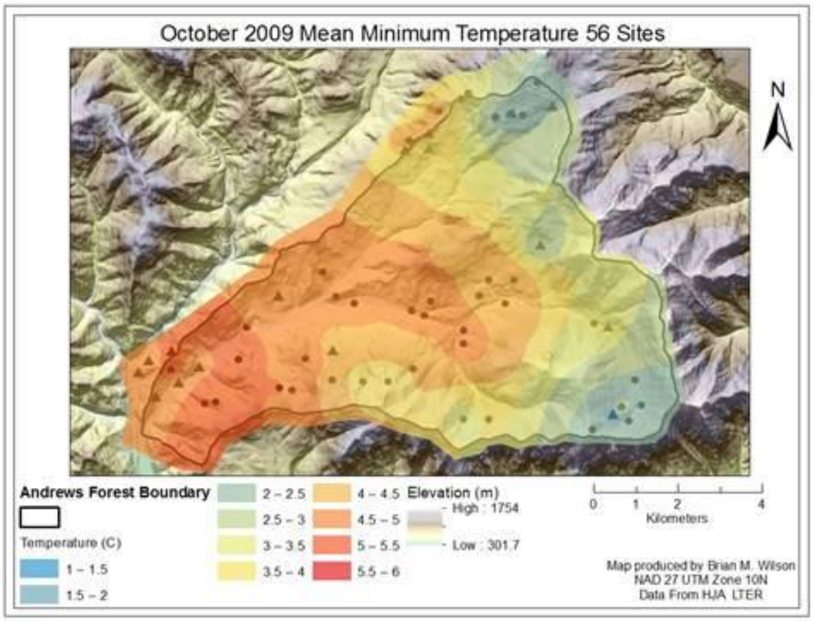




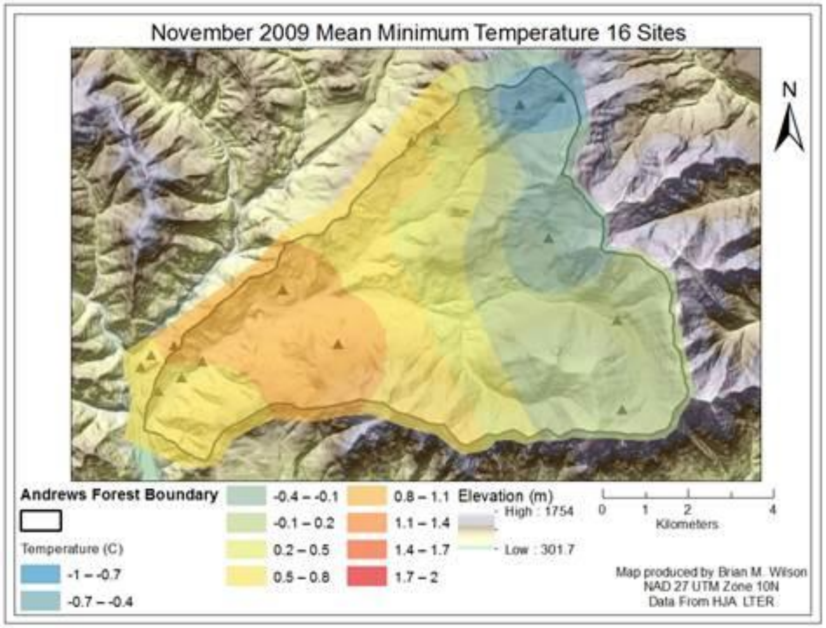
Minimum mean monthly temperature September 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

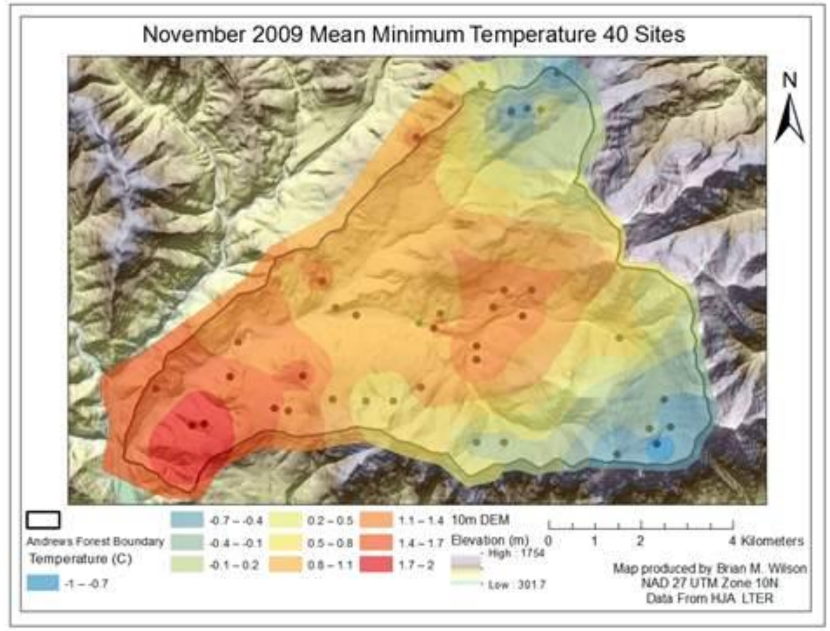


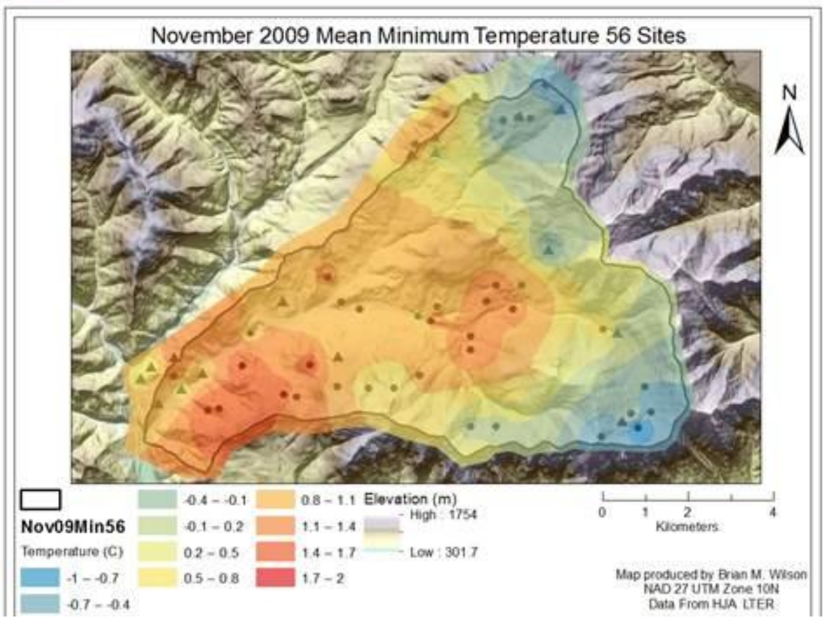




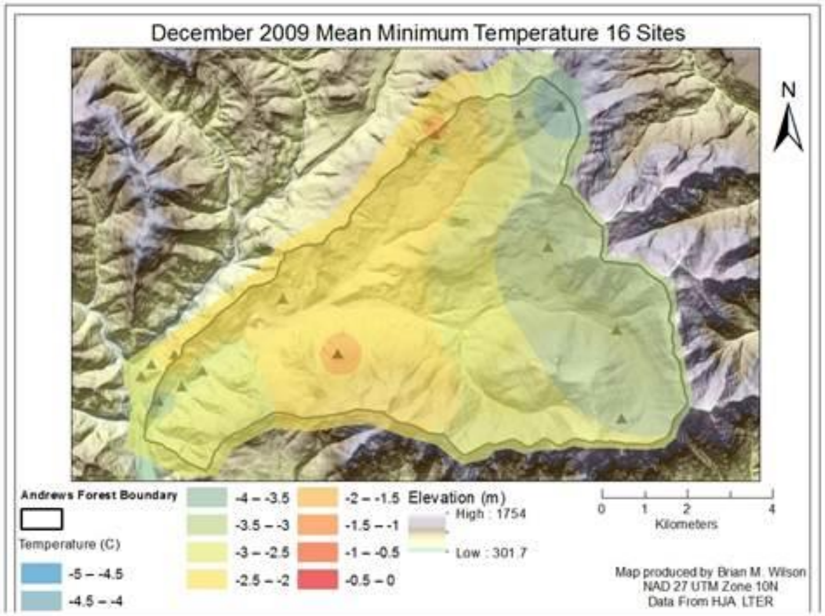
Minimum mean monthly temperature October 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

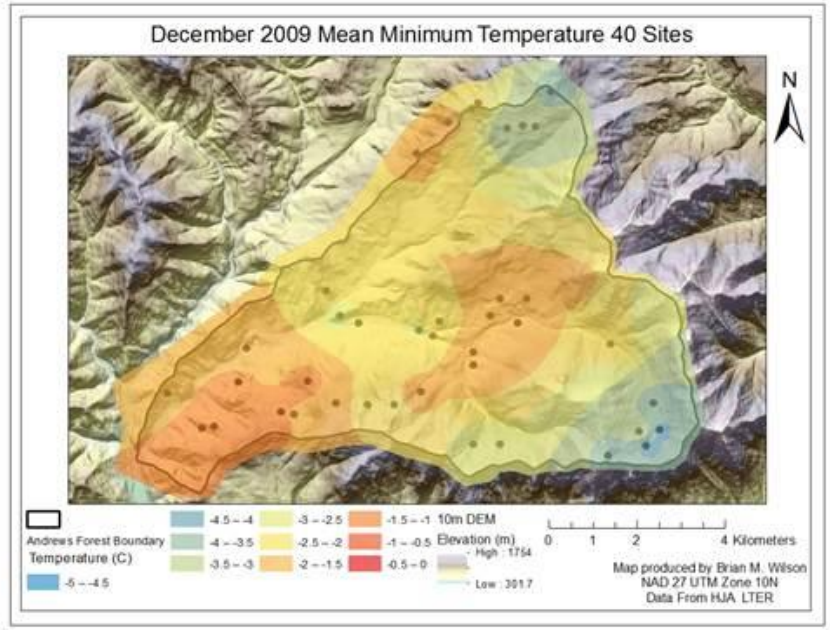


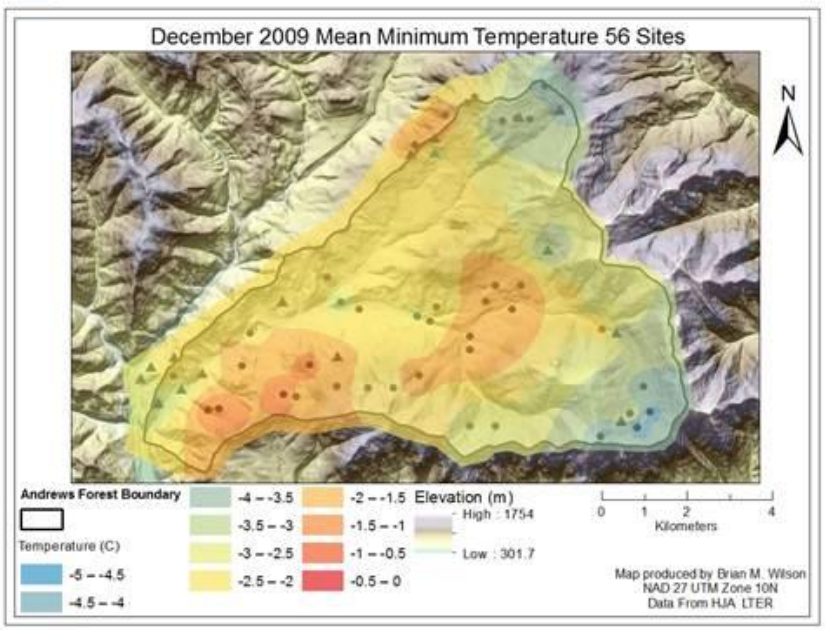




Minimum mean monthly temperature November 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.



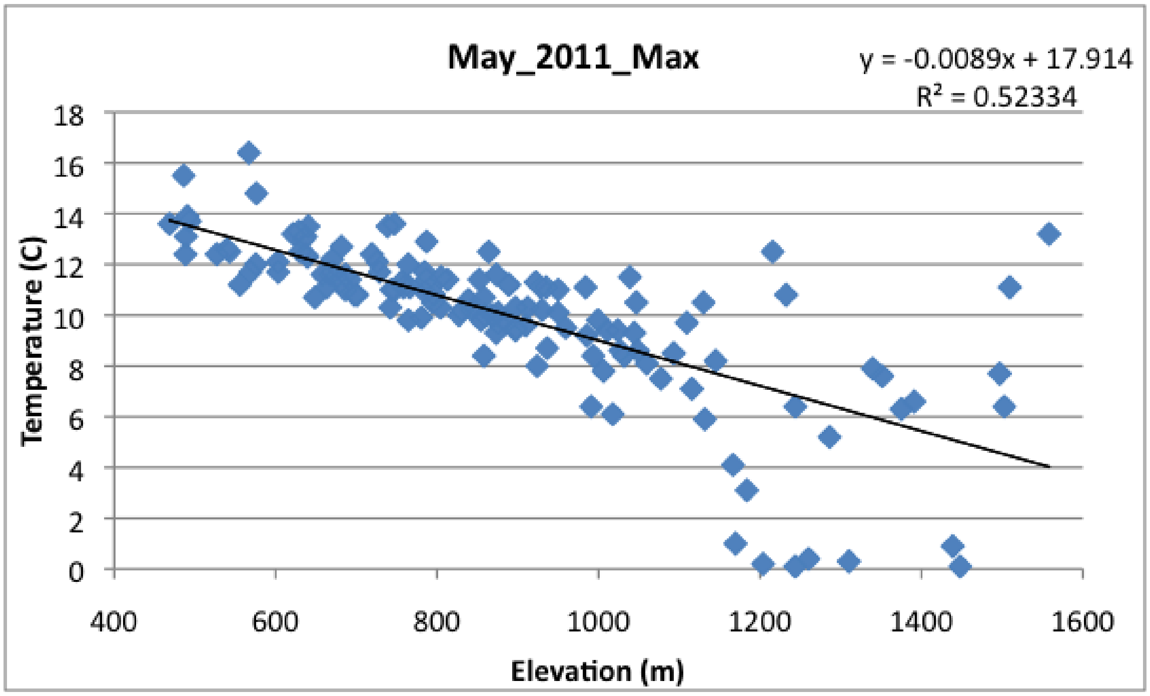




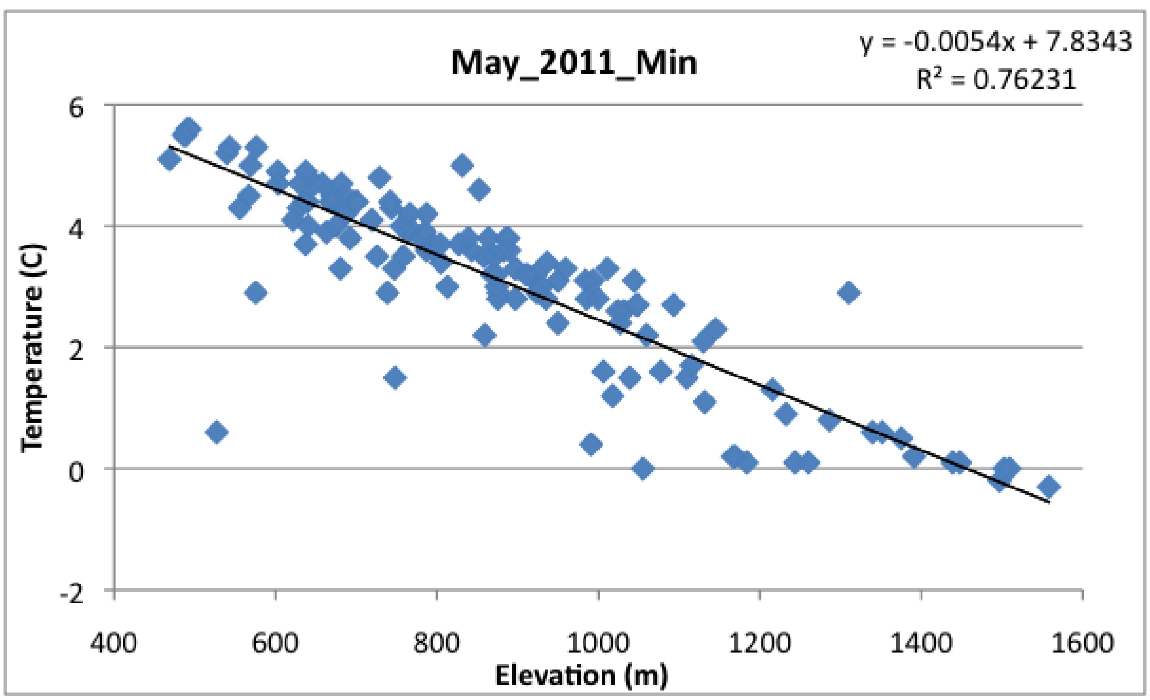
Minimum mean monthly temperature December 2009 using 16 (Benchmark and Reference stand sites), 40 (BIRD sites), and 56 (combination of both BIRD, Benchmark, and Reference Stand sites) sensor sites.

Figure 15. The relationship between temperature and elevation for minimum and maximum temperature for 166 BIRD Sites at the HJ Andrews Experimental Forest, by month, May 2011 to June 2012. (a, b) May 2011, (c, d), June 2011, ...

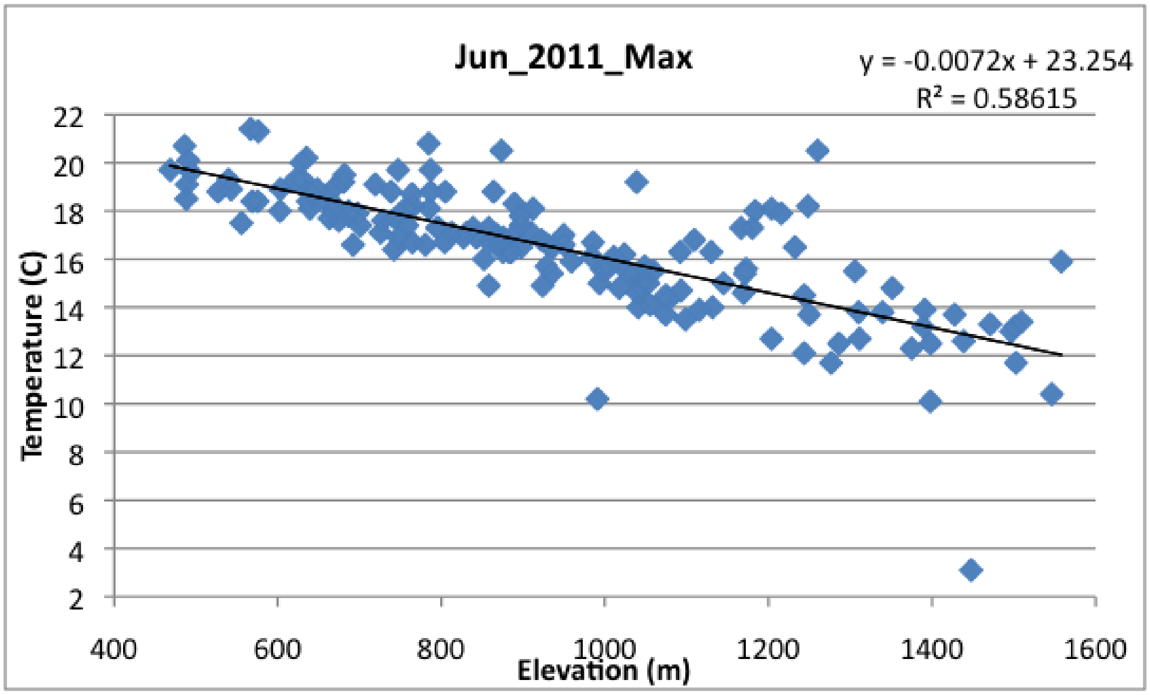
(a) May 2011, maximum T, lapse rate dominated below 1100 m, topographic shading above 1100 m. Lapse rate (10 °C), topographic shading (10-14 °C) (affected by snow?)



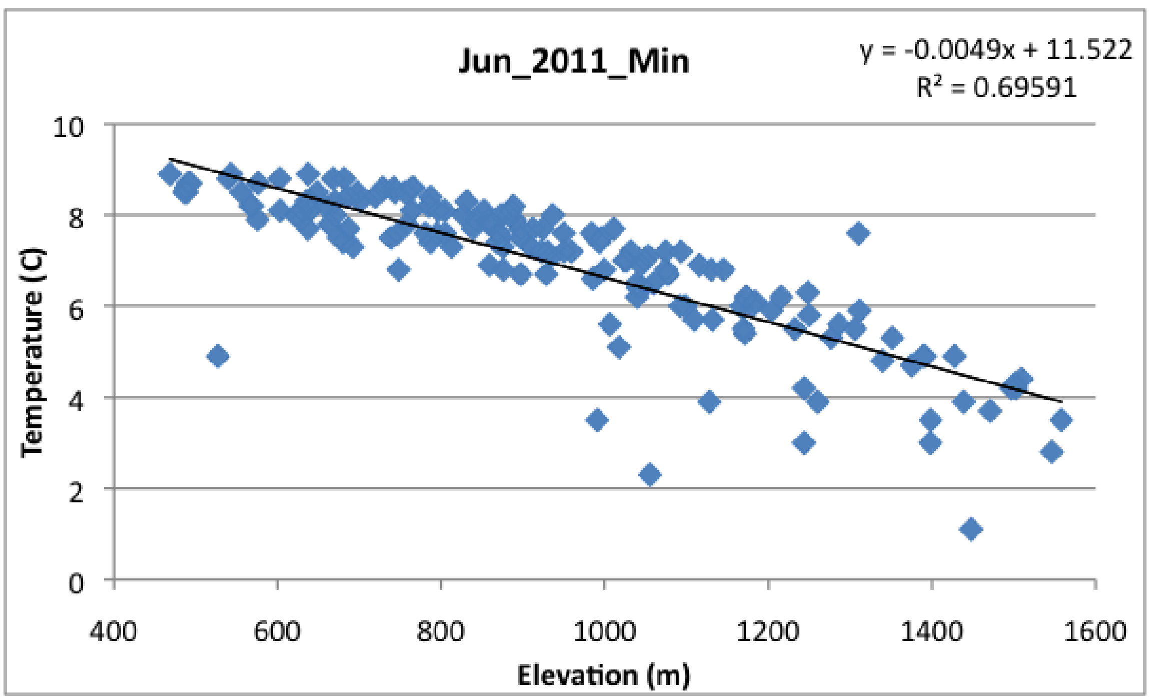
(b) May 2011 minimum T, lapse rate-dominated (5 °C).



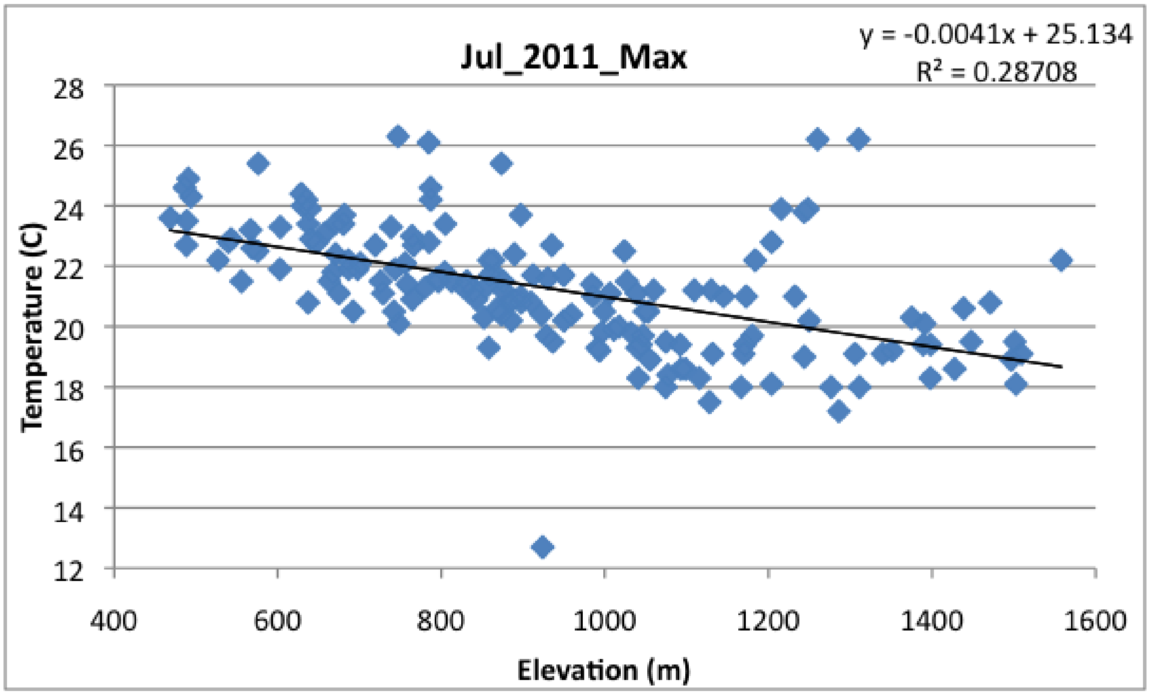
(c) June 2011 maximum T, lapse rate-dominated (8 °C).



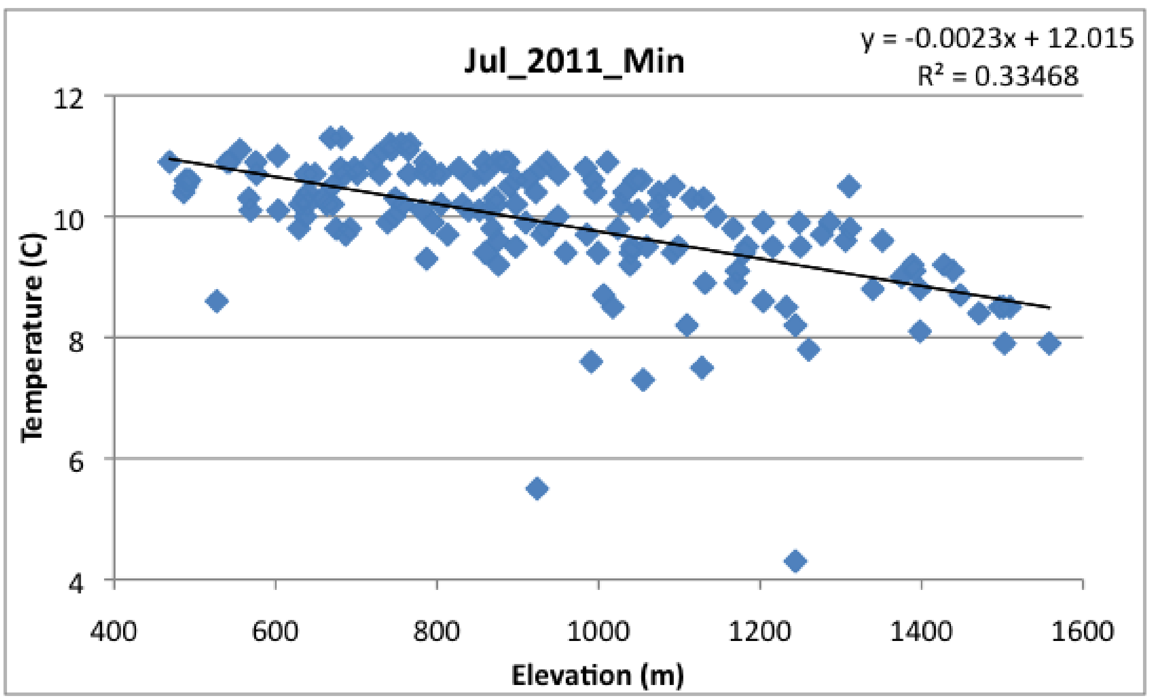
(d) June 2011 minimum T, lapse rate-dominated (5 °C).



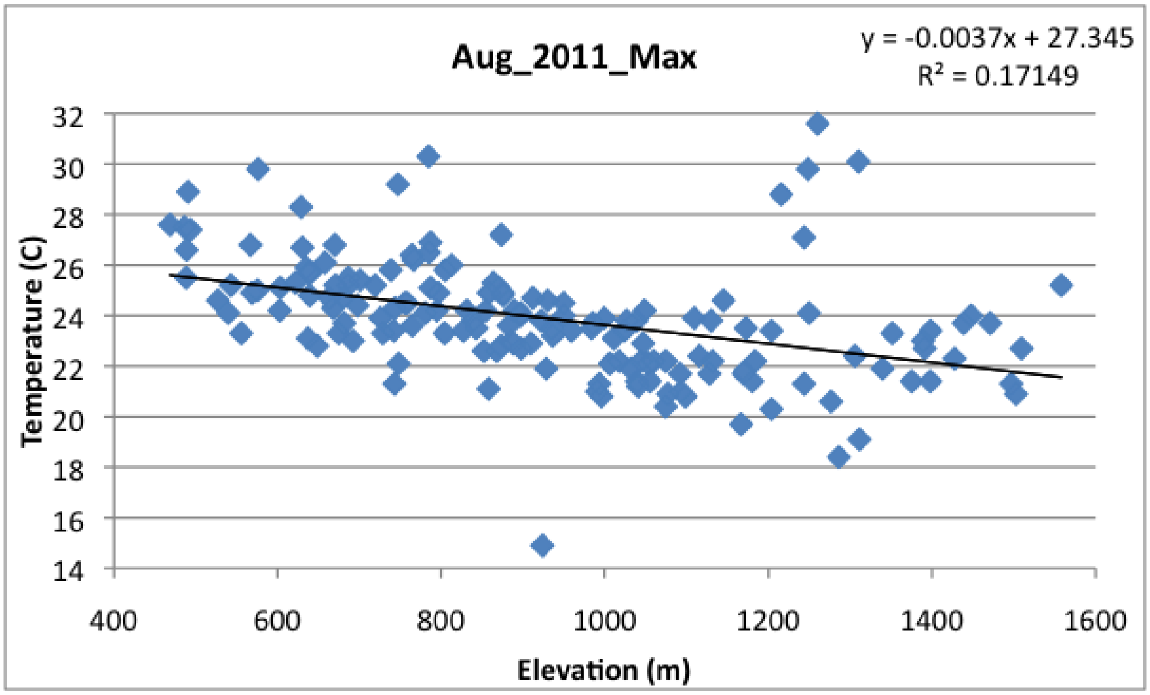
(e) July 2011 maximum T, lapse rate (4 °C) and topographic shading (8 °C)-dominated.



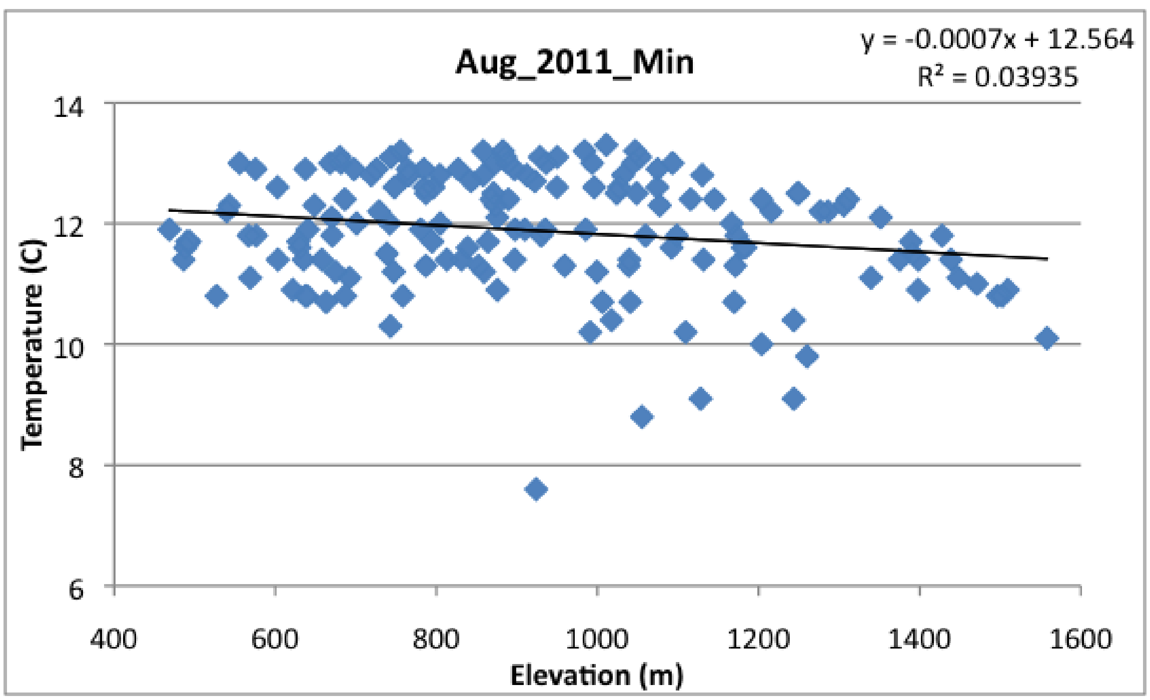
(f) July 2011 minimum T, lapse rate (2 °C) and cold air pooling (400-1000 m)-dominated.



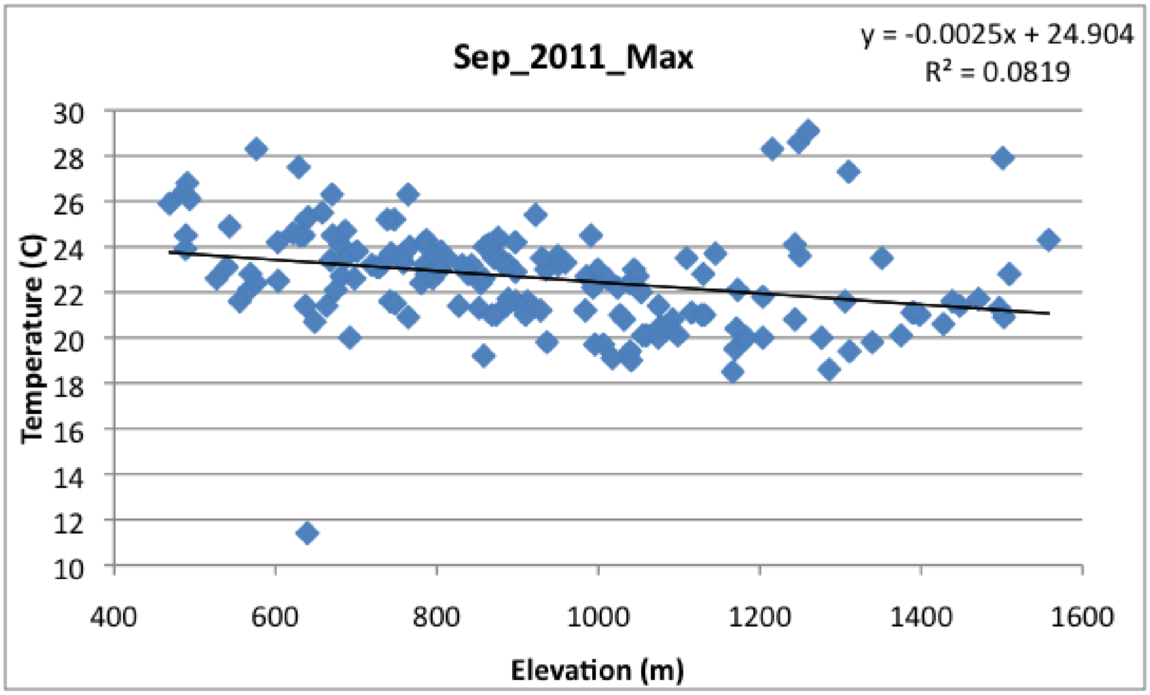
(g) August 2011 maximum T, lapse rate (4 °C)- and topographic shading (14 °C) dominated.



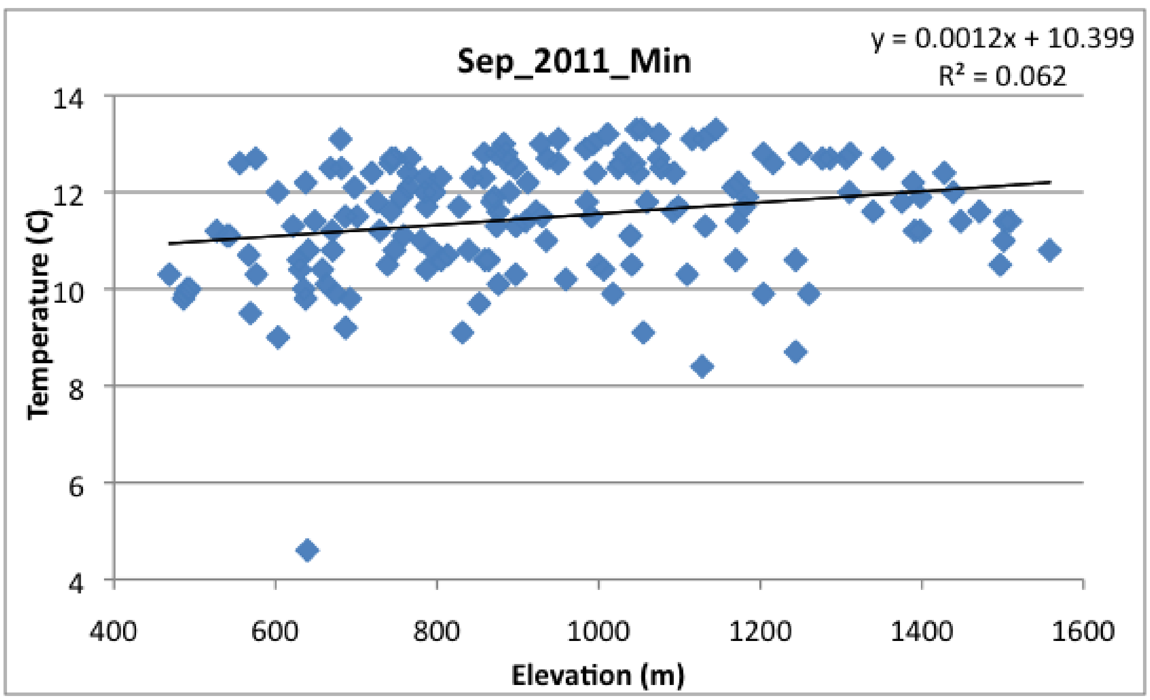
(h) August 2011 minimum T, cold air pooling (400-1000 m) dominated.



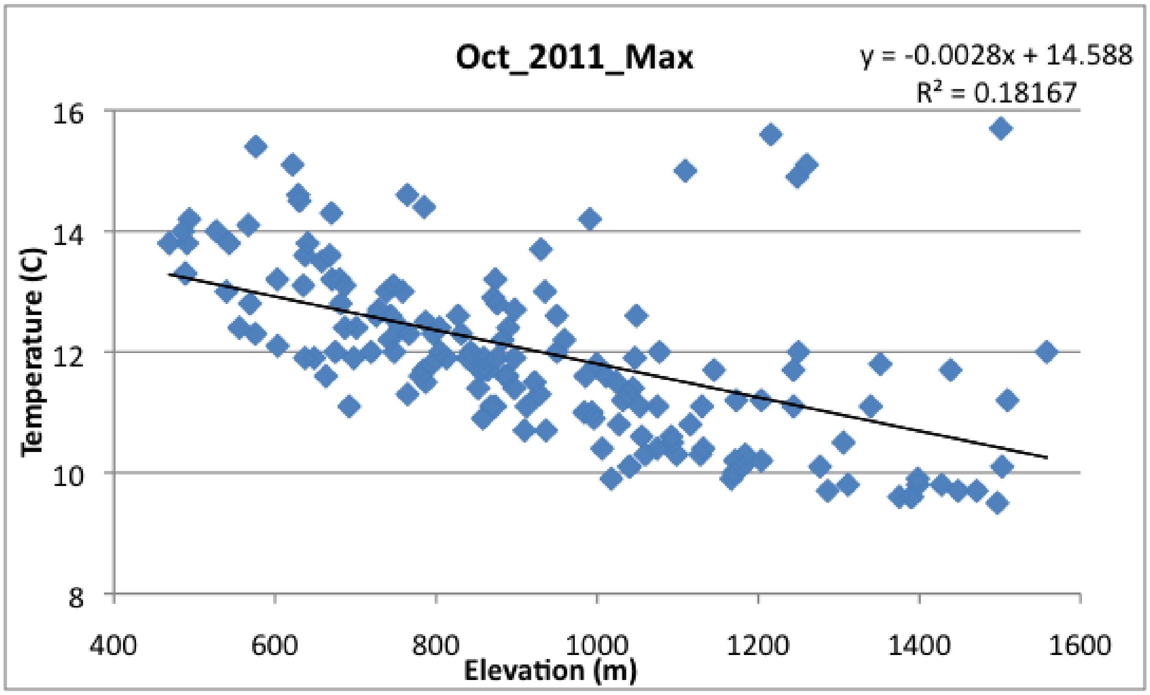
(i) September 2011 maximum T, topographic shading (12 °C) -dominated.



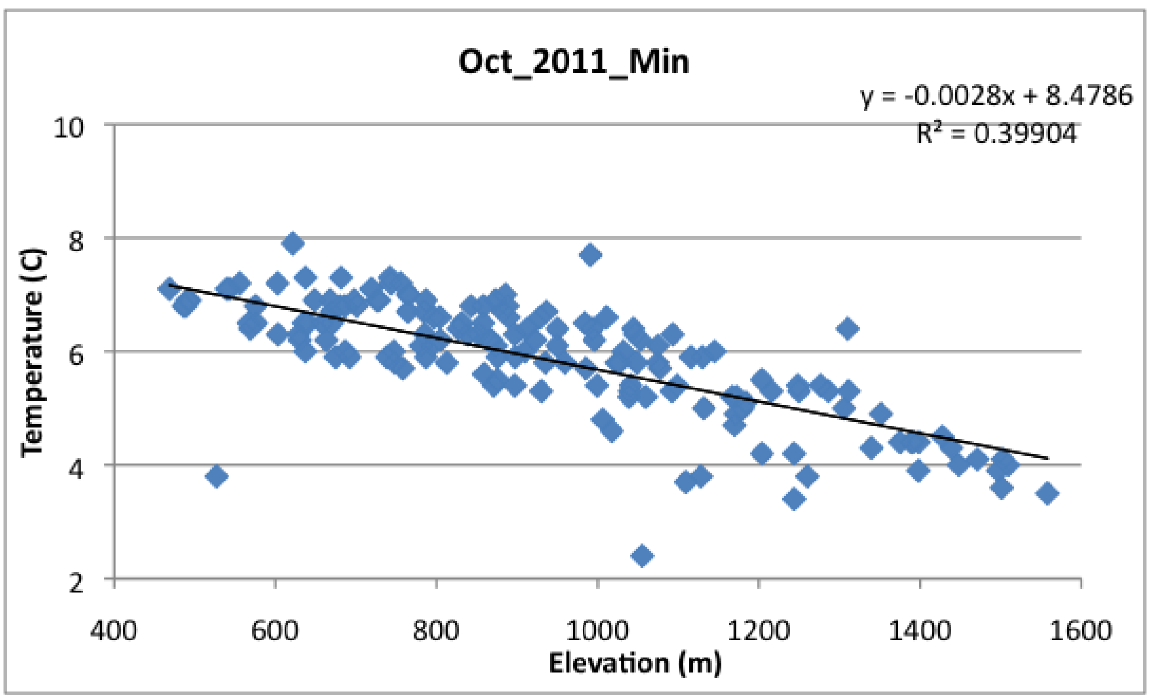
(j) September 2011 minimum T, cold air pooling (3 °C, 400-1000 m)-dominated.



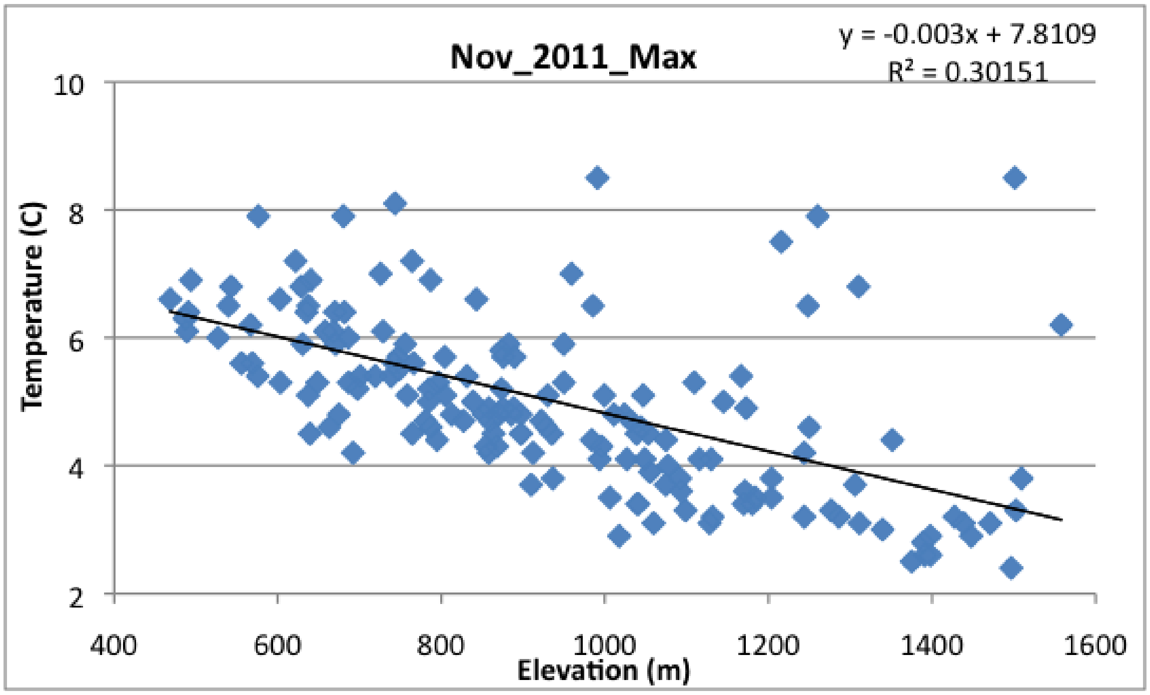
(k) October 2011 maximum T, lapse rate (3 °C) and topographic shading (6 °C)-dominated.



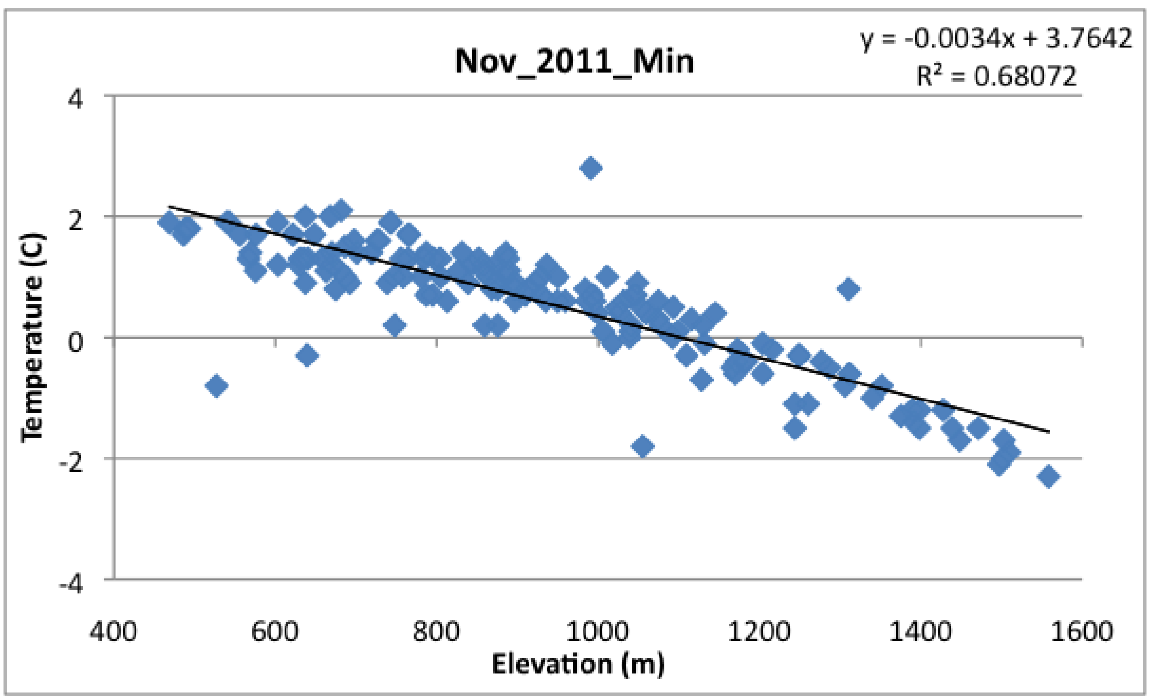
(l) October 2011 minimum T, lapse rate (5 °C) -dominated.



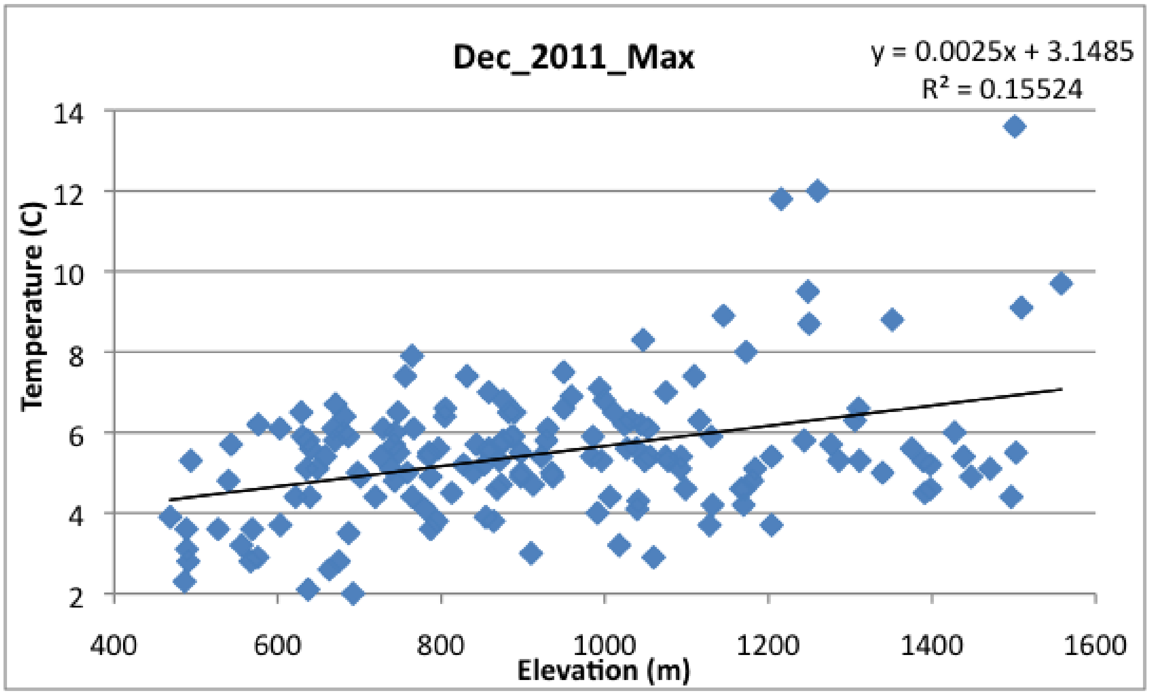
(m) November 2011 maximum T, lapse rate (3 °C) and topographic shading (6 °C)-dominated.



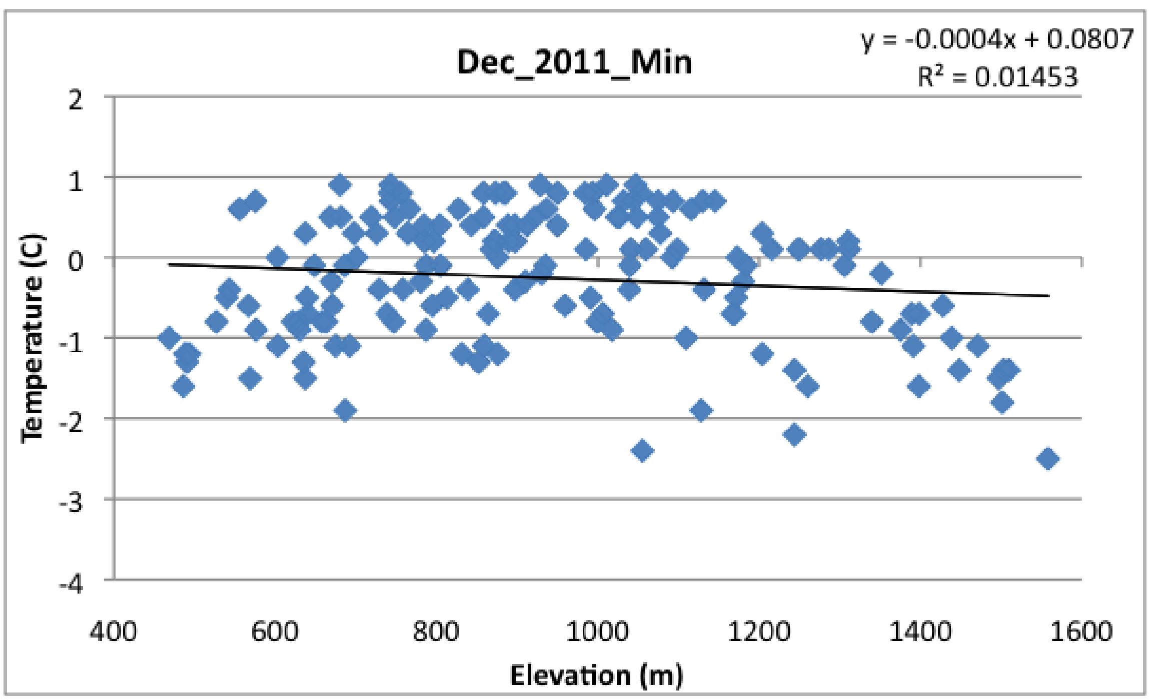
(n) November 2011 minimum T, lapse rate (4 °C) -dominated.



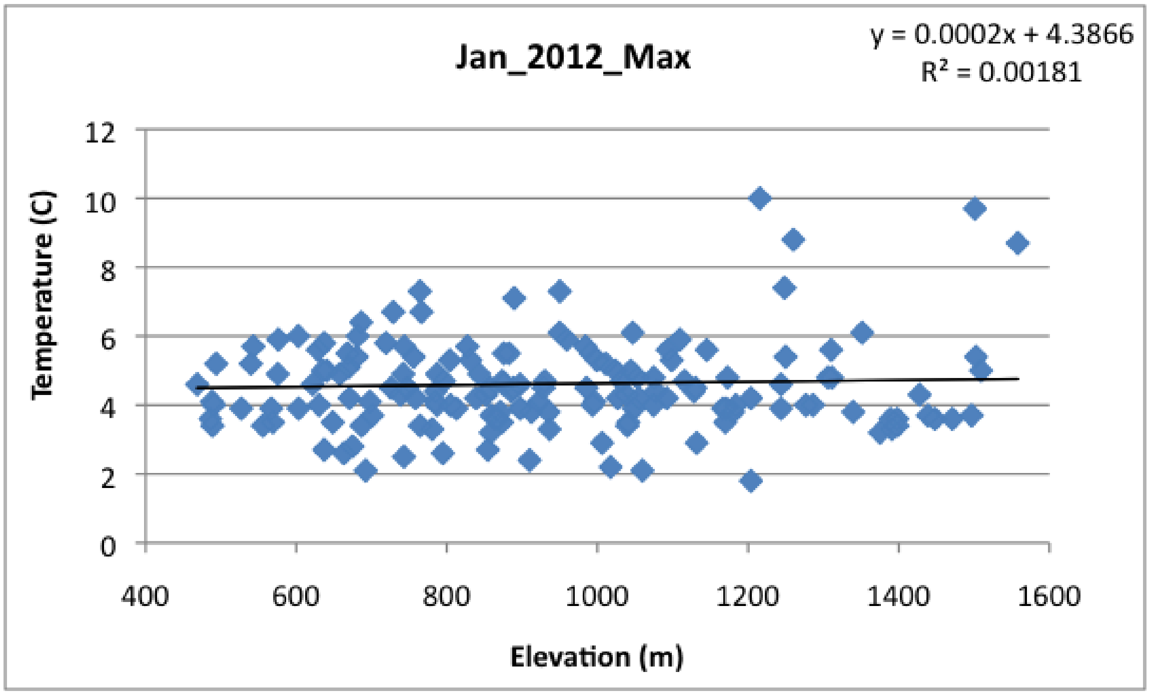
(o) December 2011 maximum T, topographic shading (12 °C)-dominated.



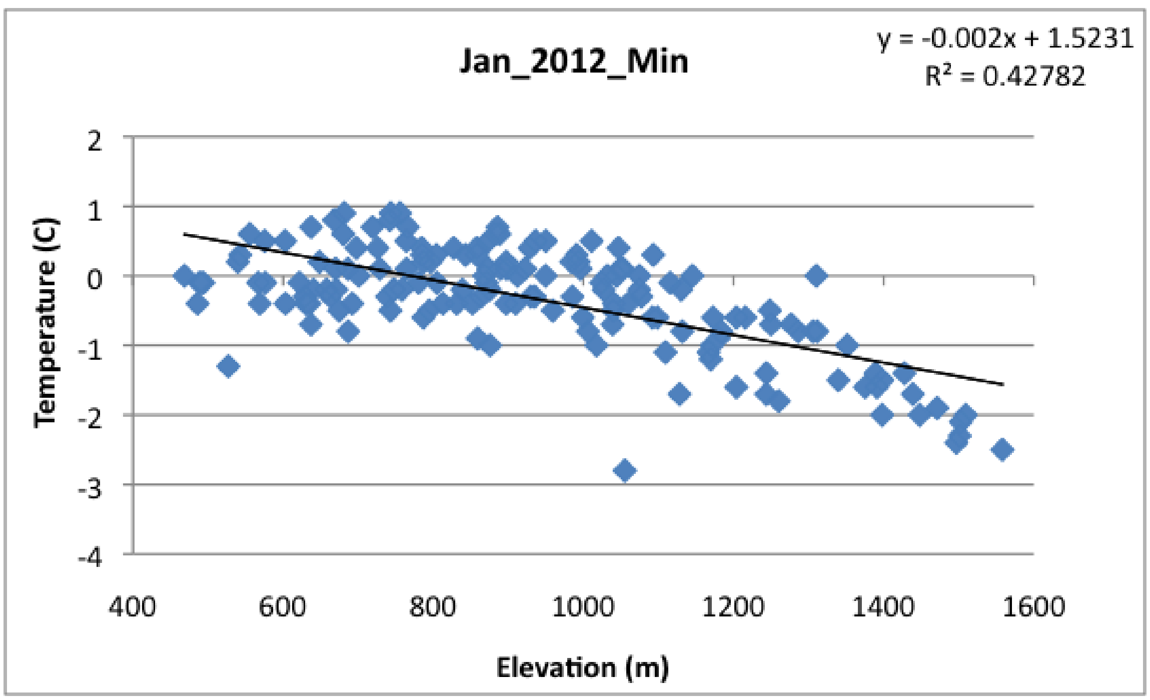
(p) December 2011 minimum T, cold air pooling (2 °C, 400-800m)-dominated.



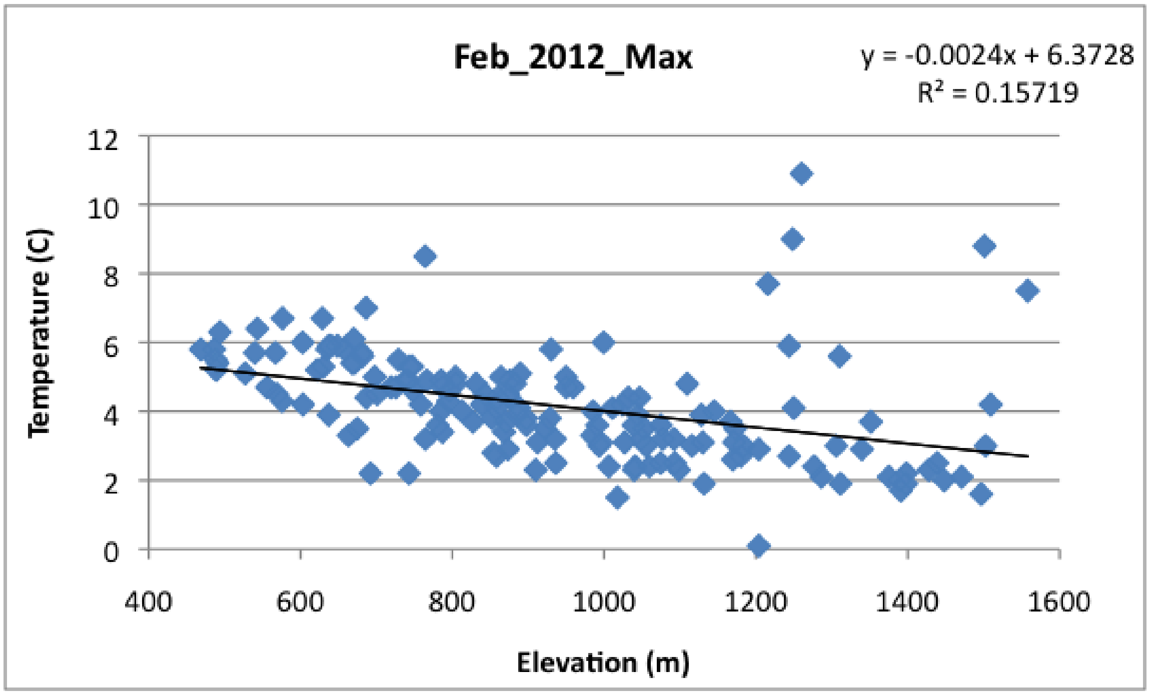
(q) January 2012 maximum T, topographic shading (8 °C)-dominated



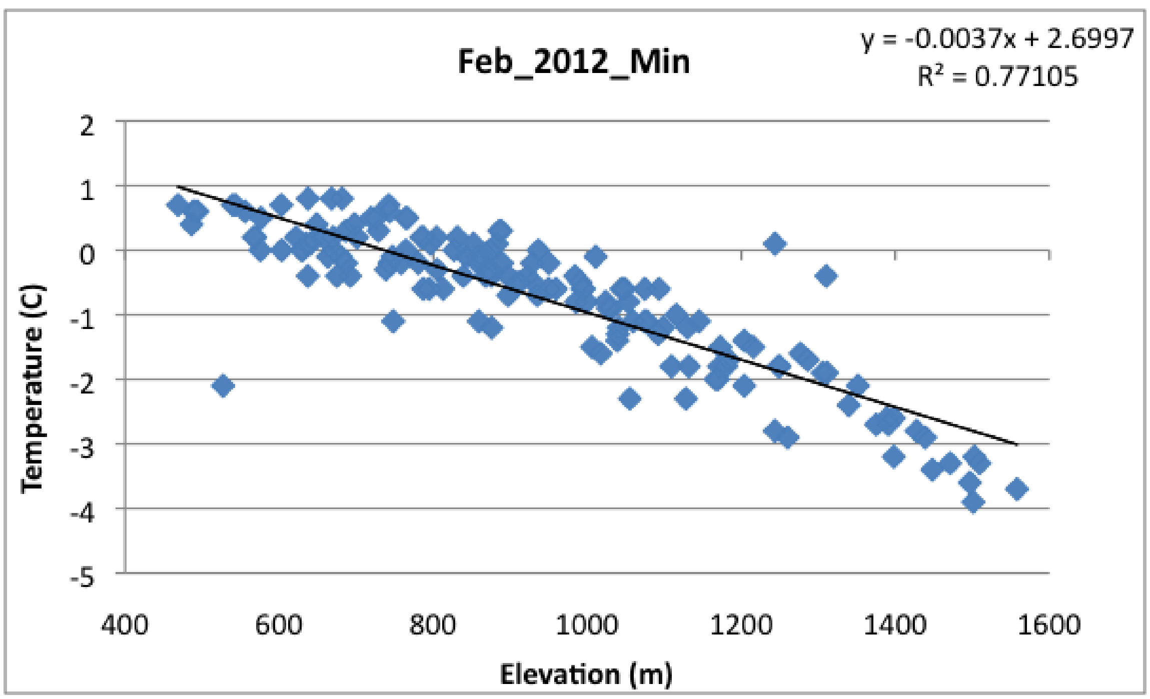
(r) January minimum T, cold air pooling (1 °C, 400-800m) and lapse rate (2 °C)-dominated.



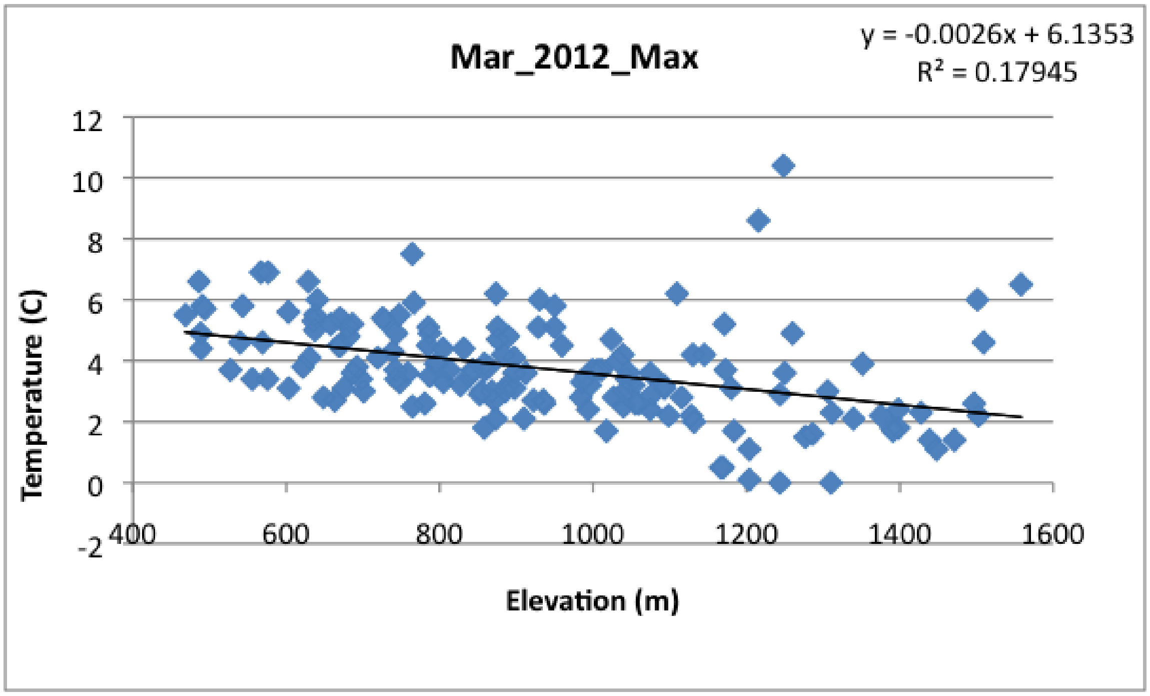
(s) February 2012 maximum T, topographic shading (9 °C) and lapse rate (2 °C)-dominated



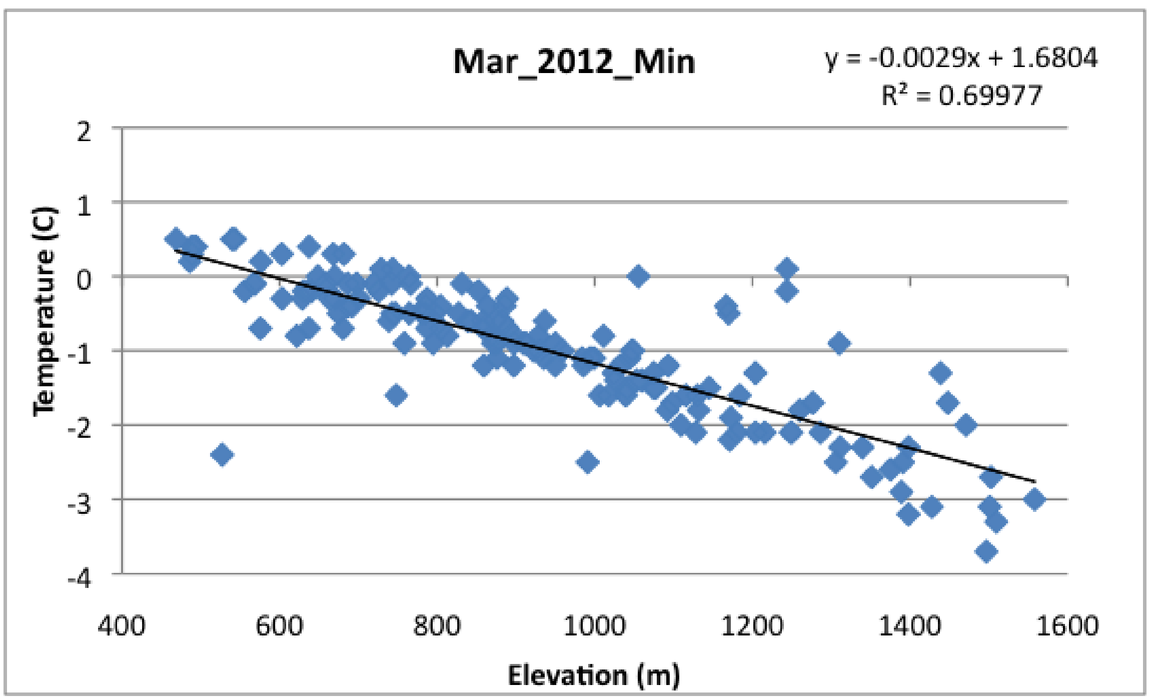
(t) February minimum T, lapse rate (4 °C) and cold air pooling (400-700 m)-dominated.



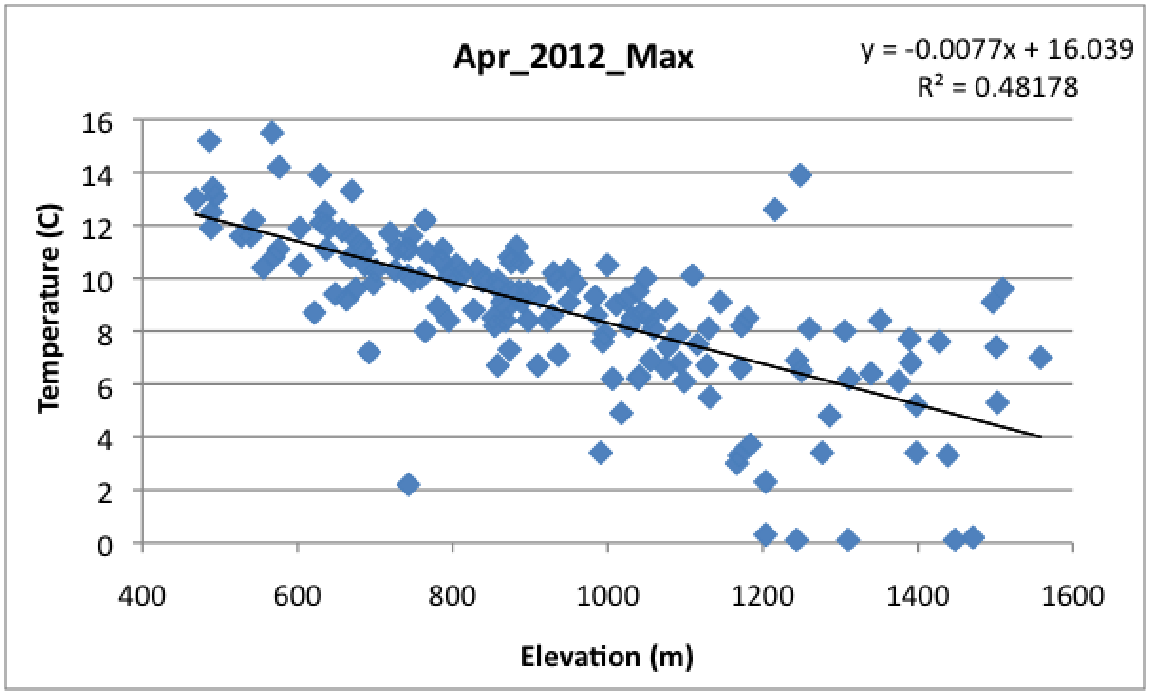
(u) March 2012 maximum T, topographic shading (10 °C) and lapse rate (2 °C)-dominated



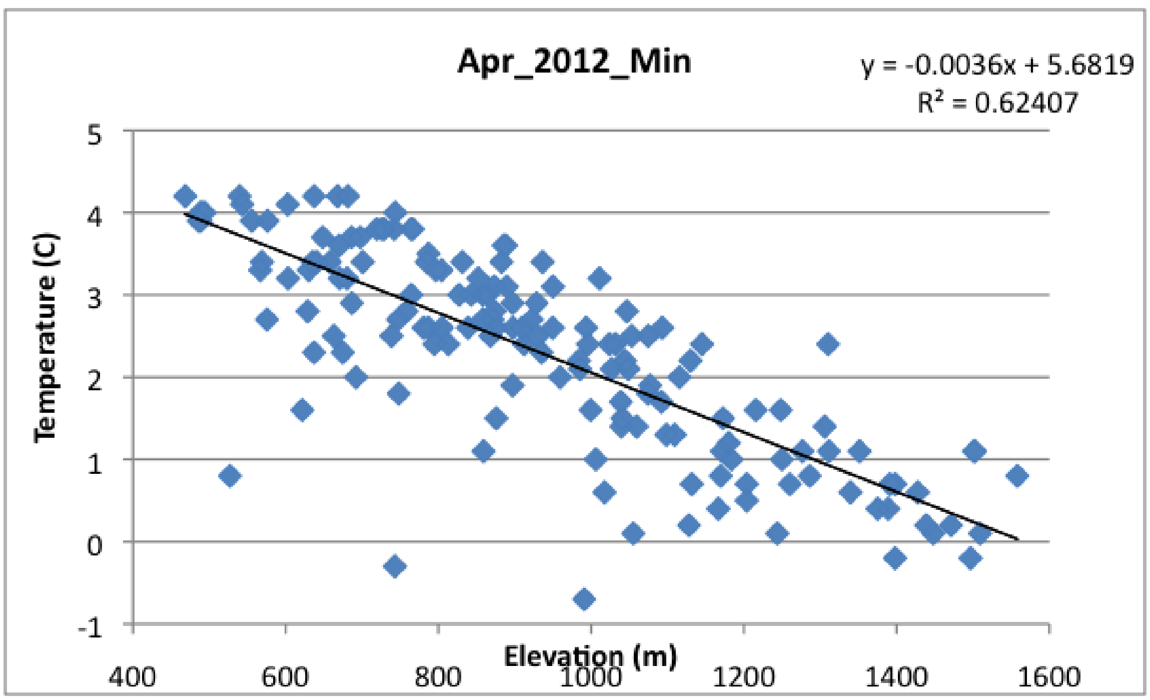
(v) March minimum T, lapse rate (3 °C)-dominated.



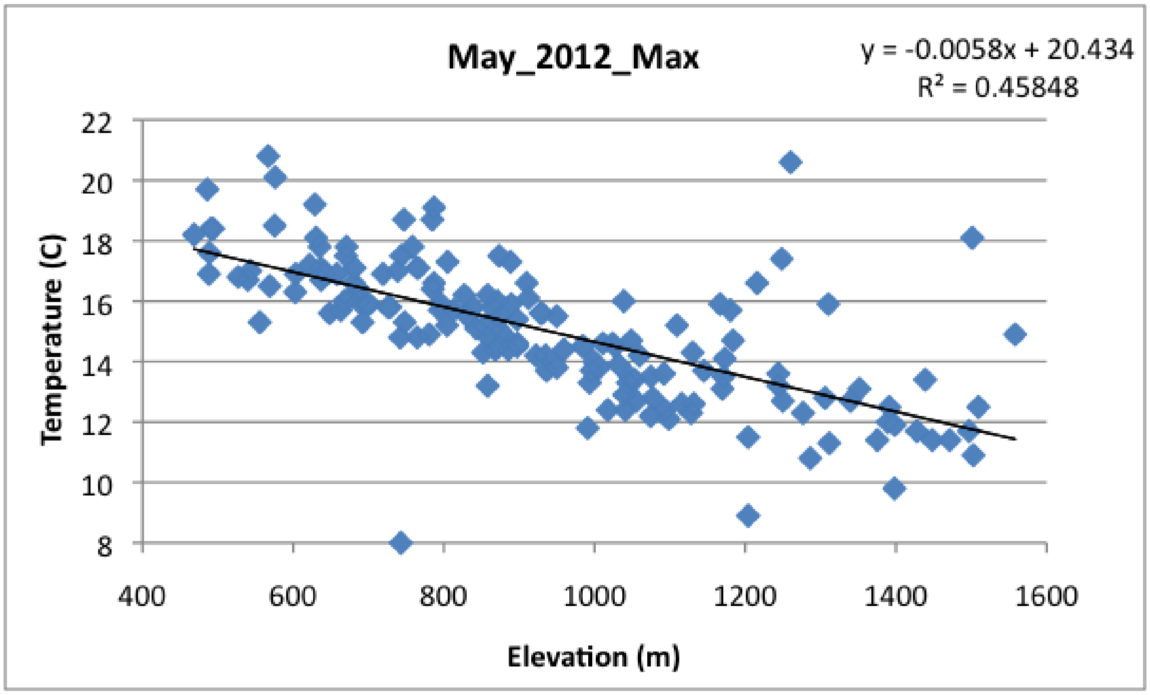
(w) April 2012 maximum T, topographic shading (12 °C) and lapse rate (6 °C)-dominated



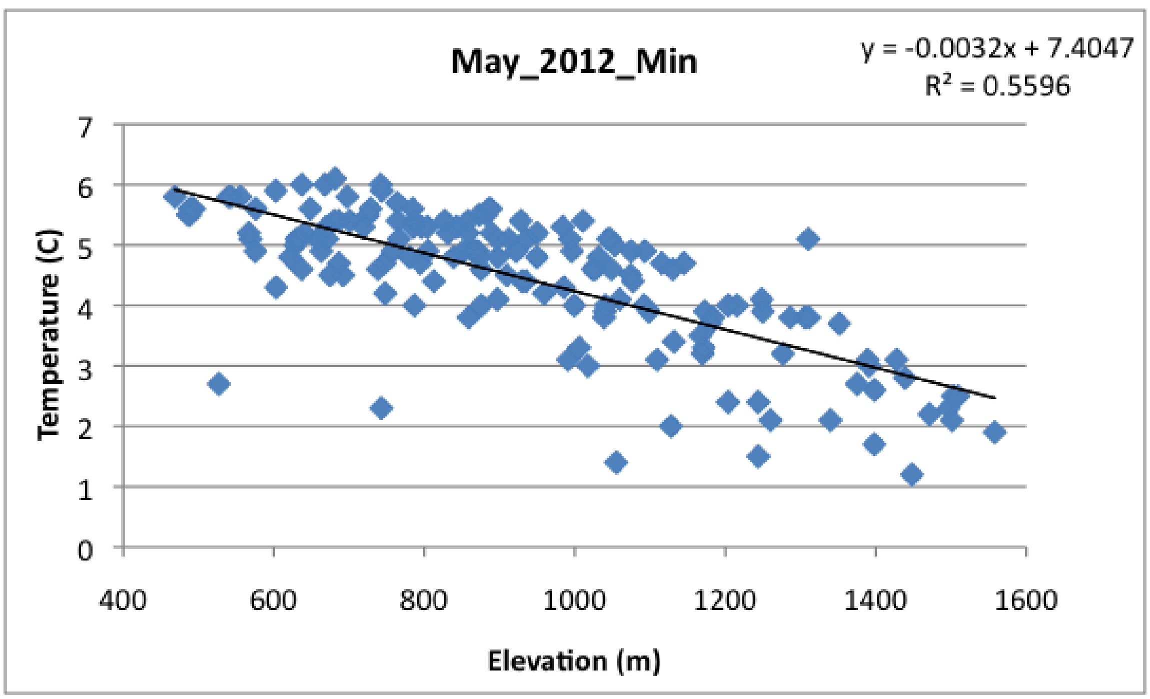
(x) April minimum T, lapse rate (4 °C)-dominated.



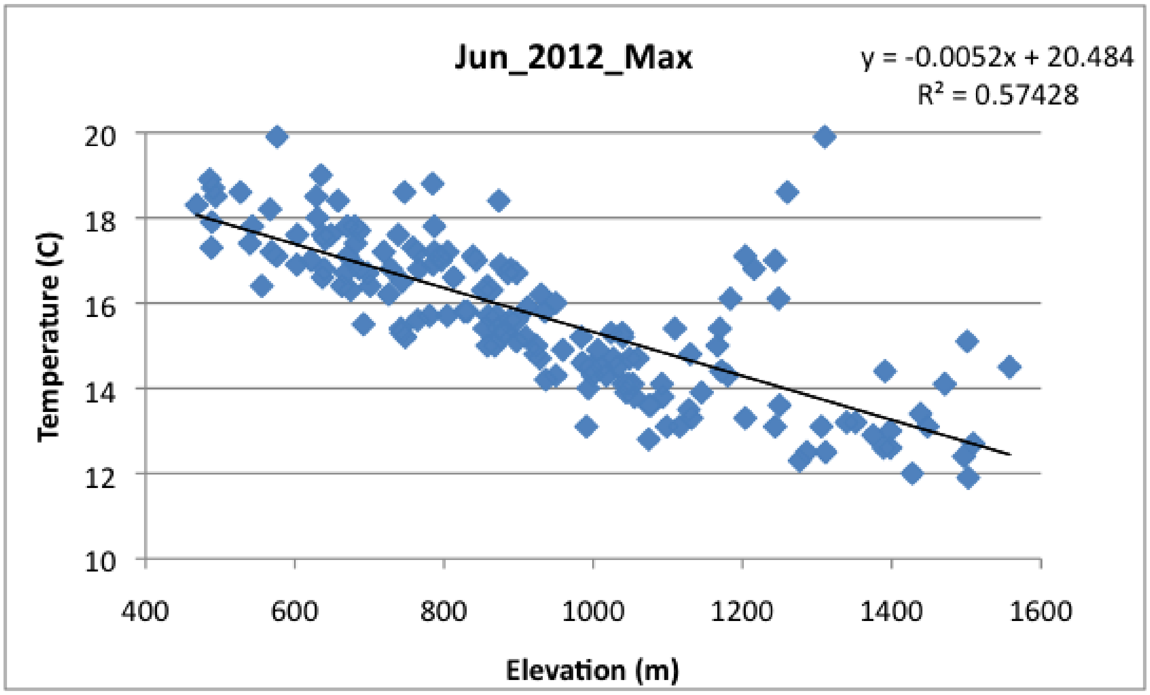
(y) May 2012 maximum T, topographic shading and lapse rate-dominated



(z) May minimum T, lapse rate and cold air pooling-dominated.



(aa) June 2012 maximum T, lapse rate and topographic shading-dominated



(bb) June minimum T, lapse rate-dominated.

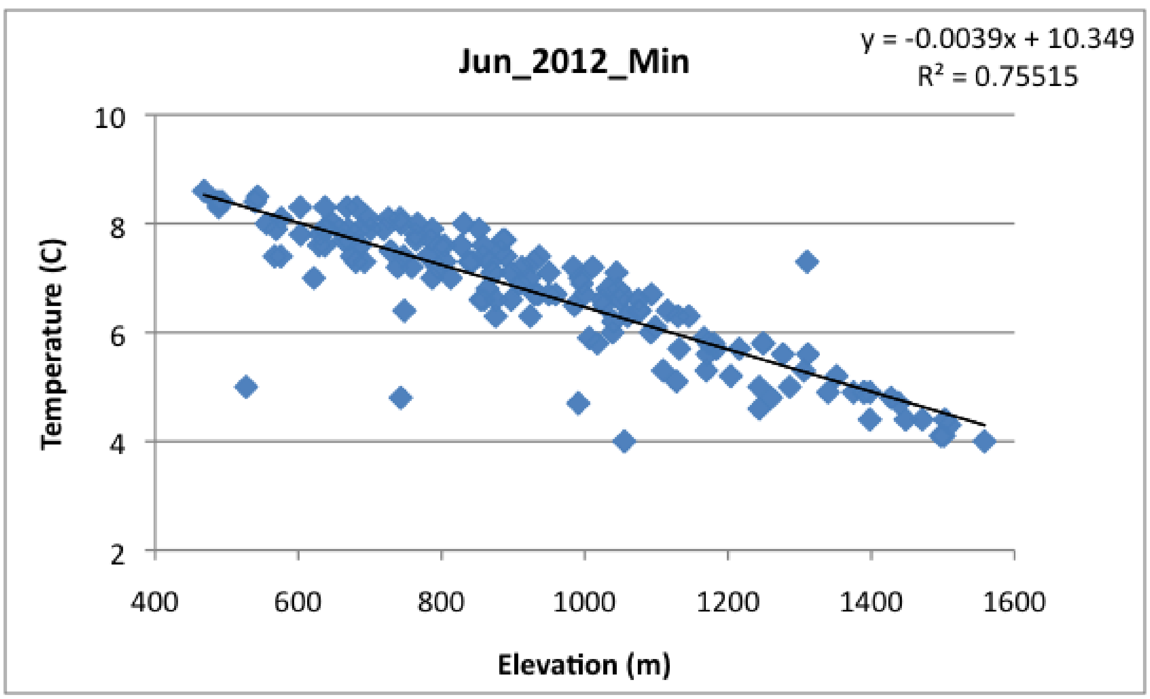
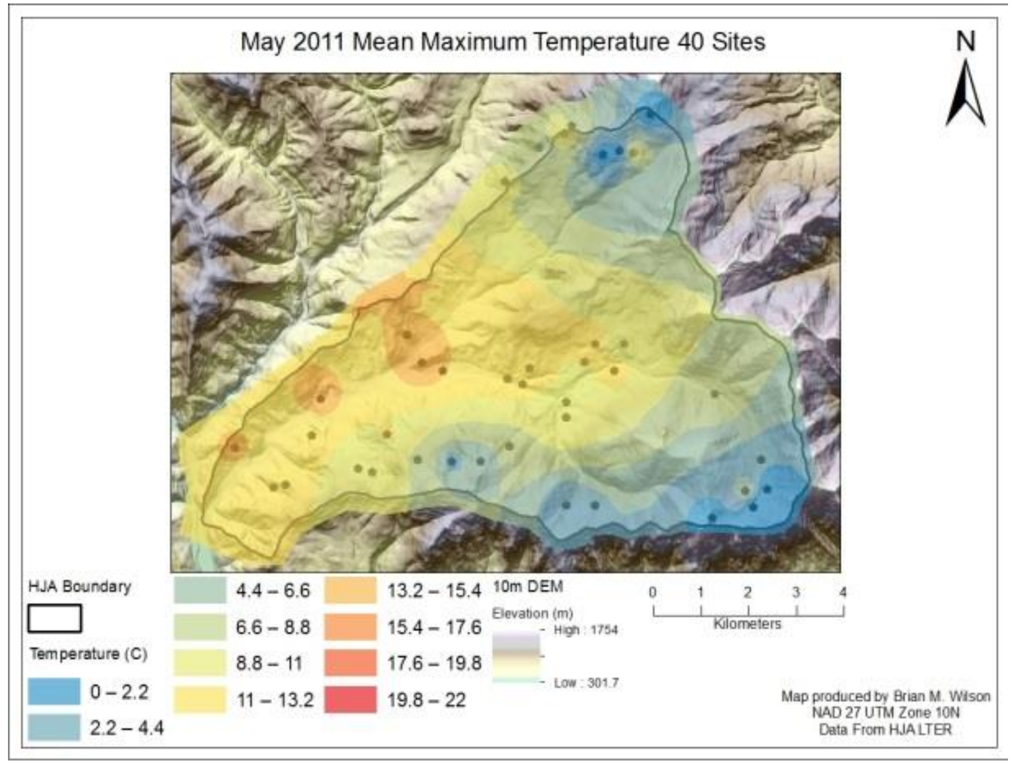
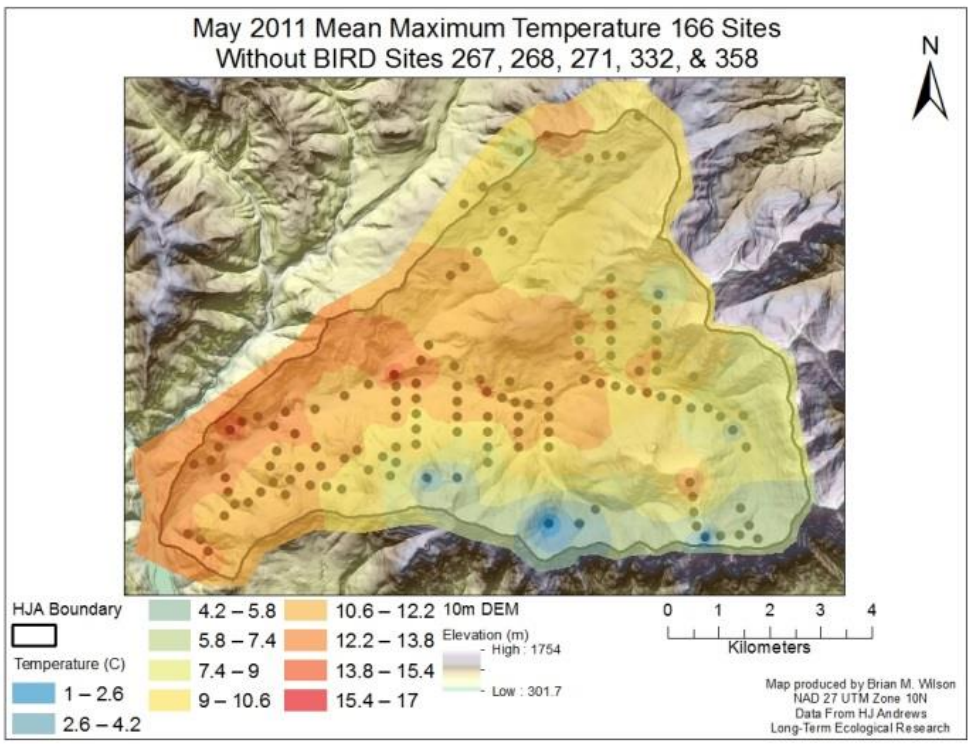
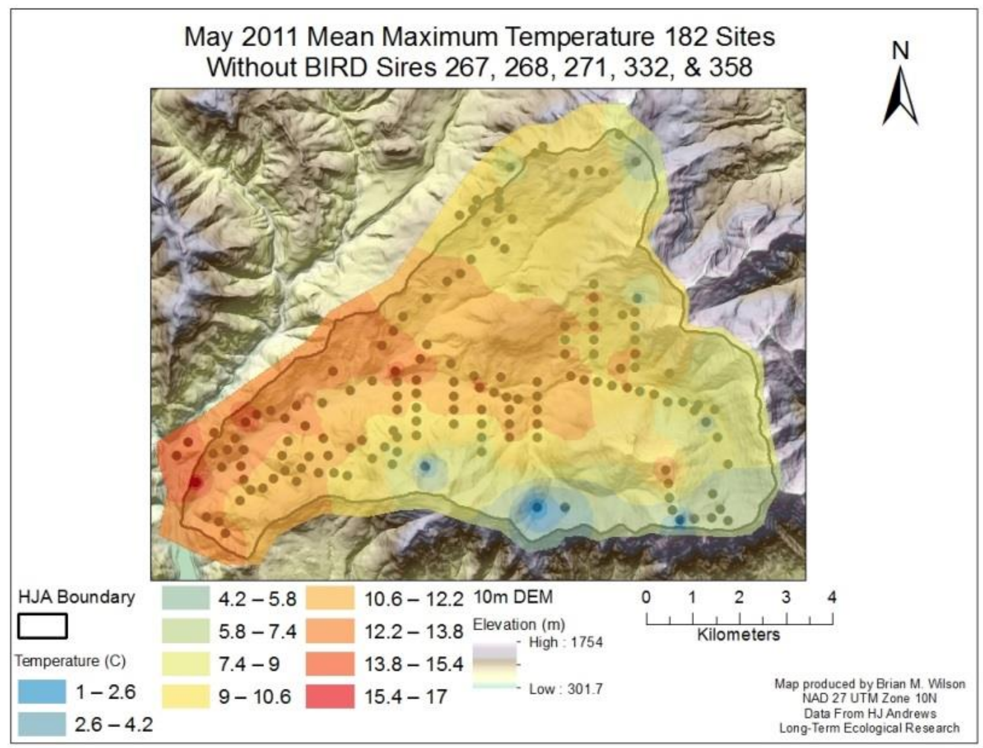


Figure 16.

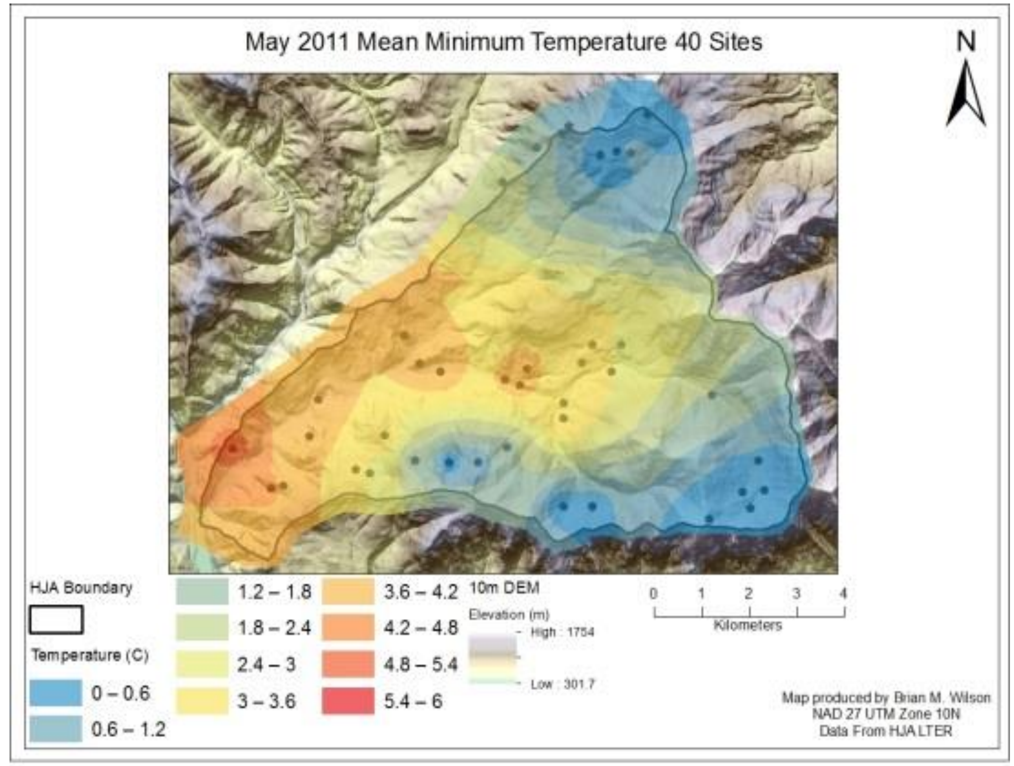
Mean monthly maximum temperature May 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

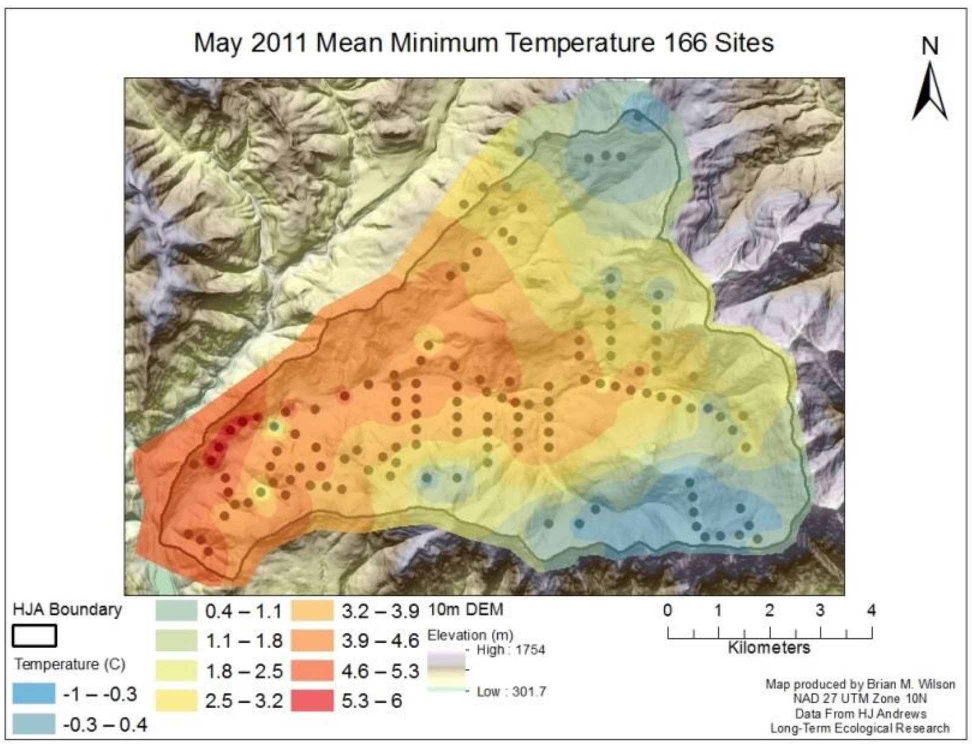


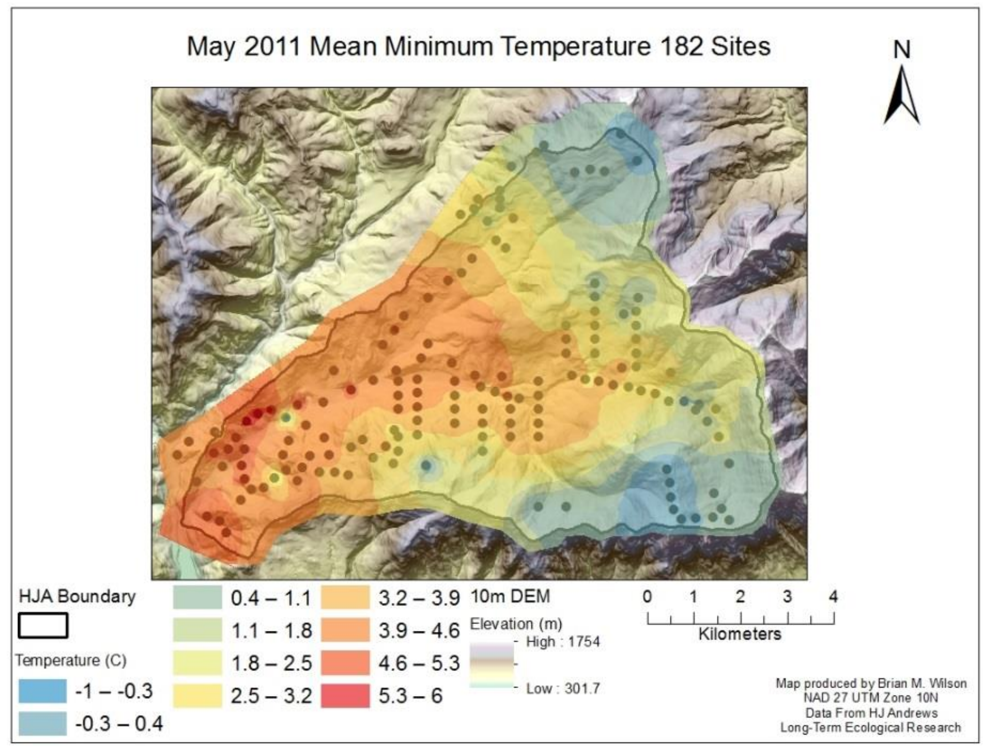




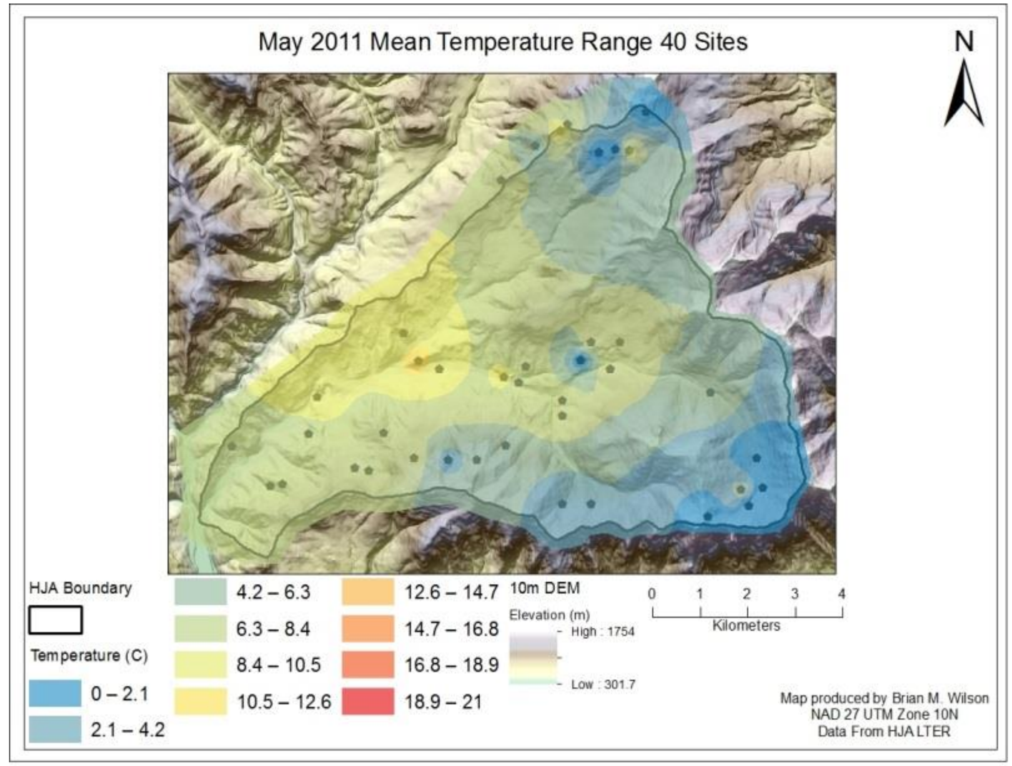
Mean monthly minimum temperature May 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

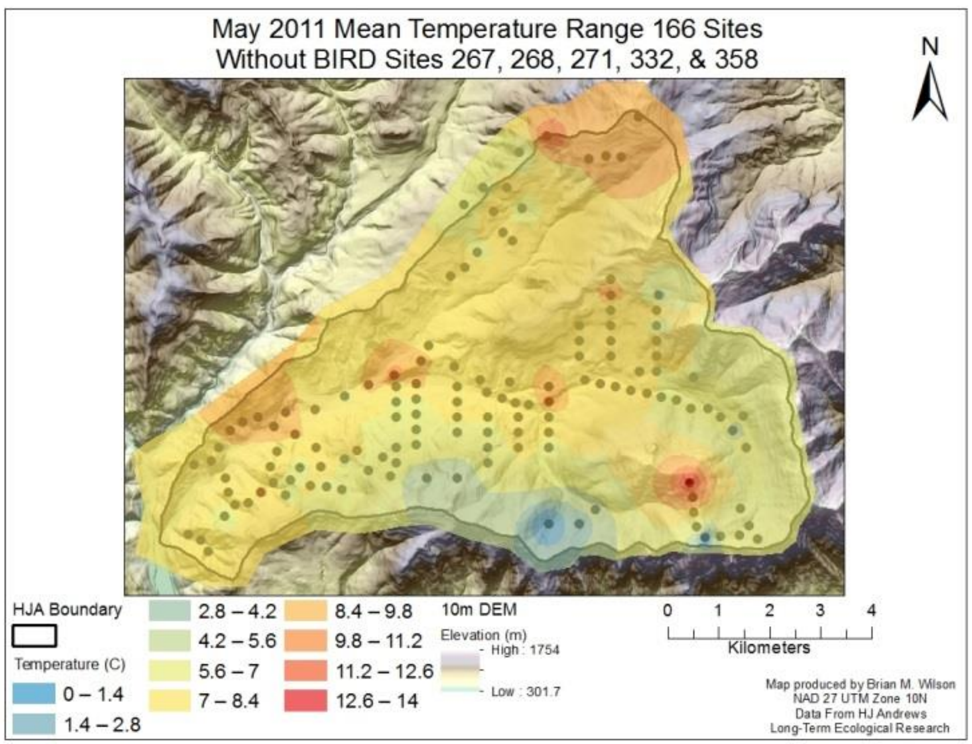


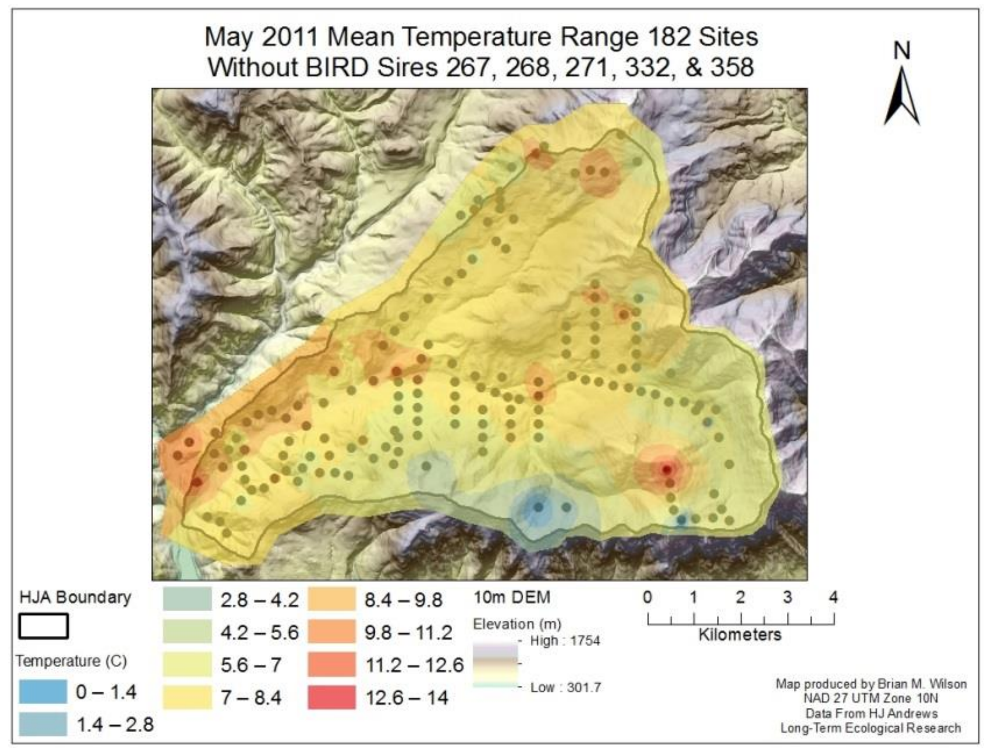




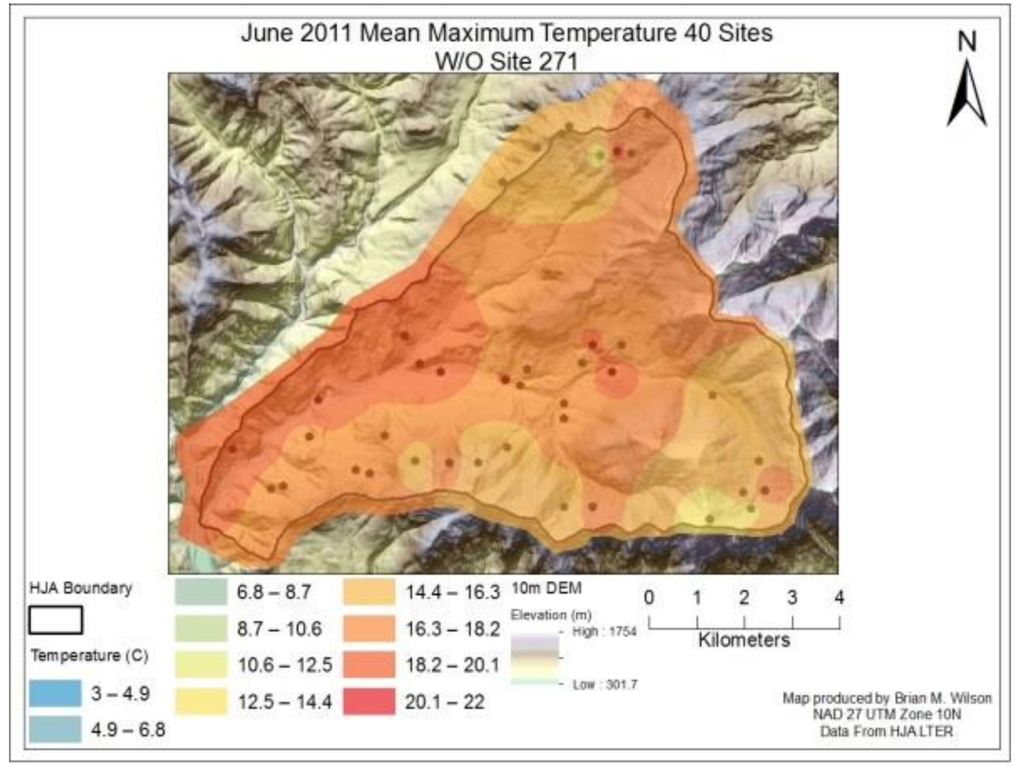
Mean monthly temperature range May 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

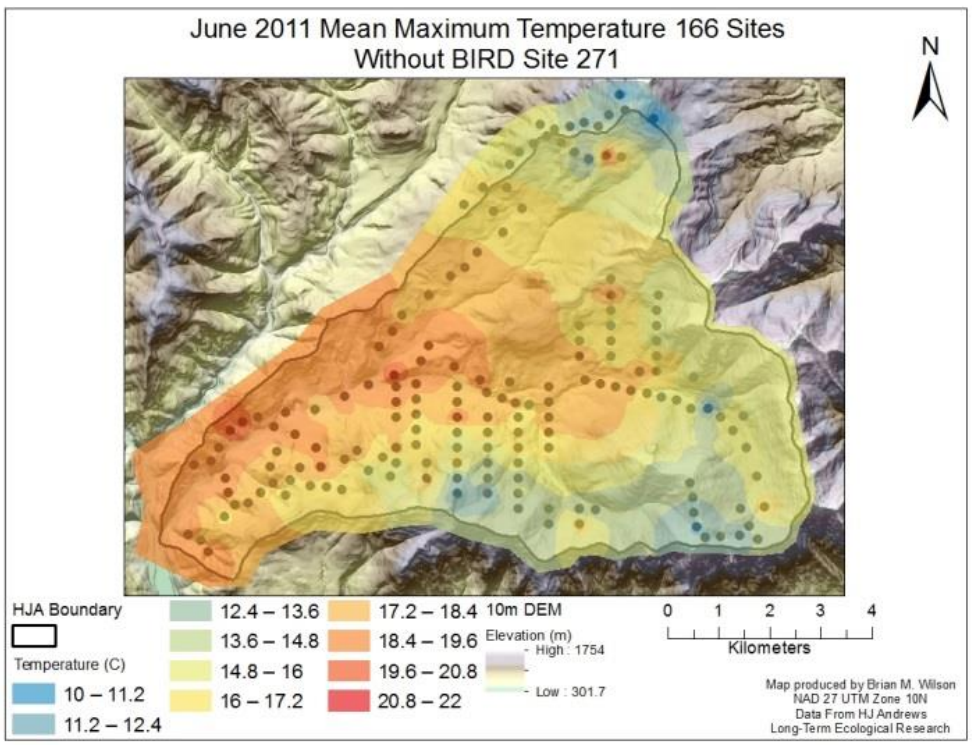


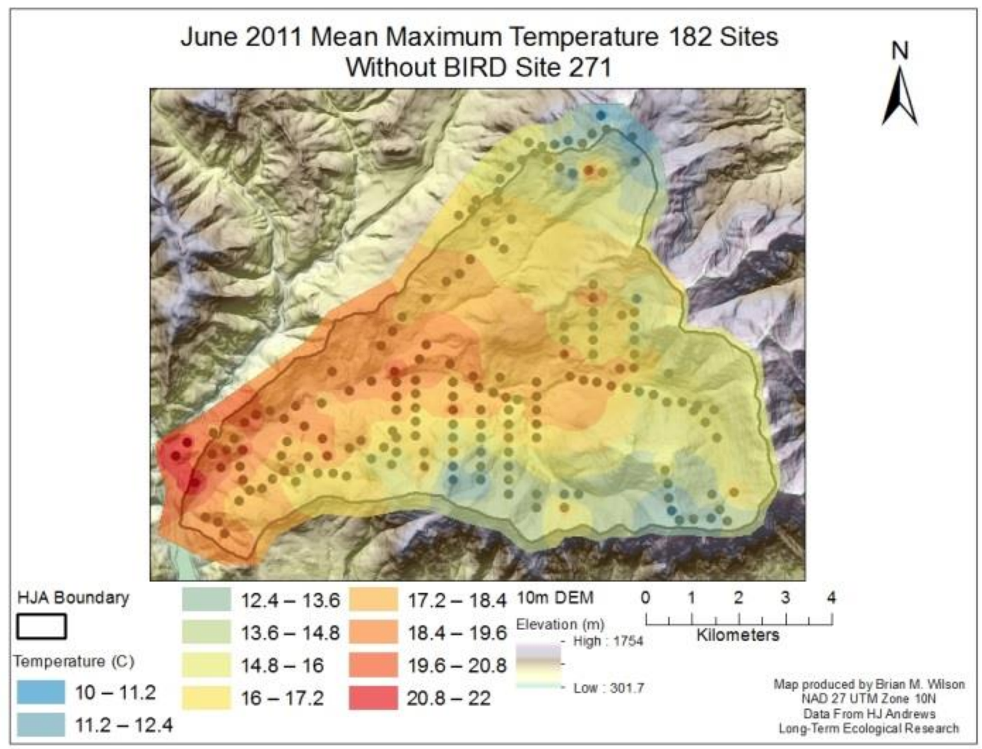




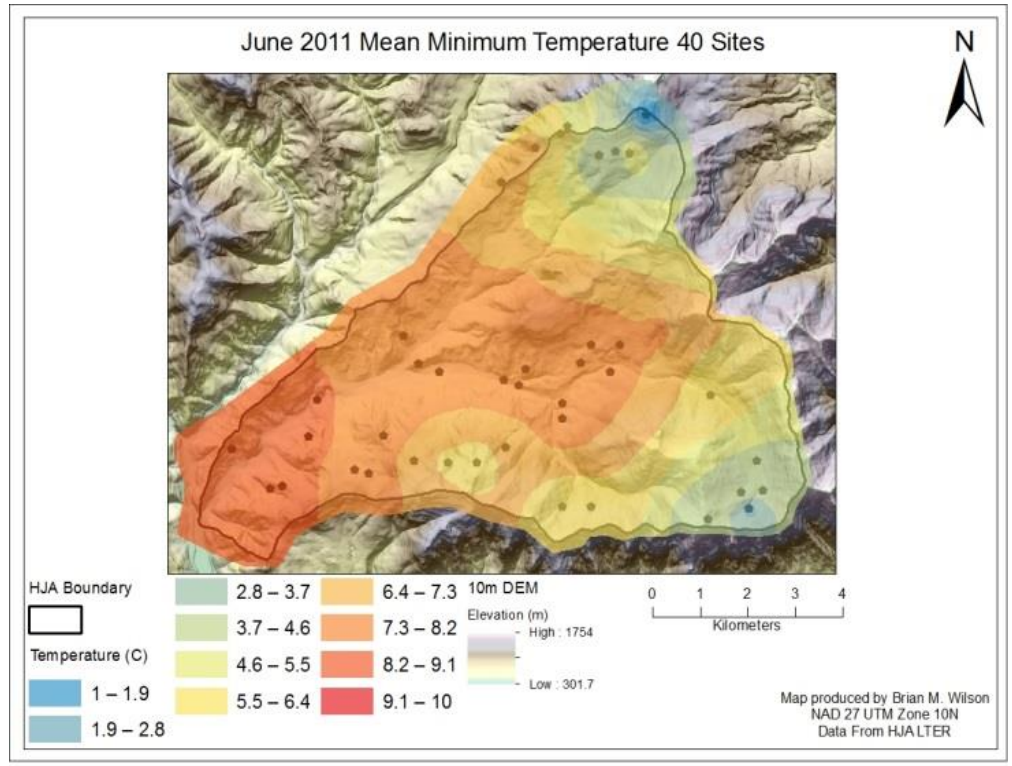
Mean monthly maximum temperature June 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

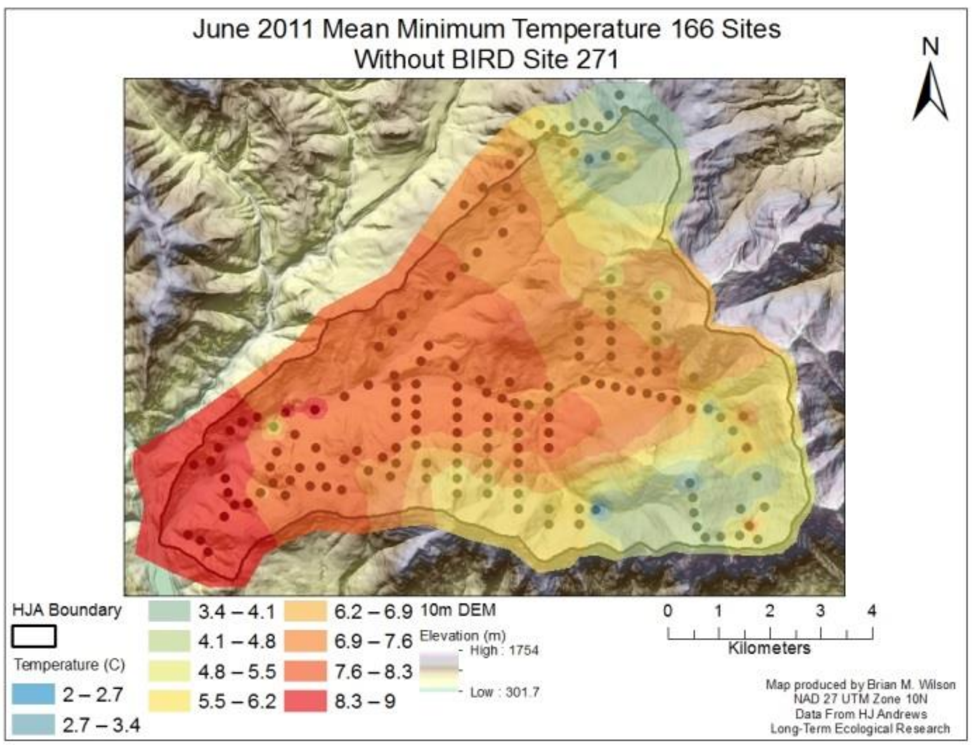


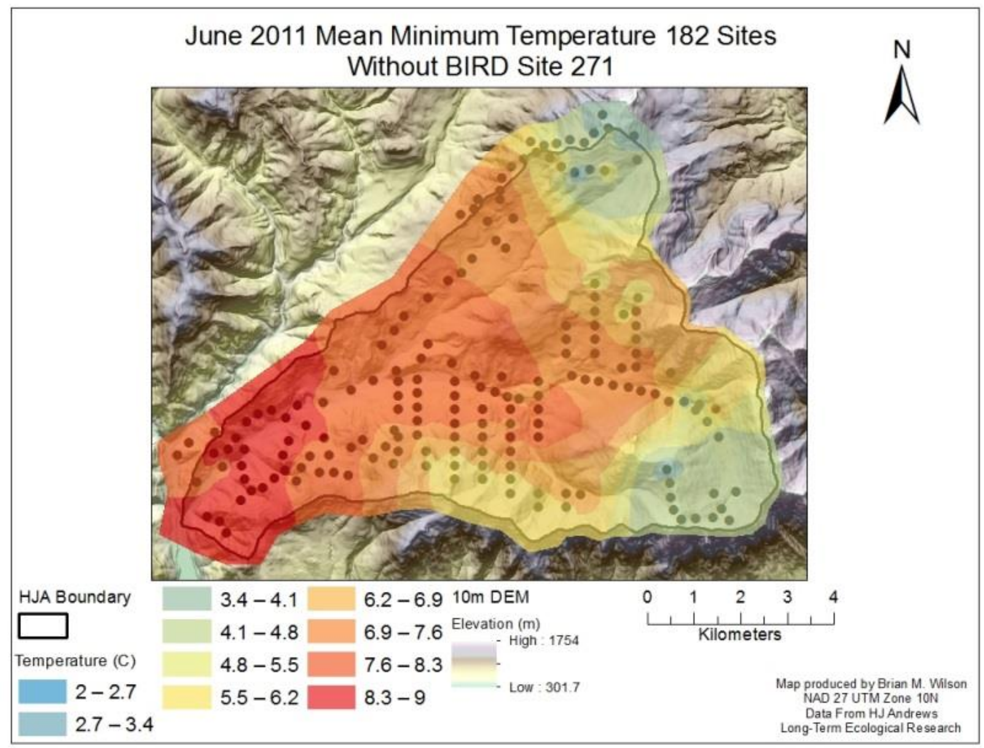




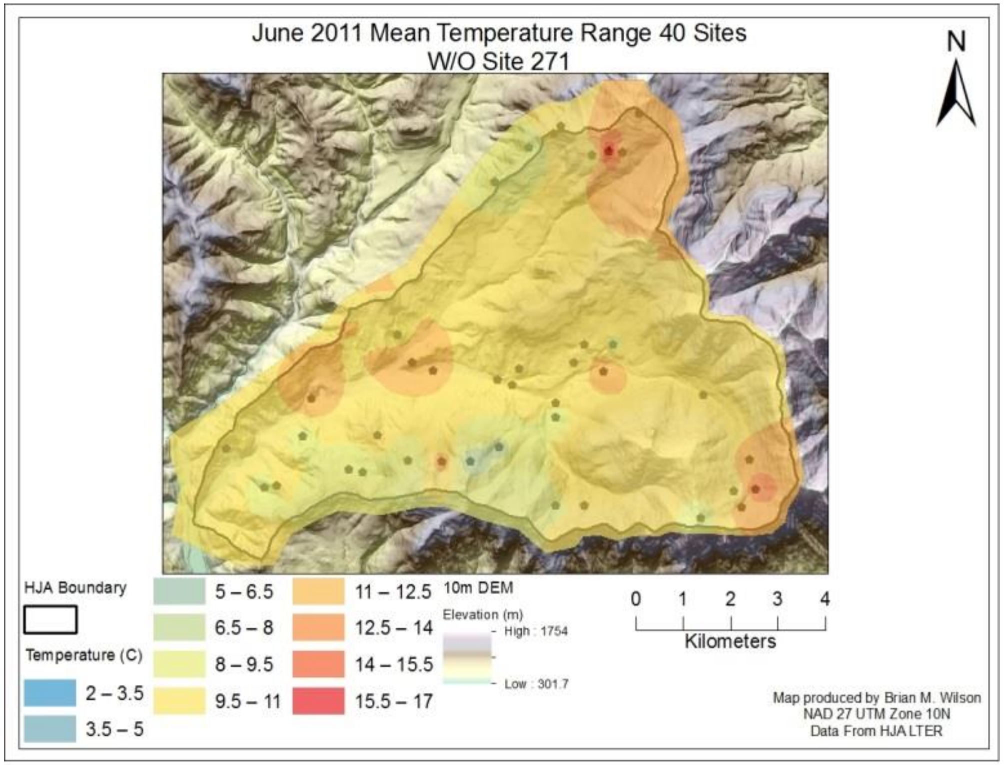
Mean monthly minimum temperature June 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

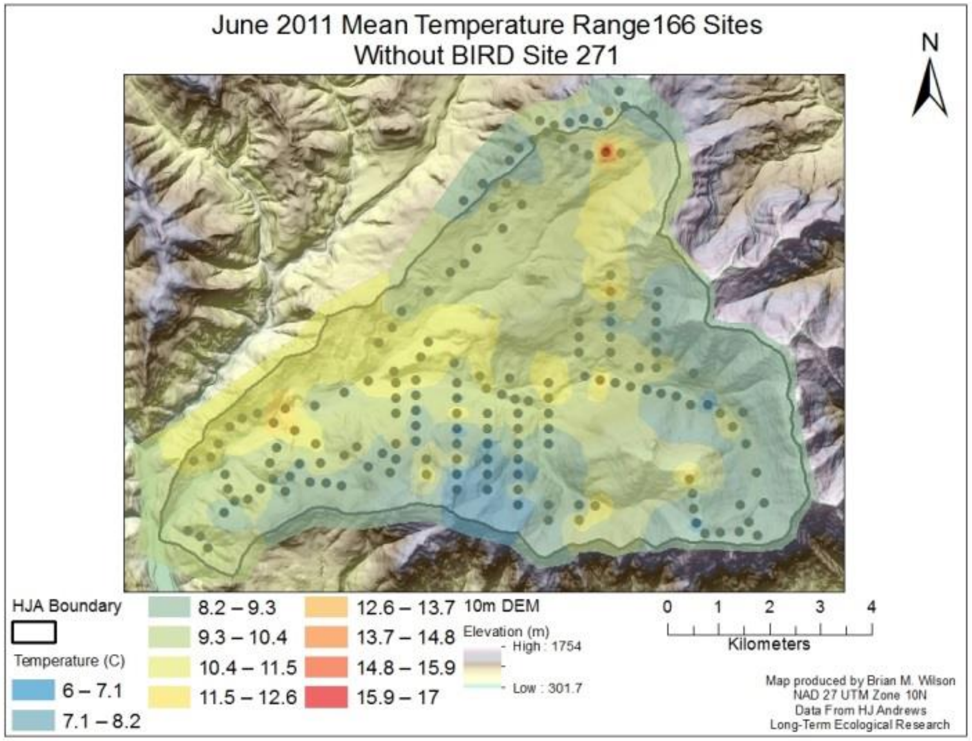


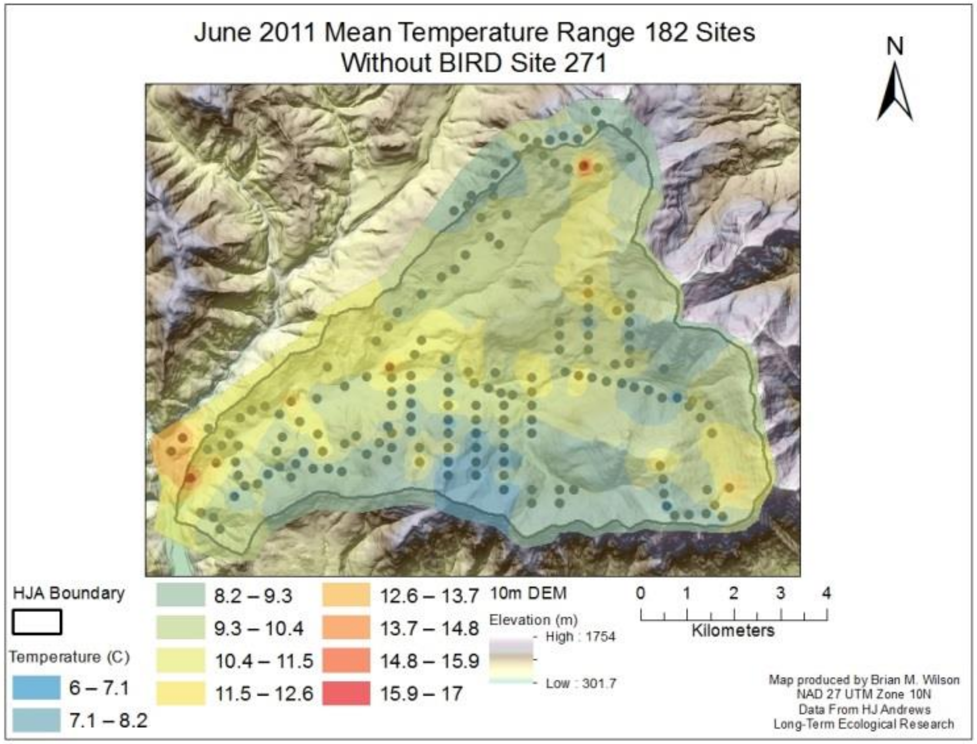




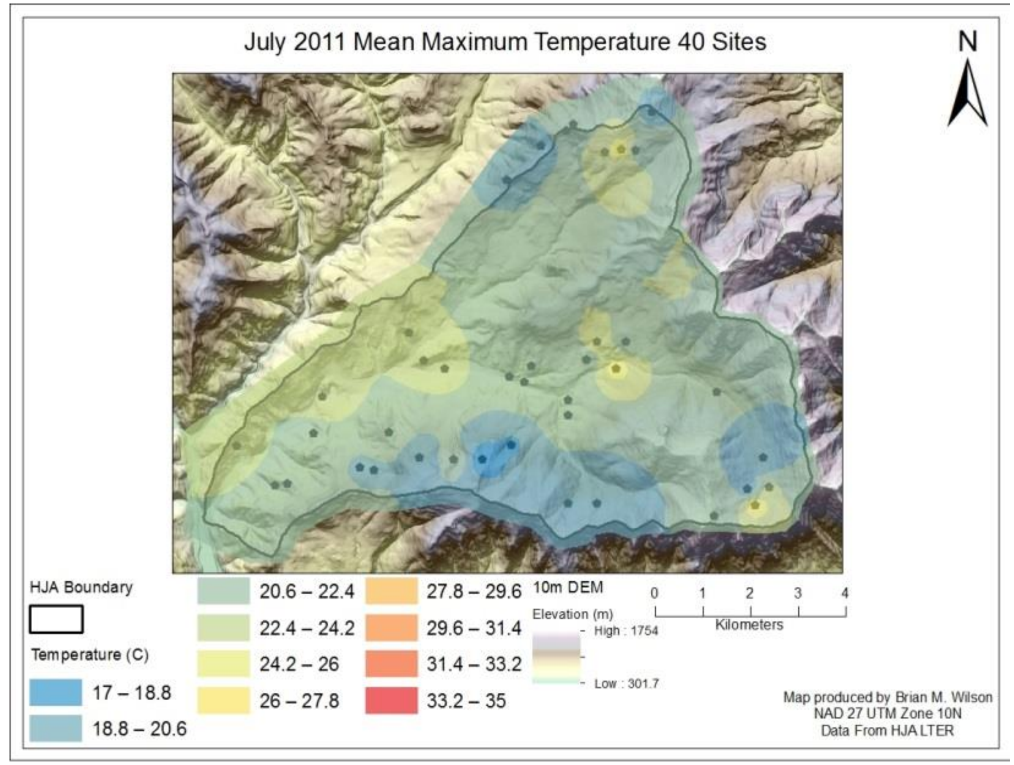
Mean monthly temperature range June 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

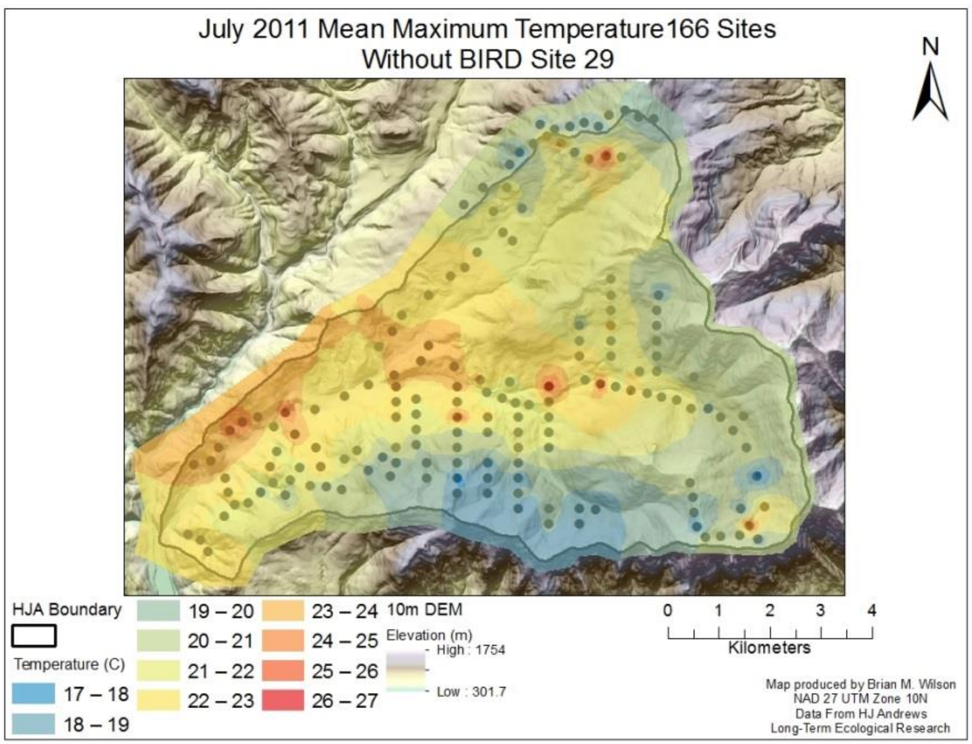


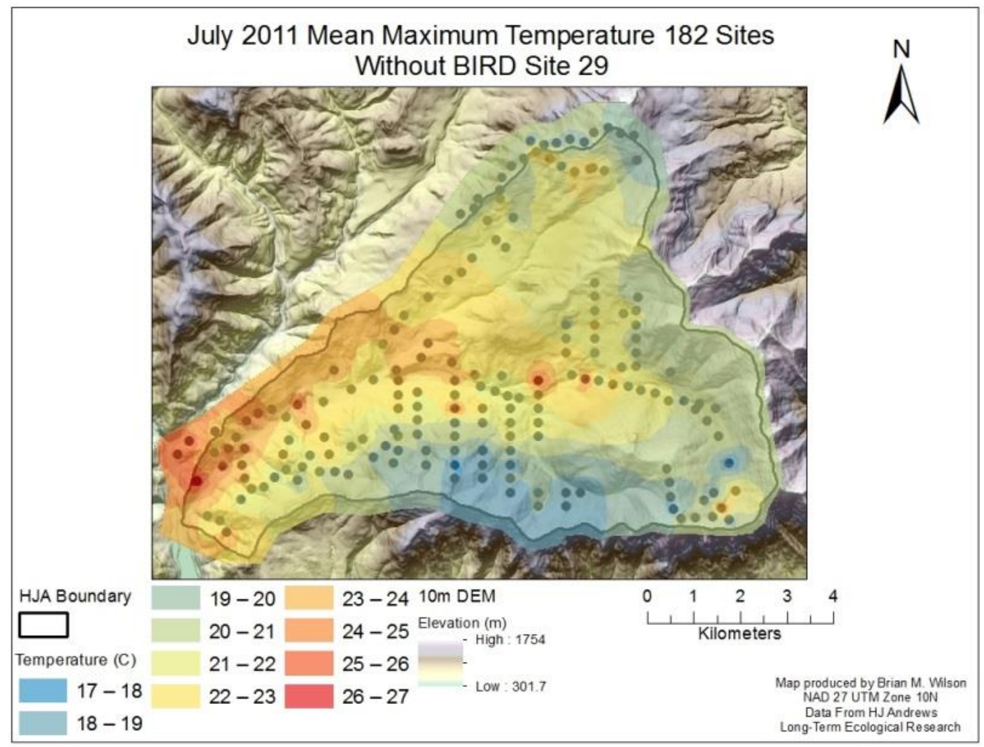




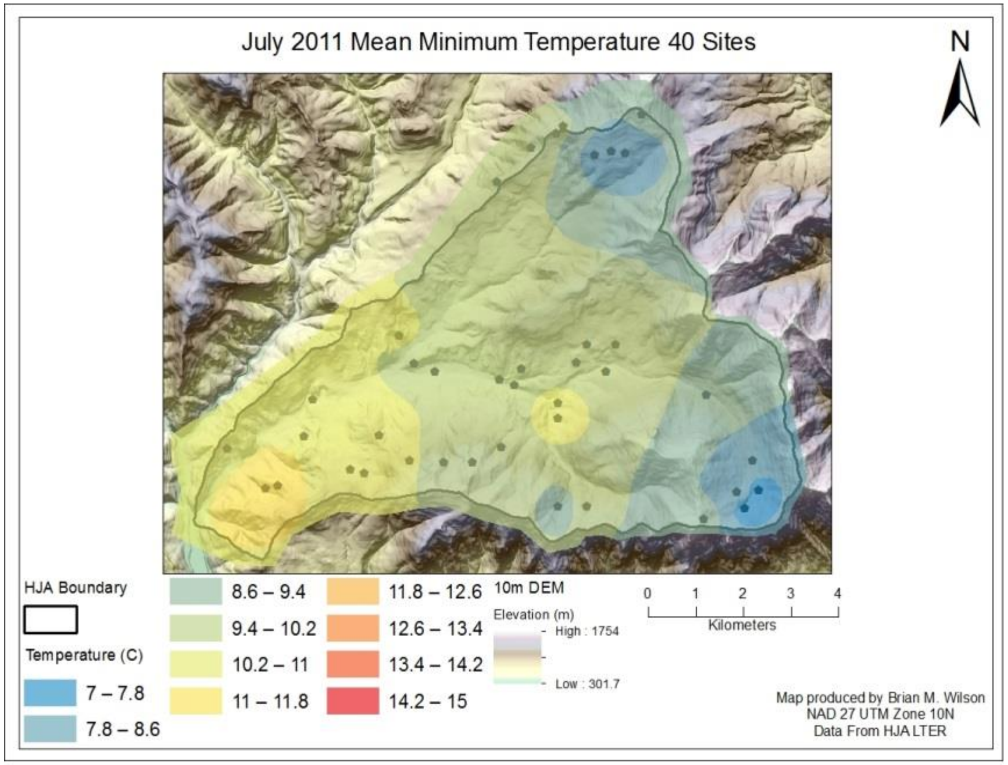
Mean monthly maximum temperature July 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

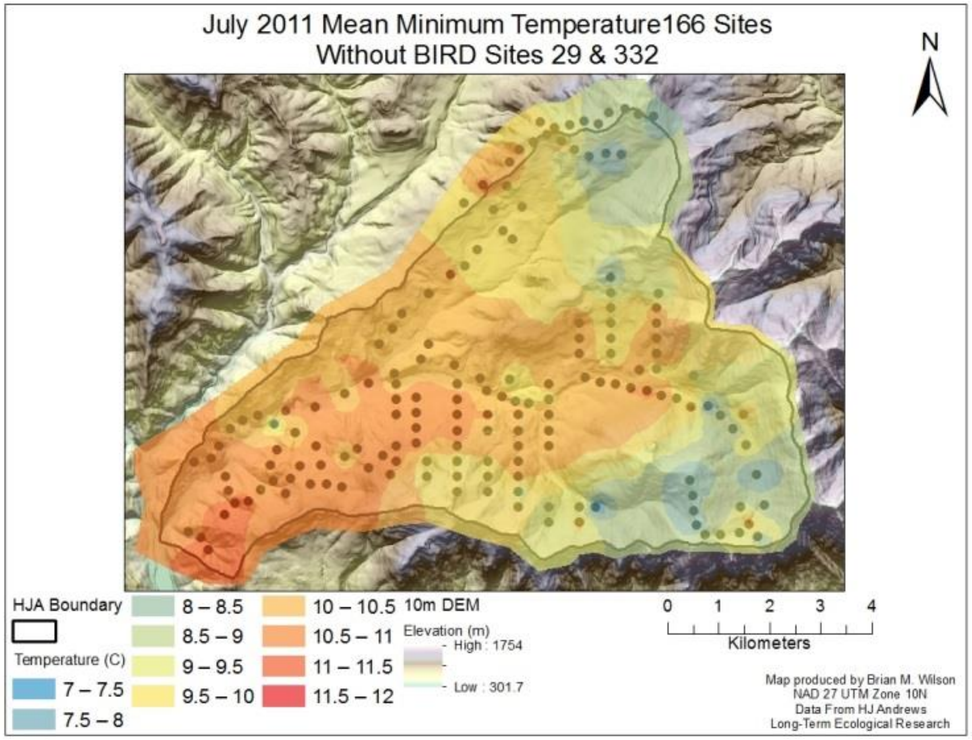


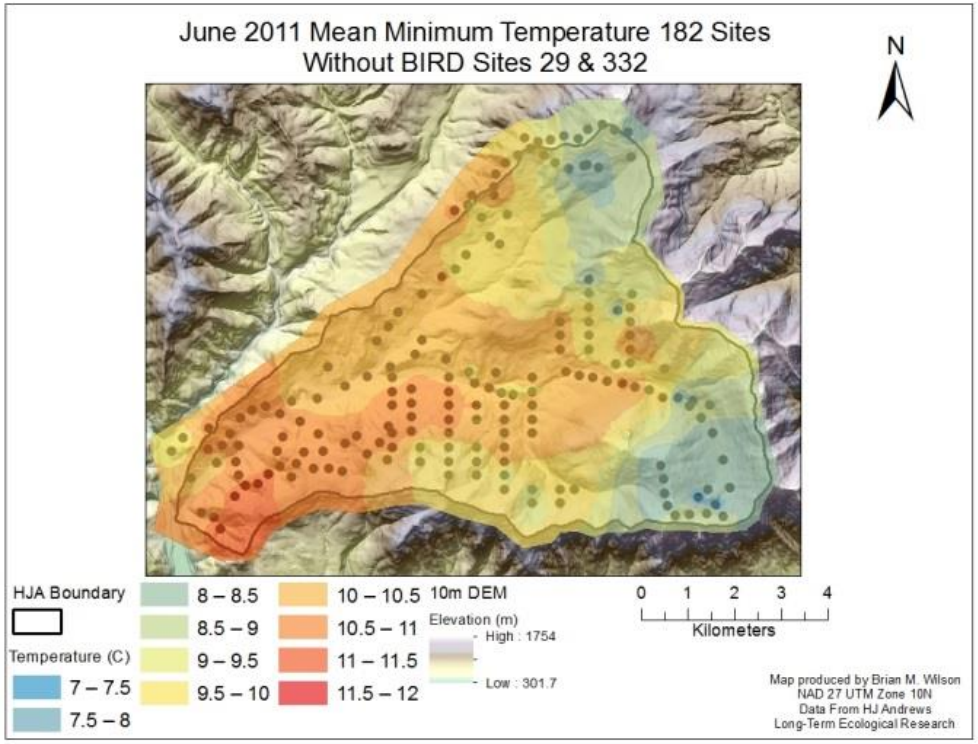




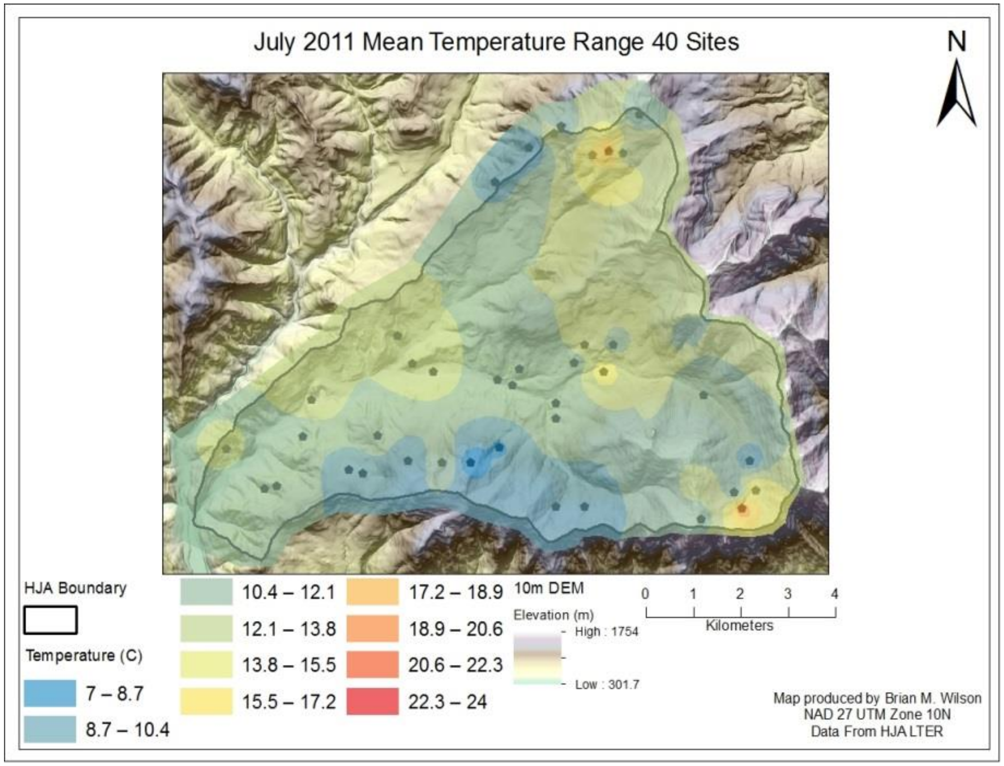
Mean monthly minimum temperature July 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

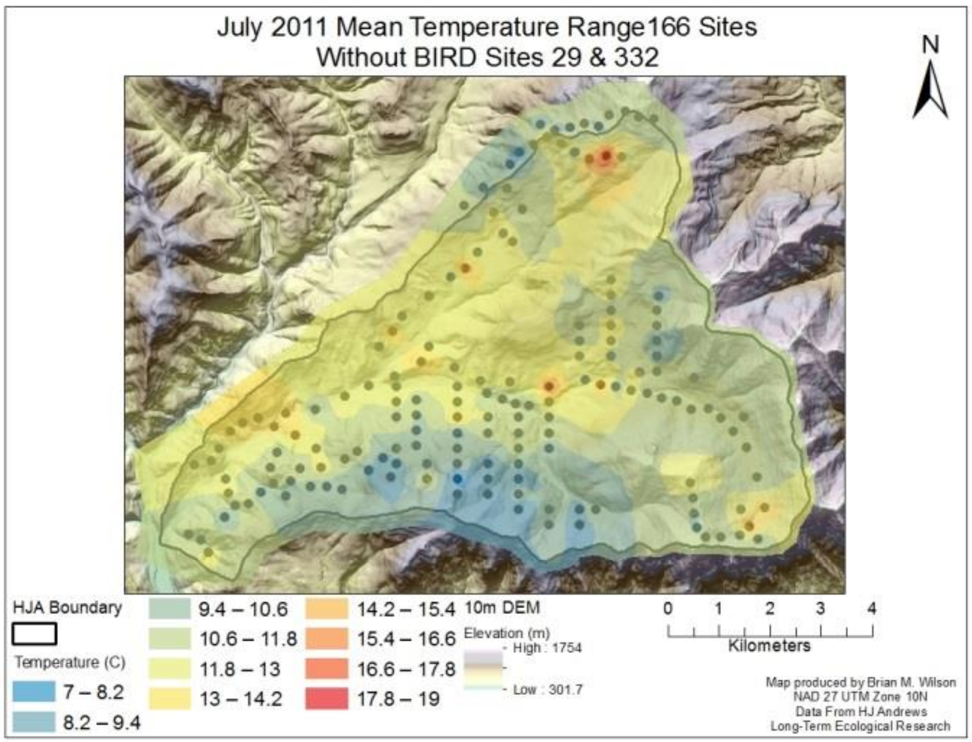


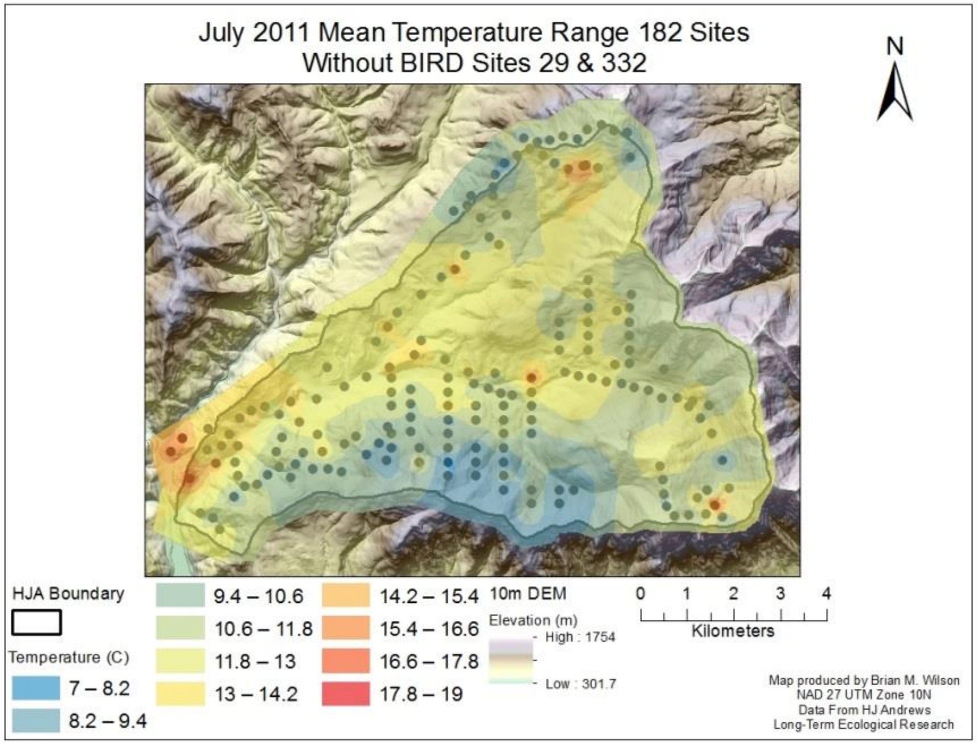




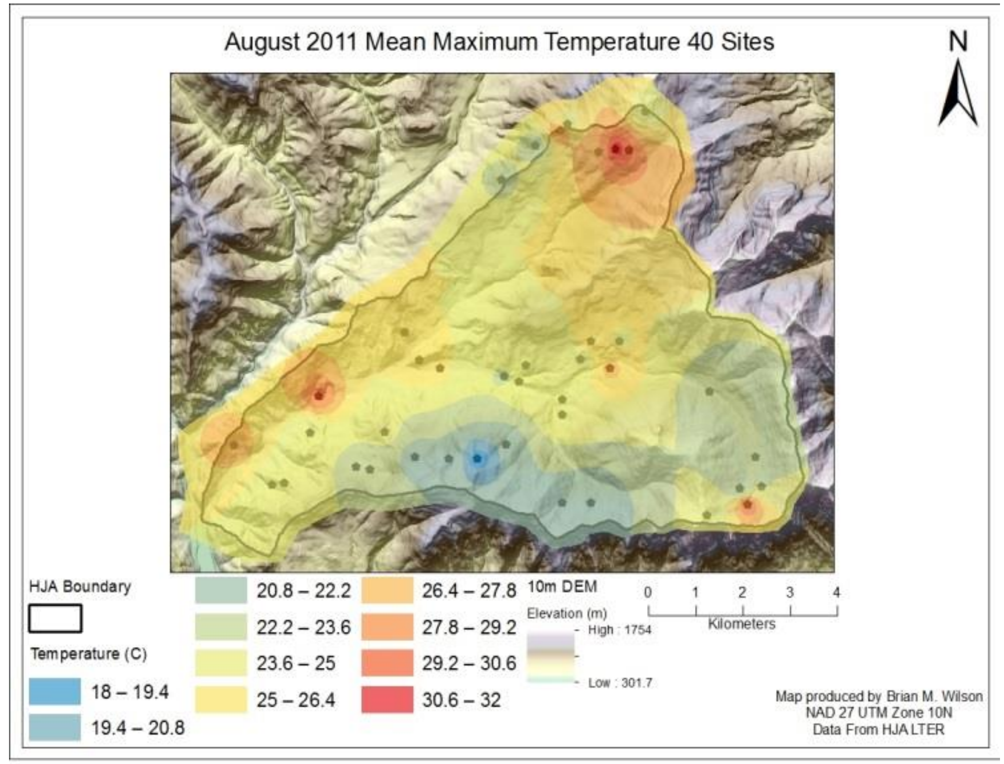
Mean monthly temperature range July 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

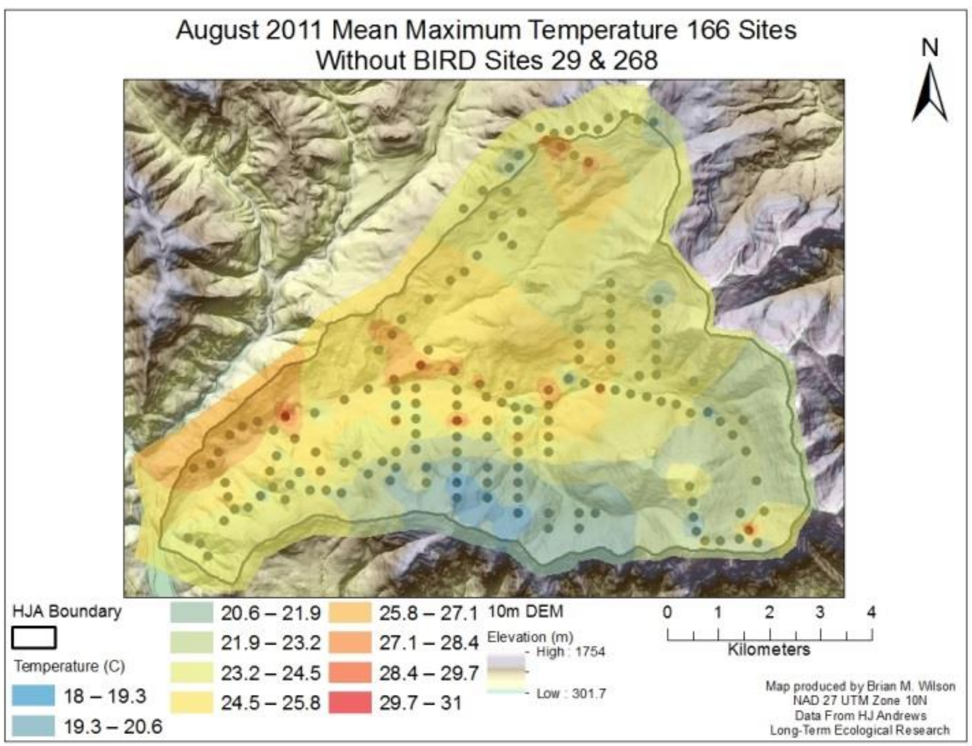


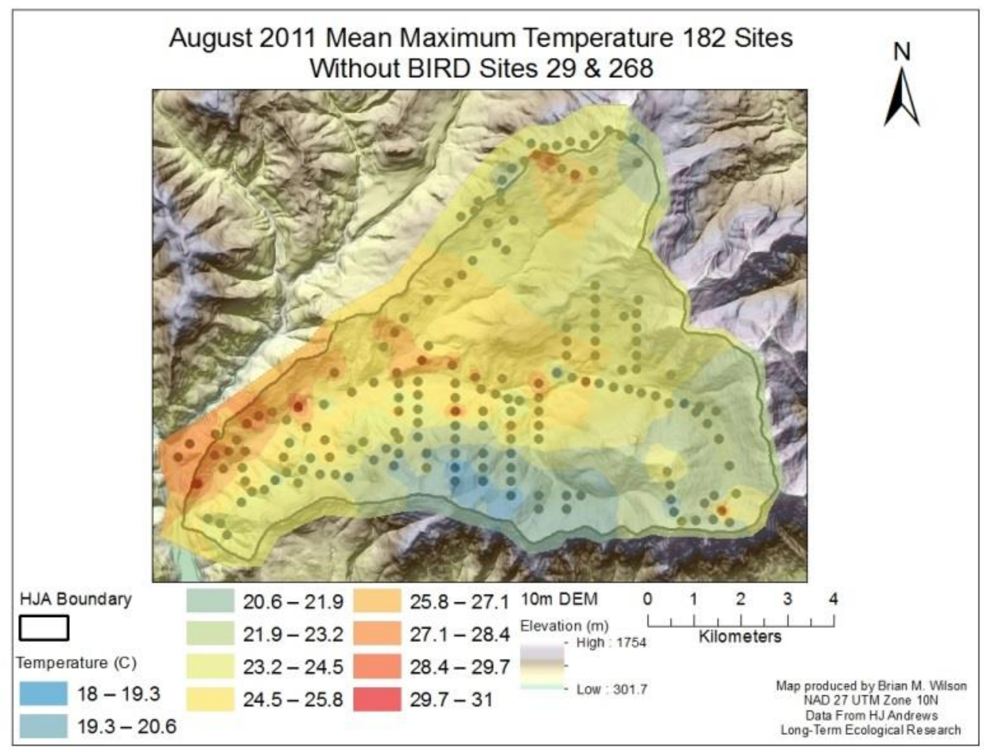




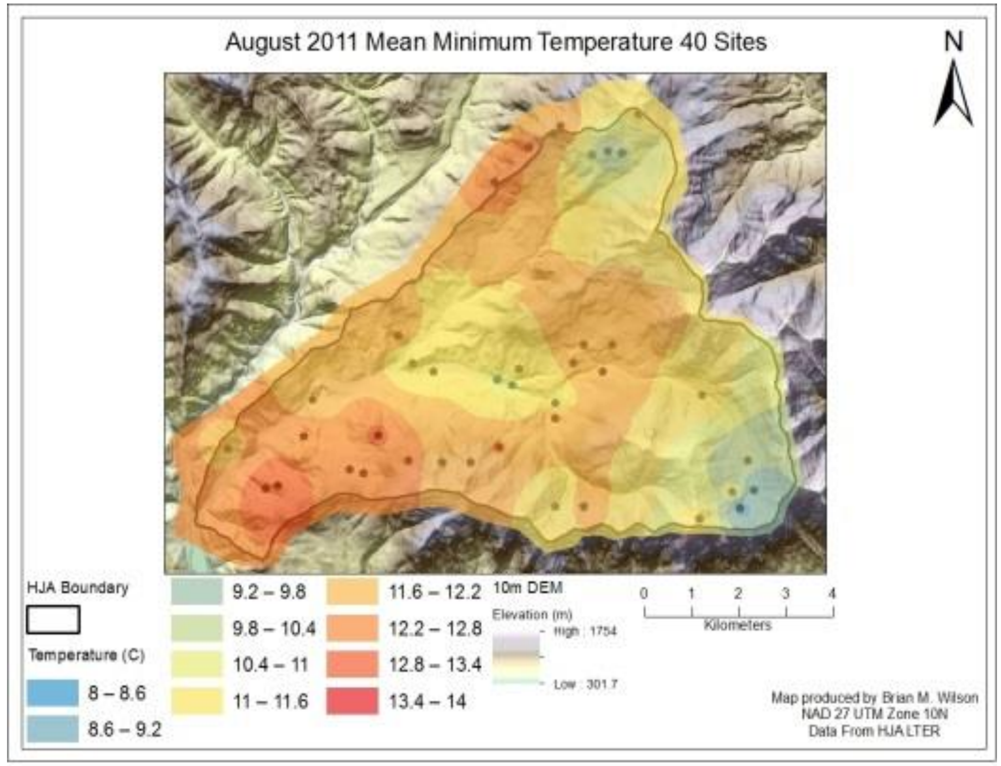
Mean monthly maximum temperature August 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

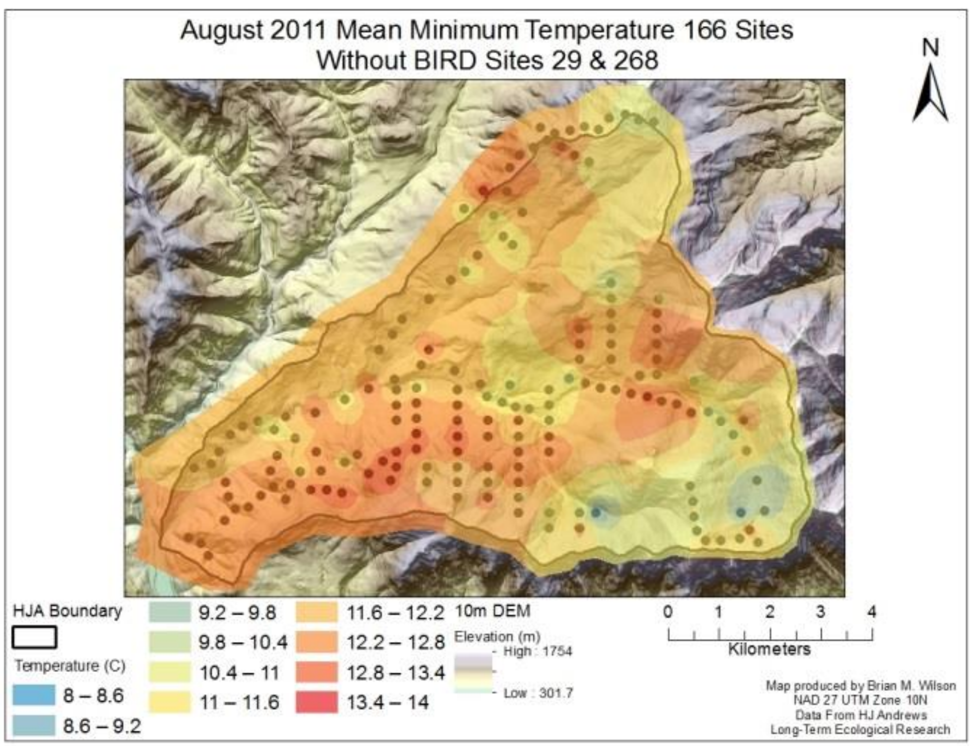


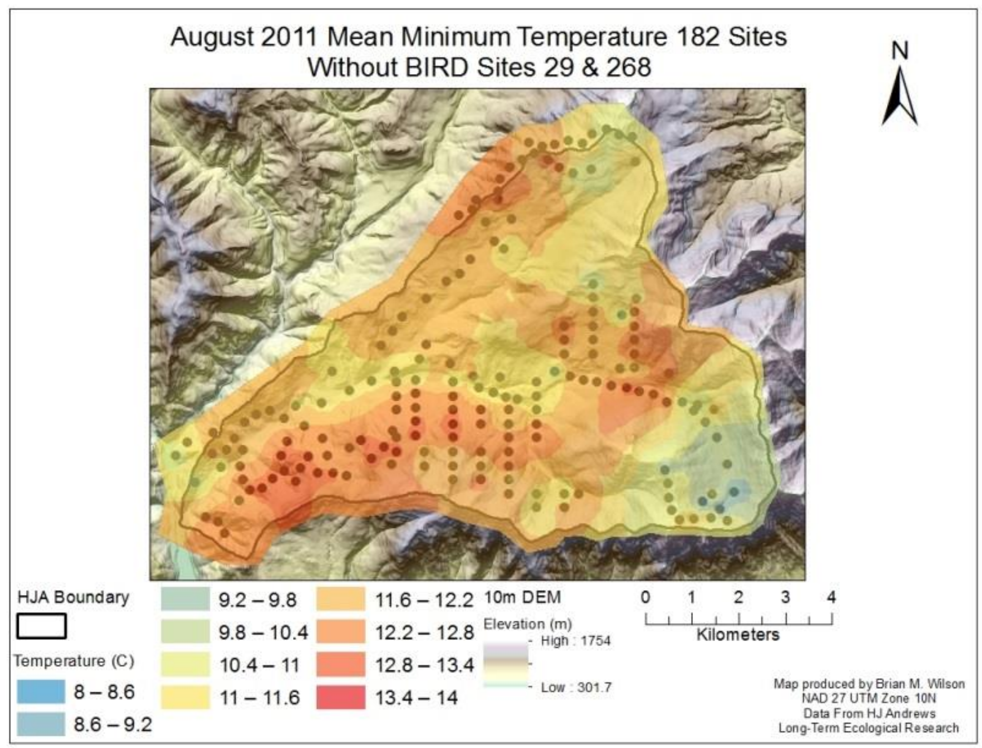




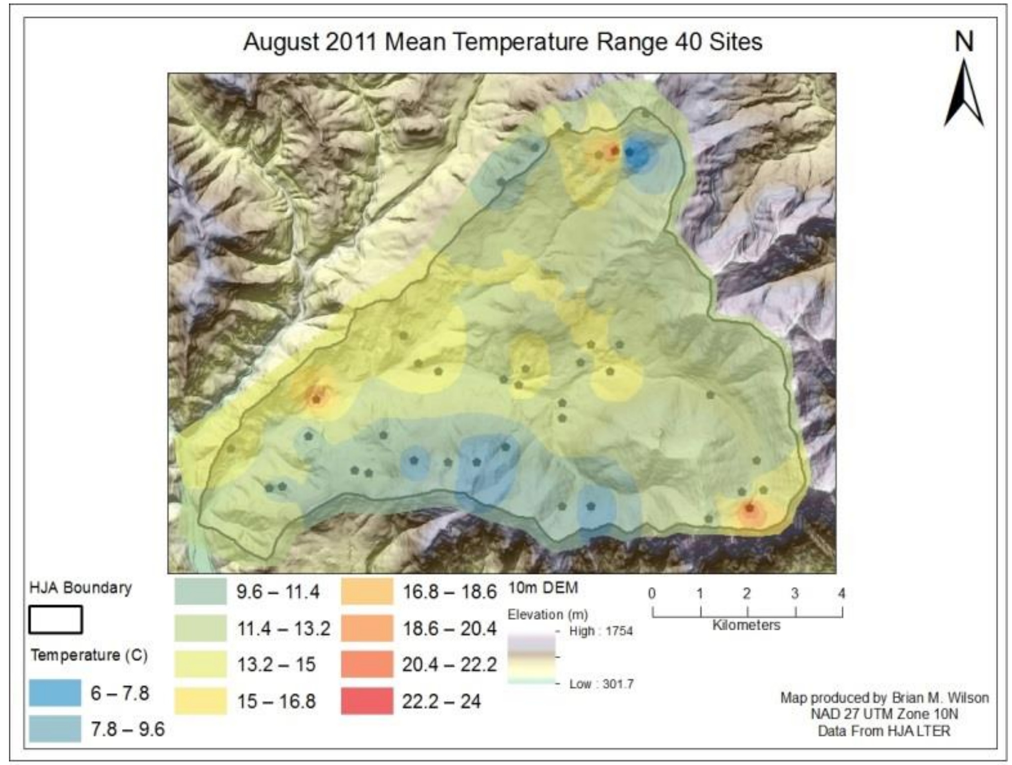
Mean monthly minimum temperature August 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

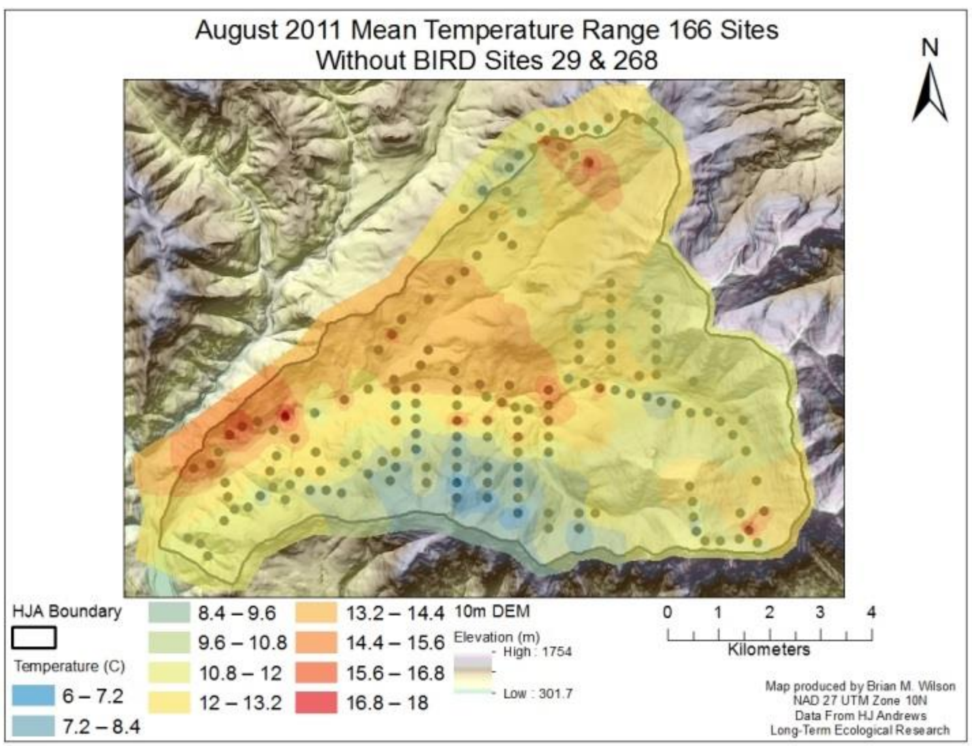


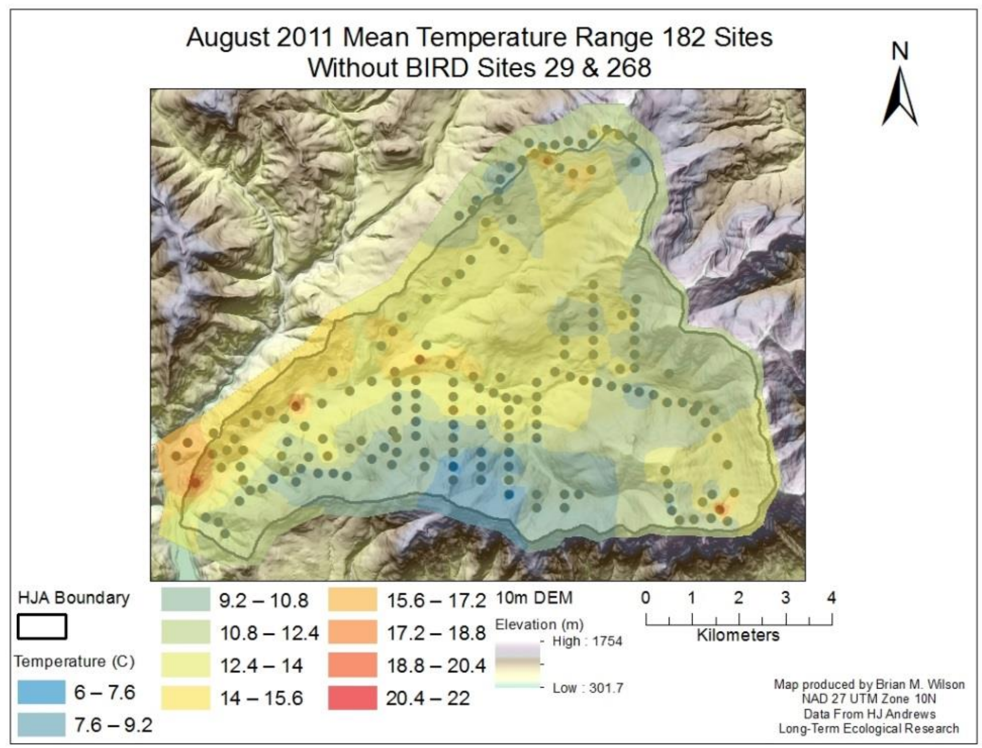




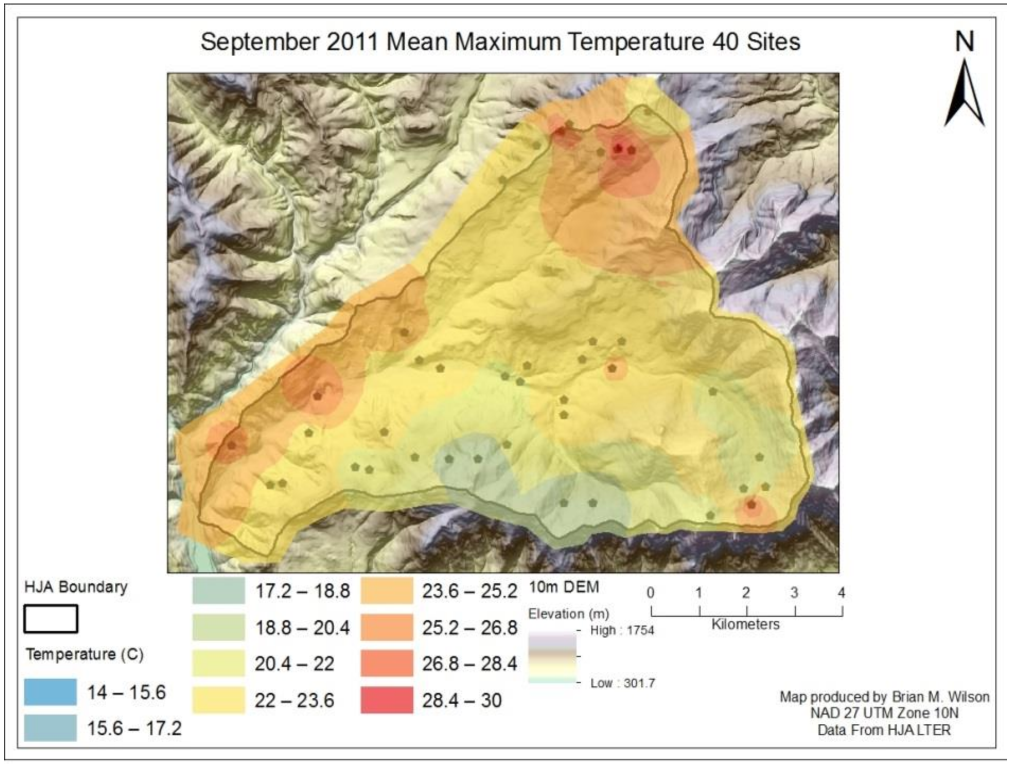
Mean monthly temperature range August 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

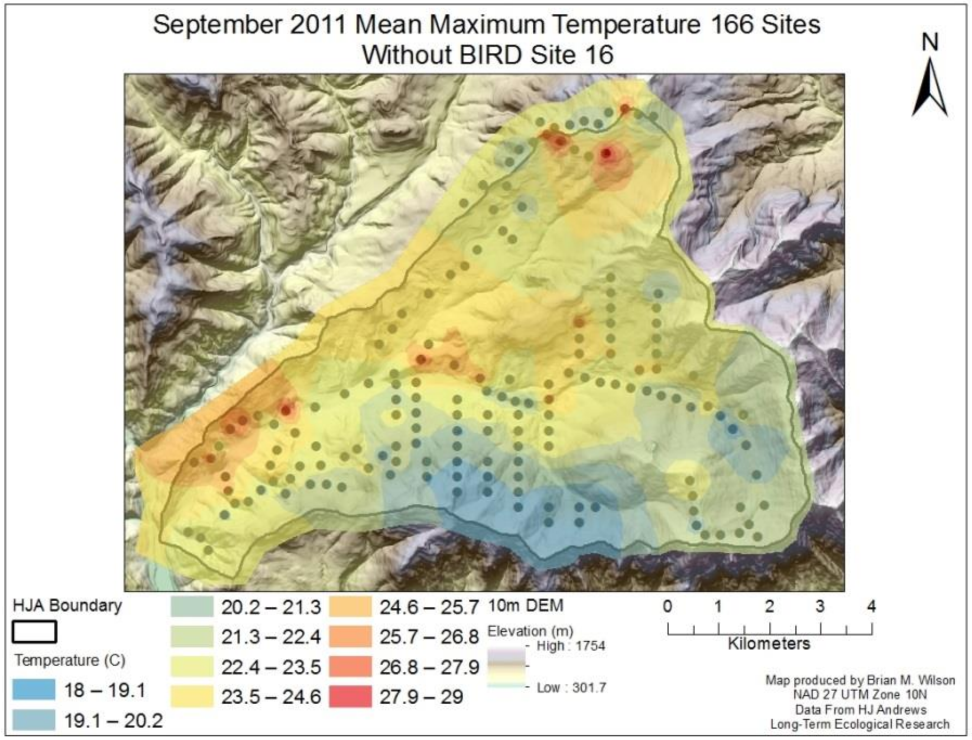


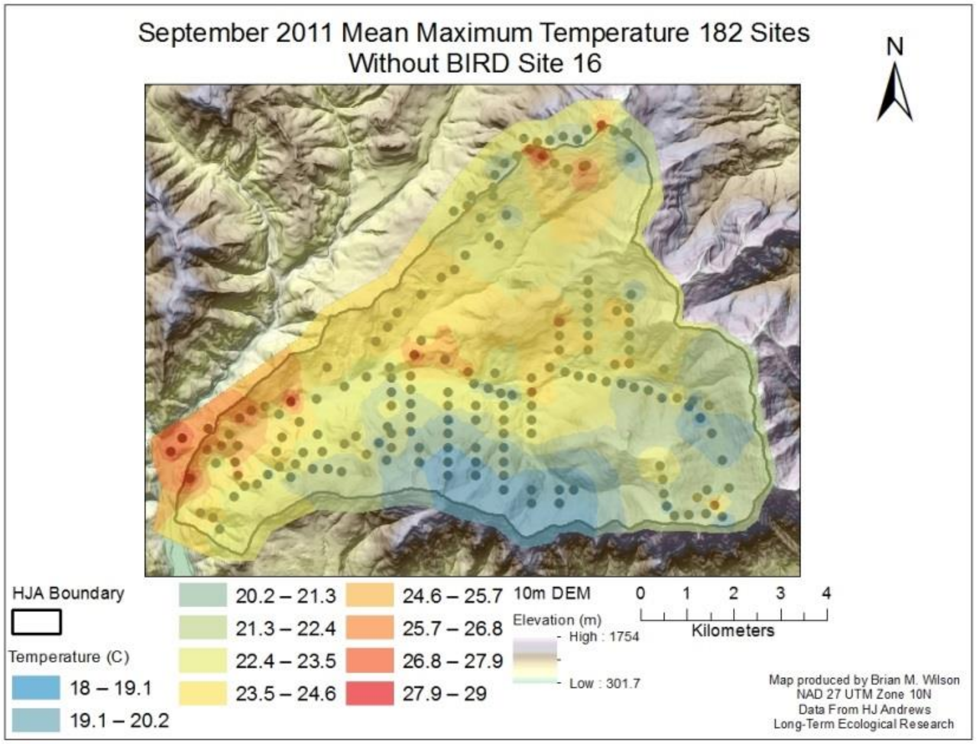




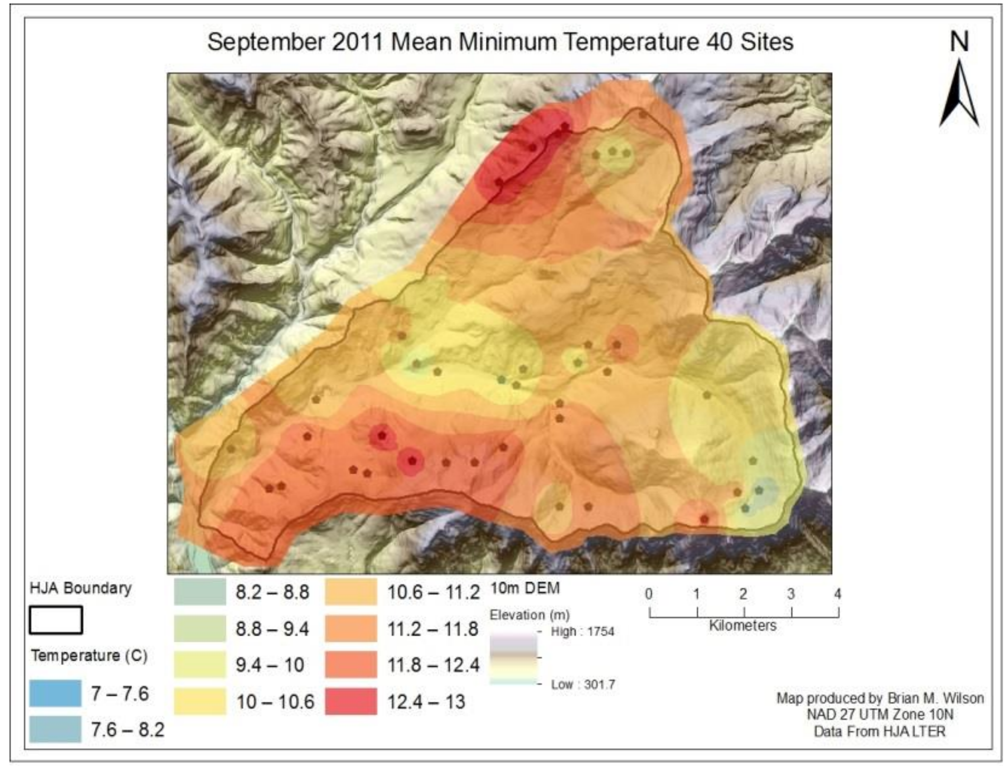
Mean monthly maximum temperature September 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

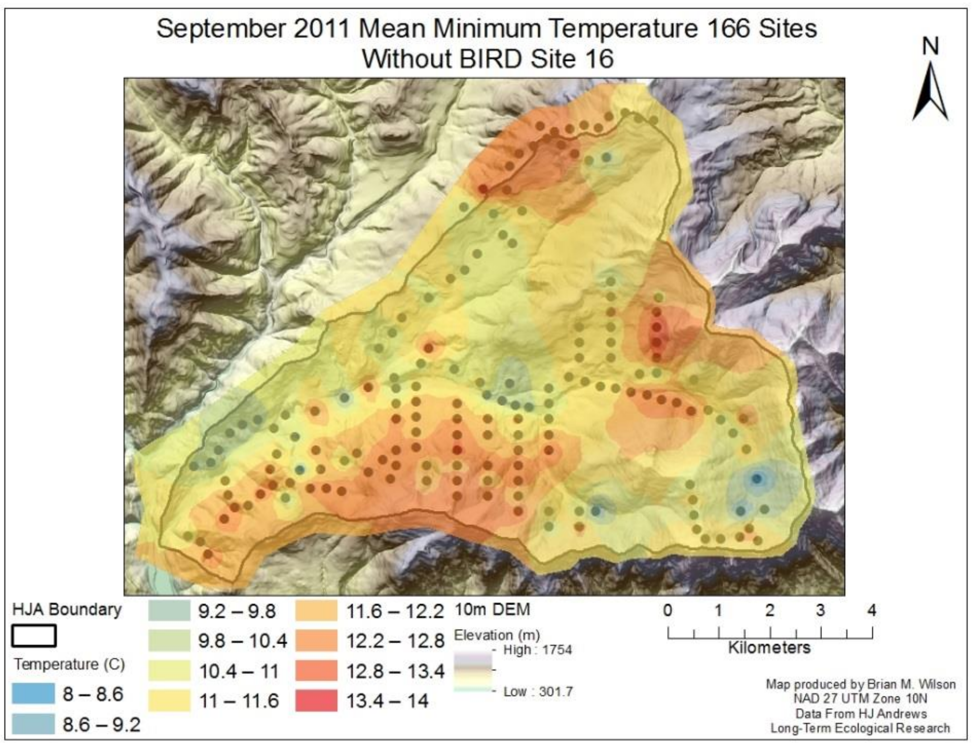


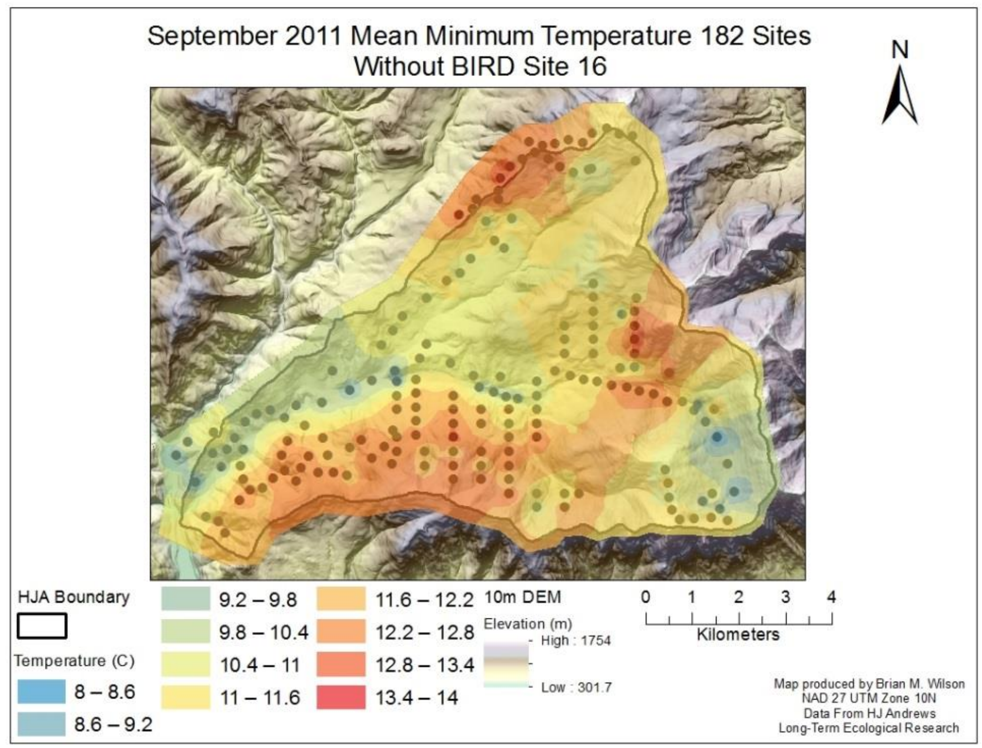




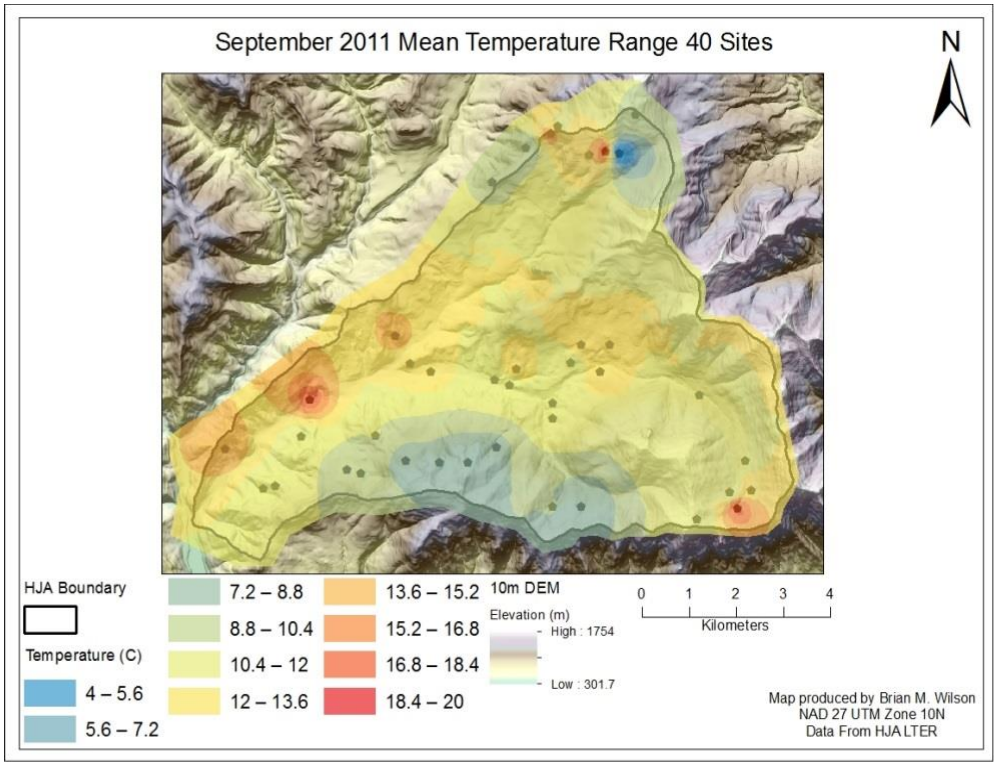
Mean monthly minimum temperature September 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

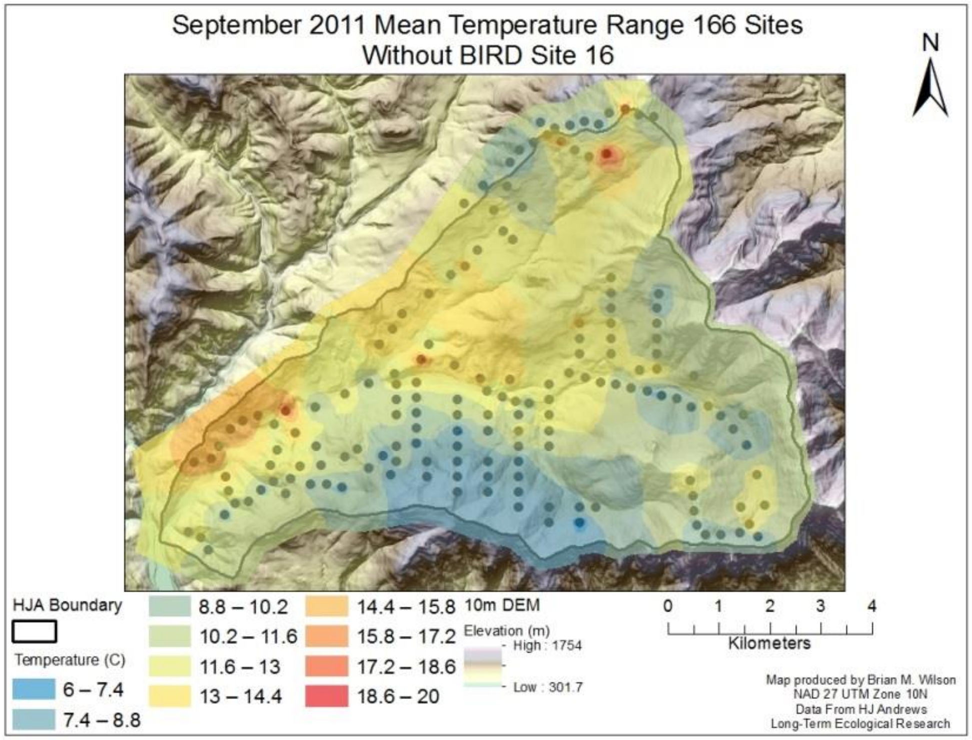


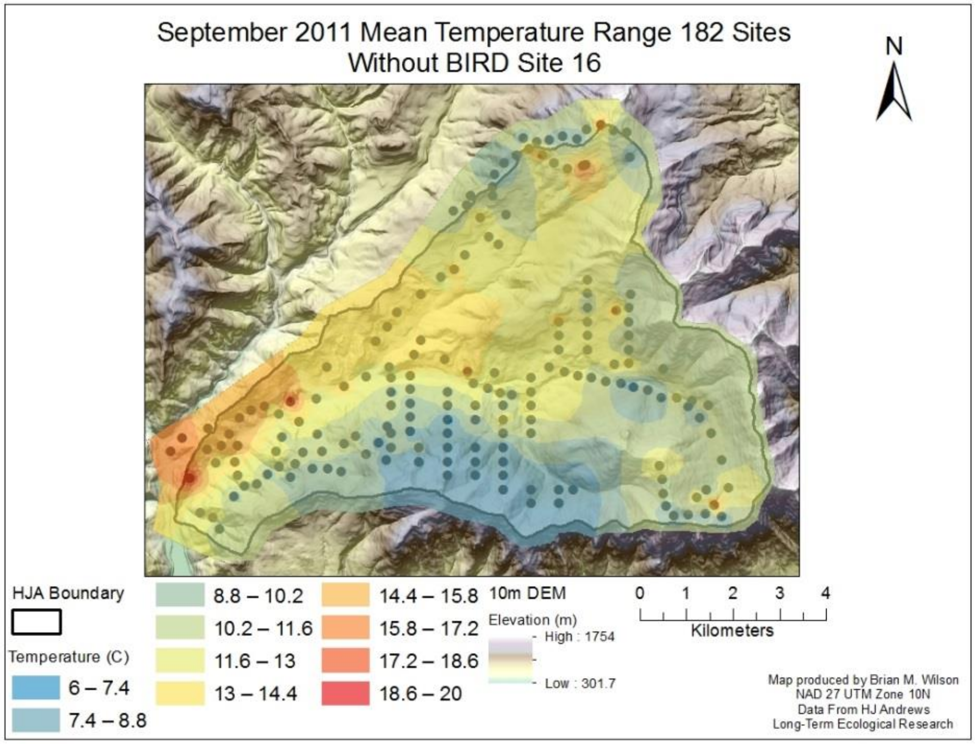




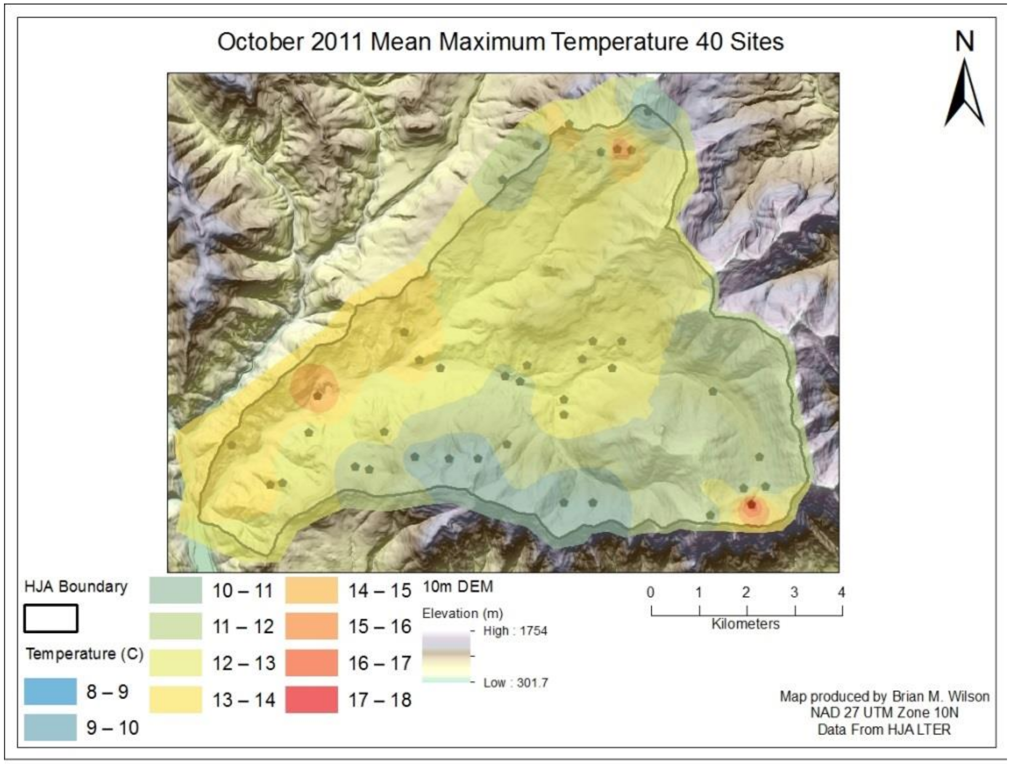
Mean monthly temperature range September 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

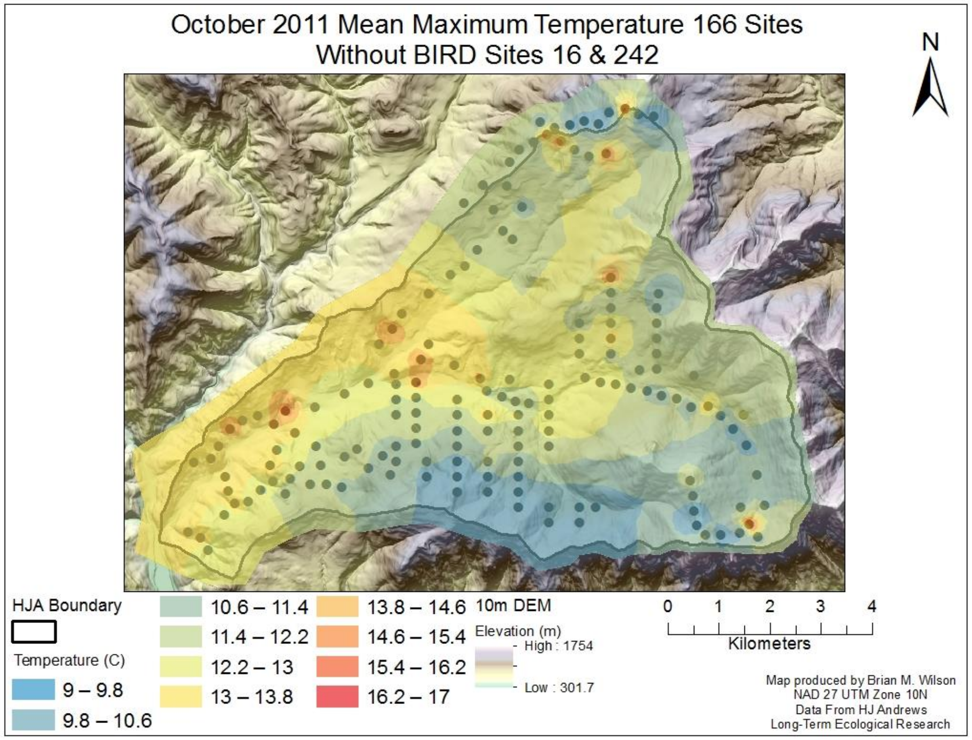


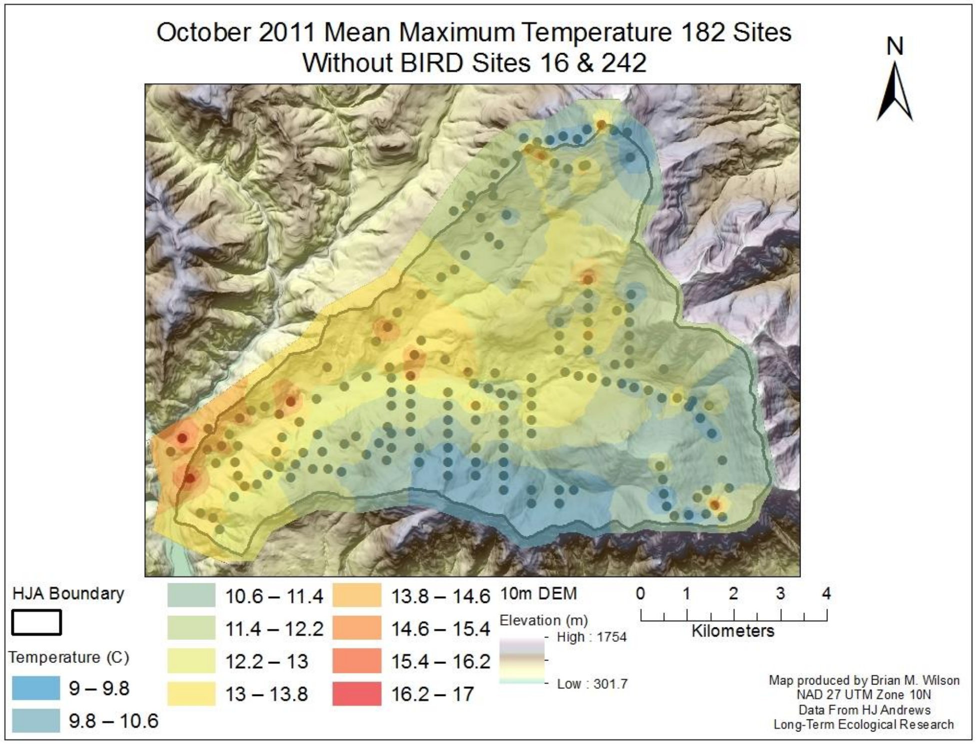




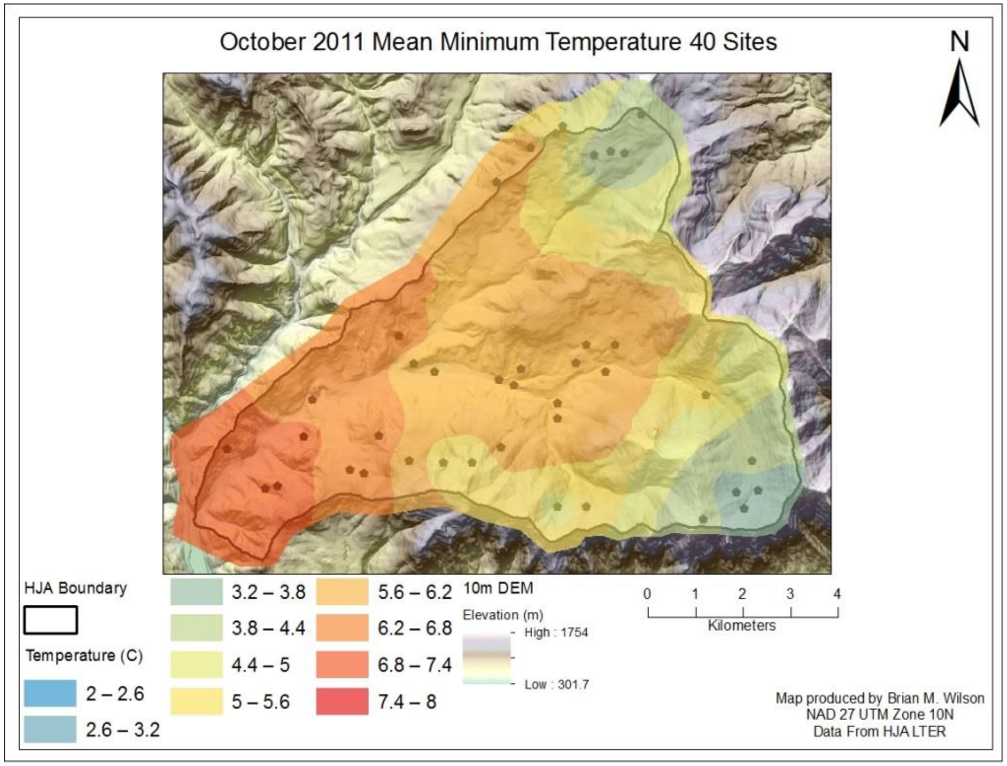
Mean monthly maximum temperature October 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

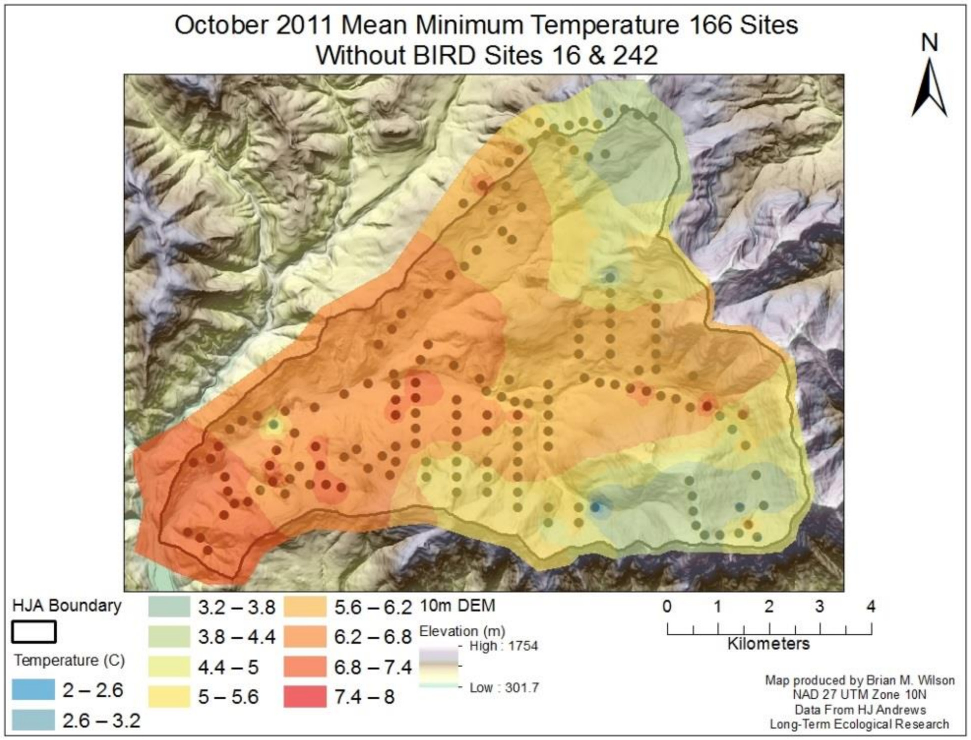


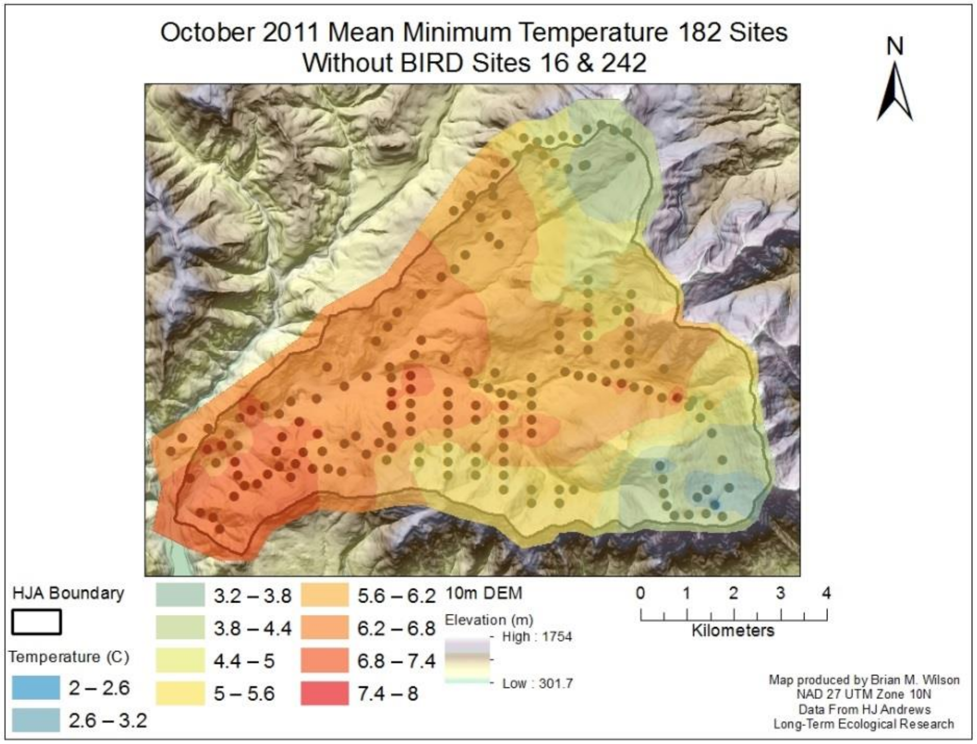




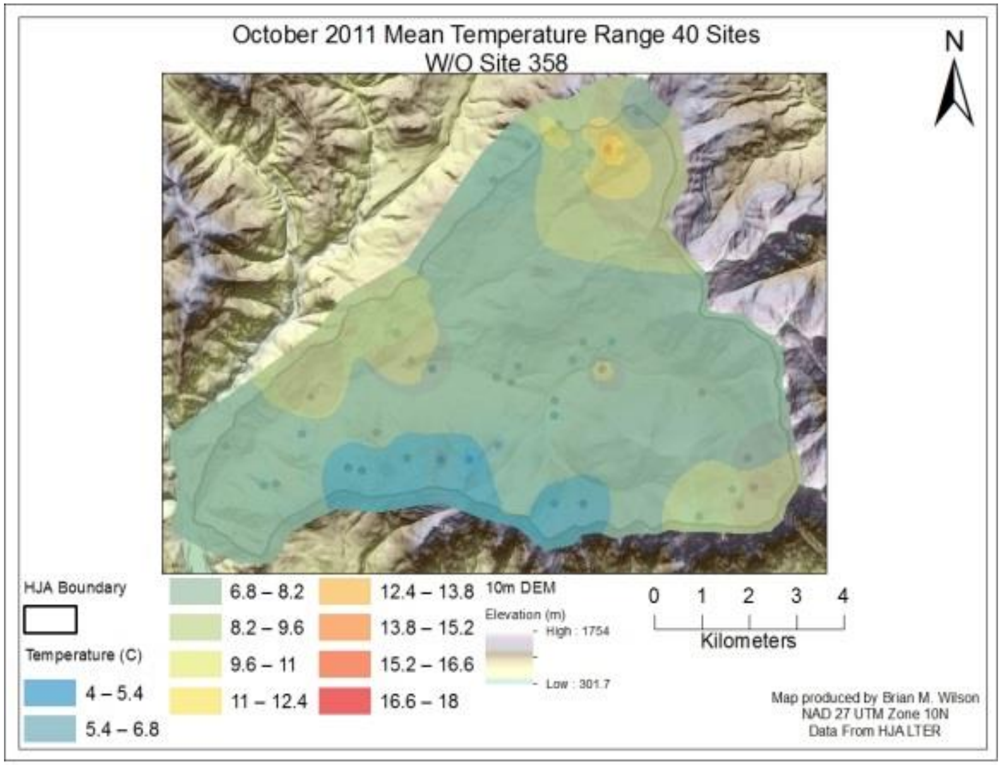
Mean monthly minimum temperature October 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

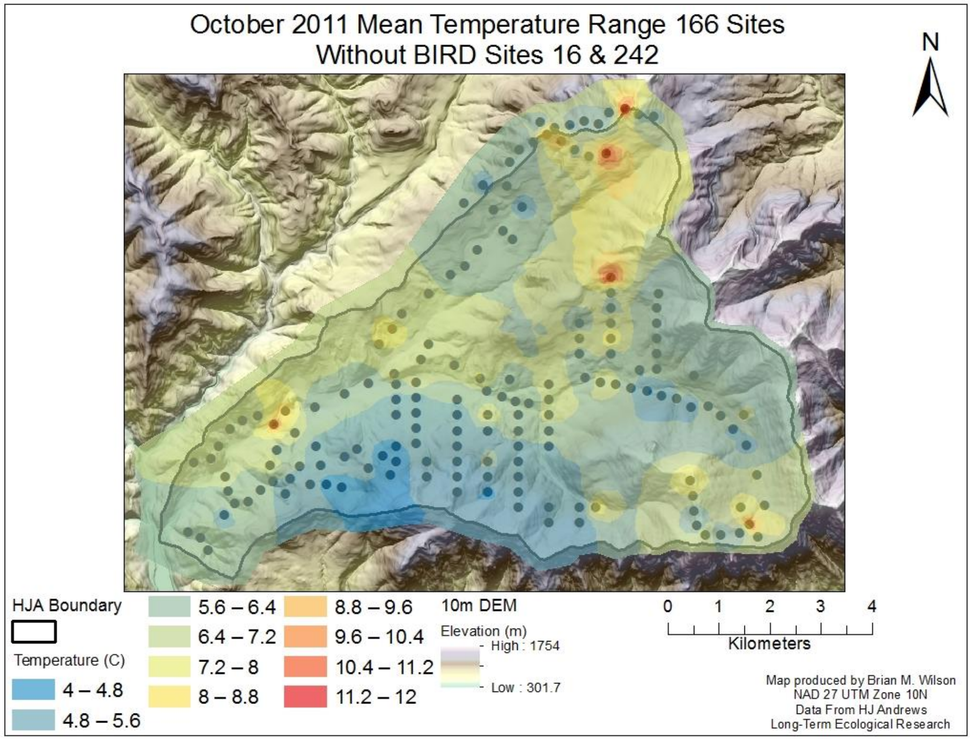


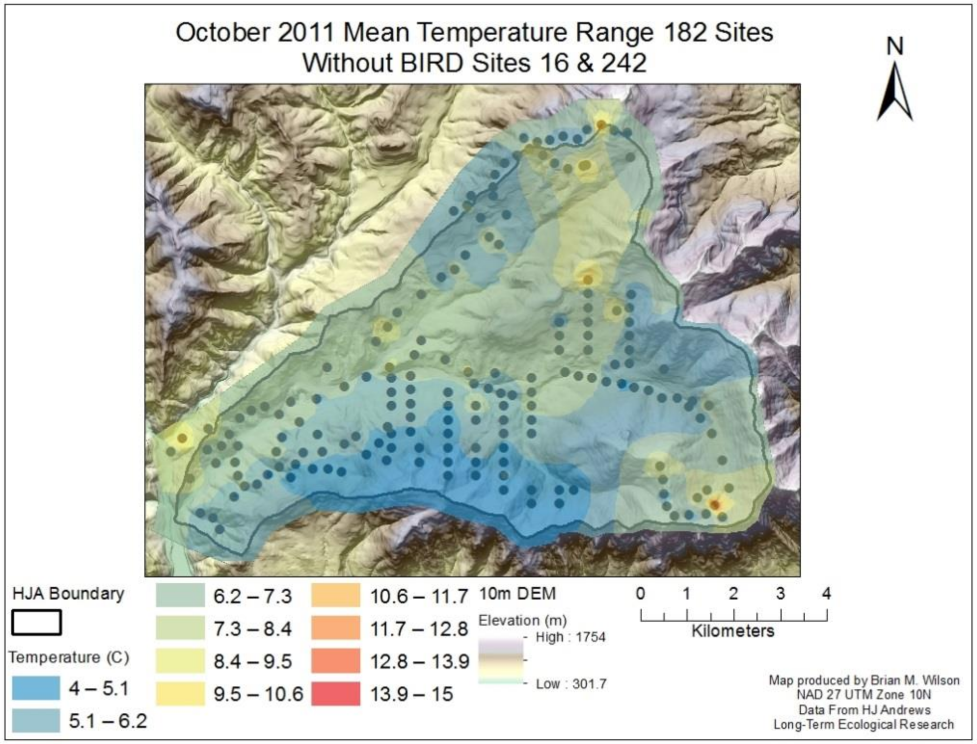




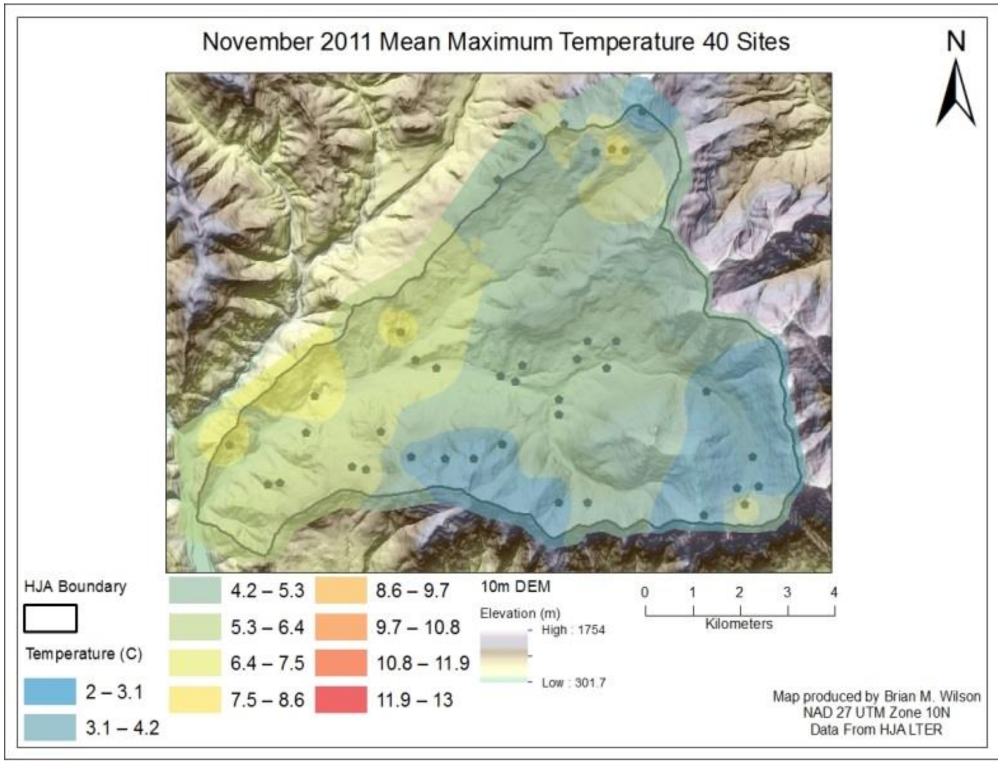
Mean monthly temperature range October 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

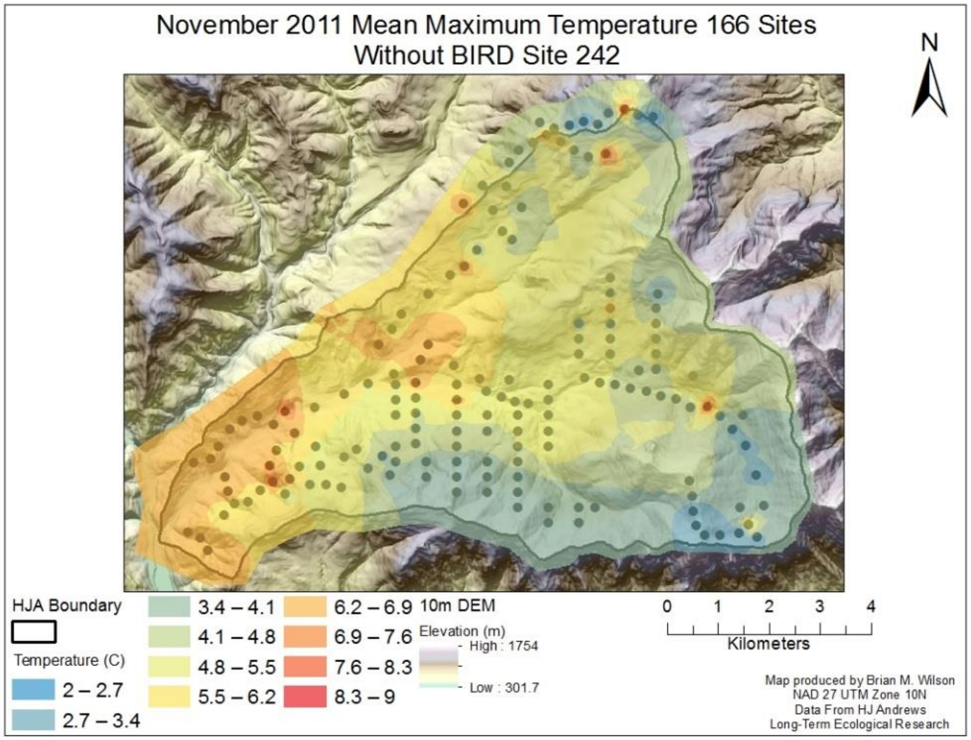


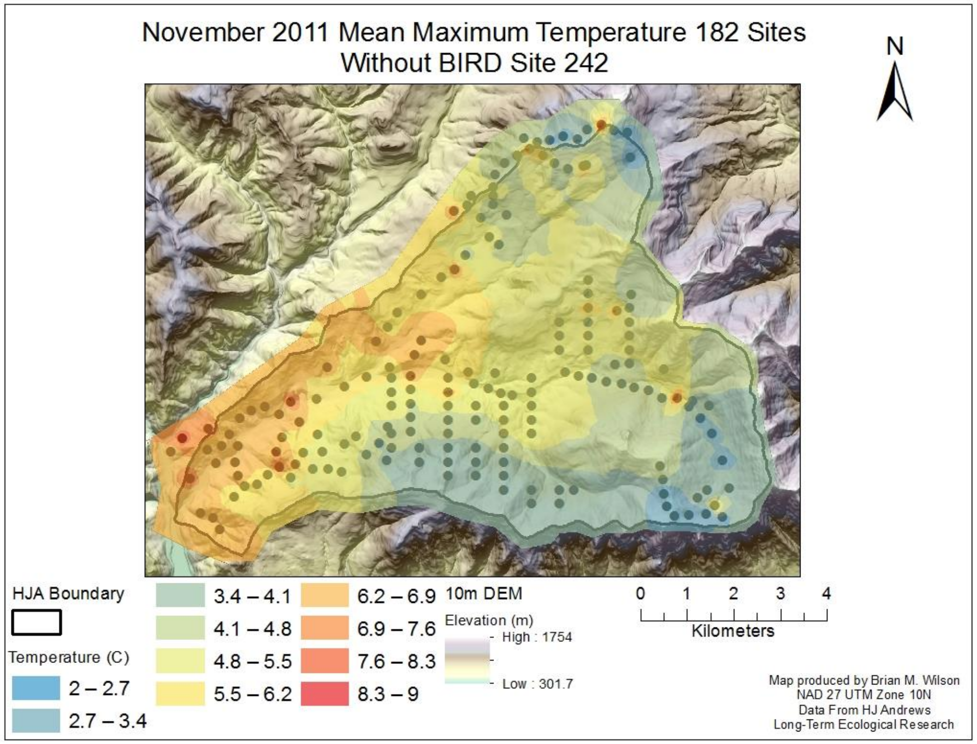




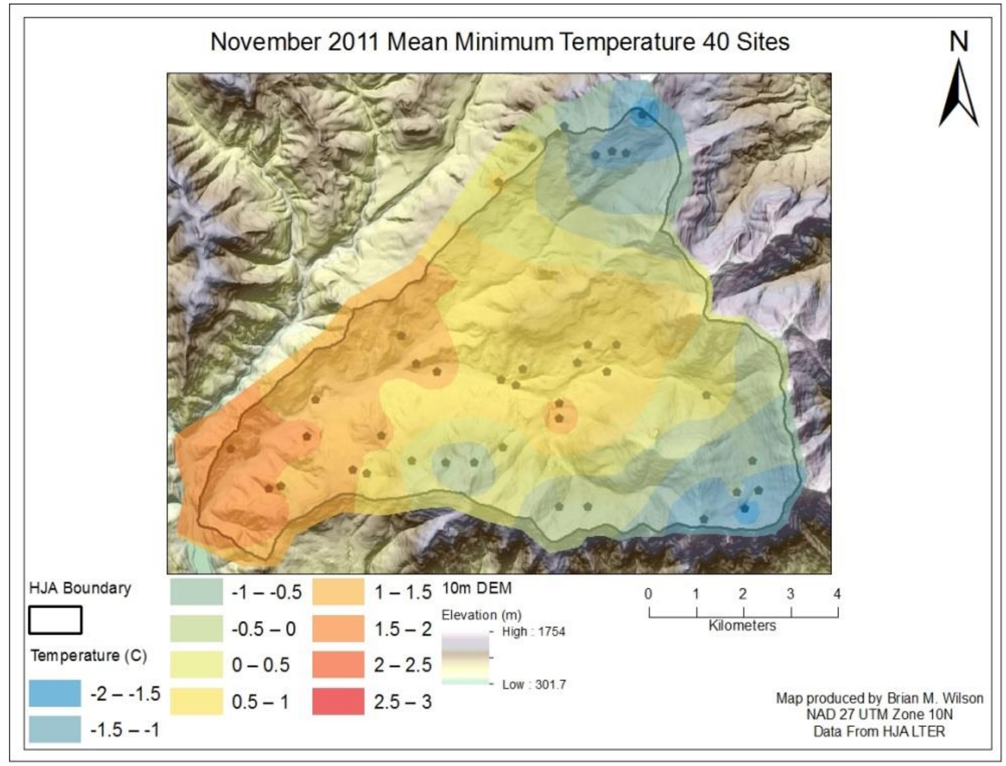
Mean monthly maximum temperature November 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

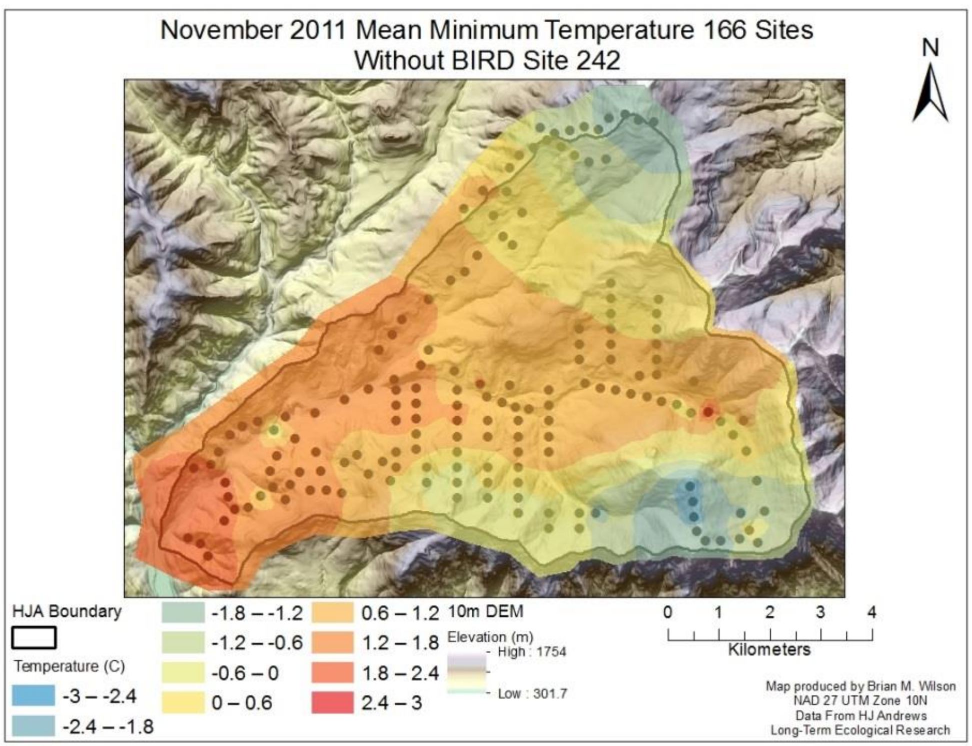


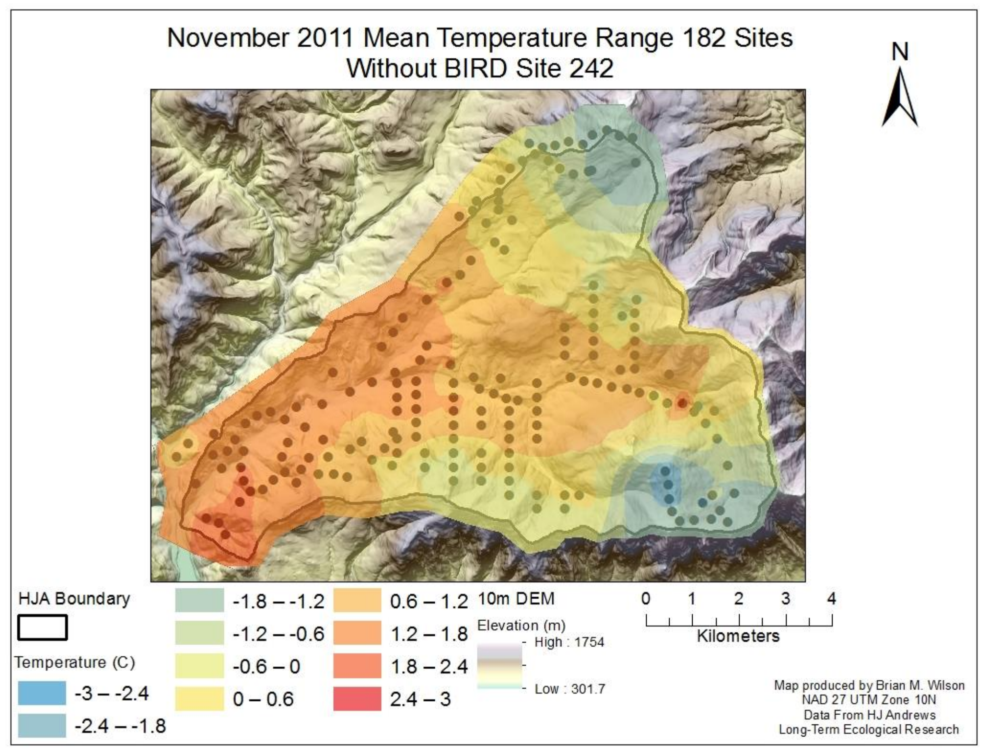




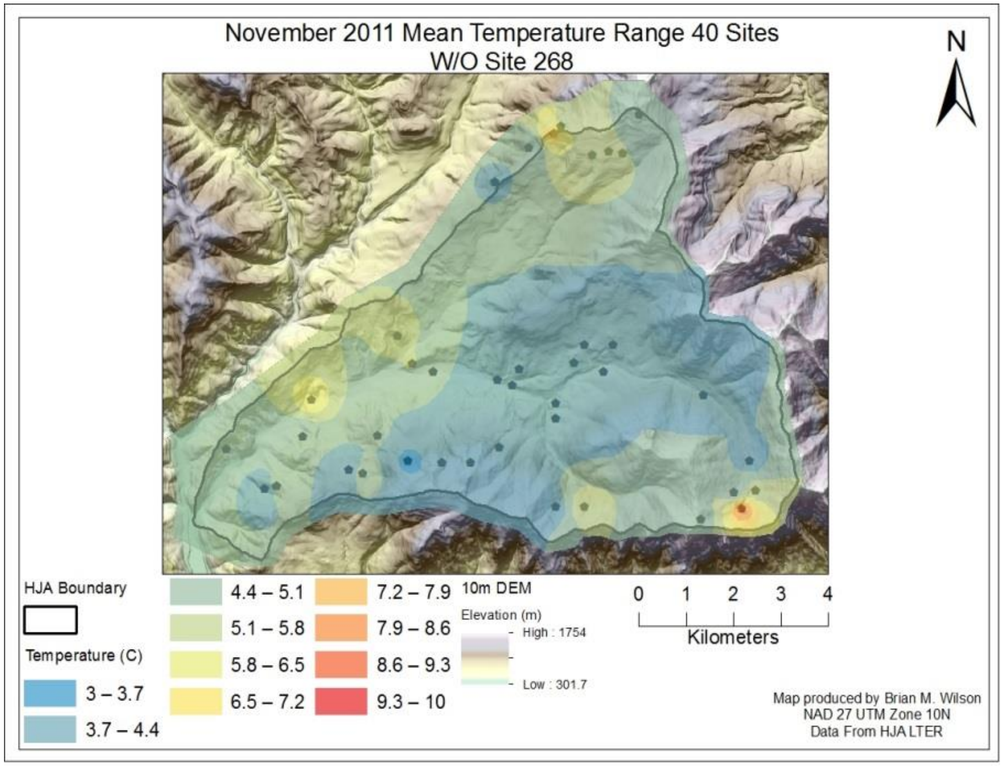
Mean monthly minimum temperature November 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

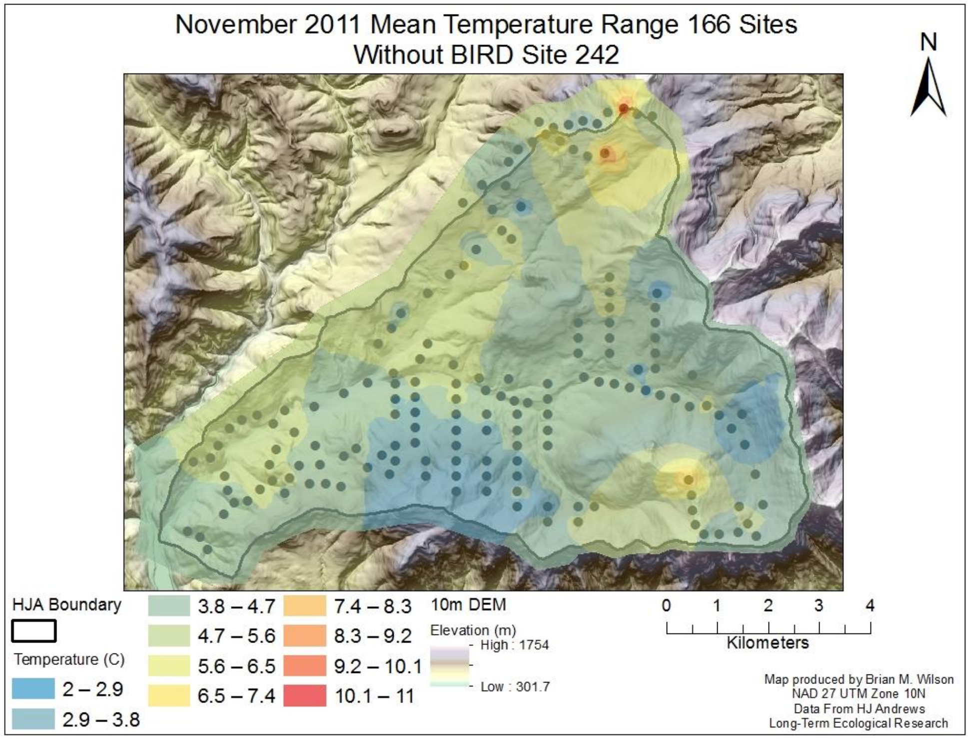


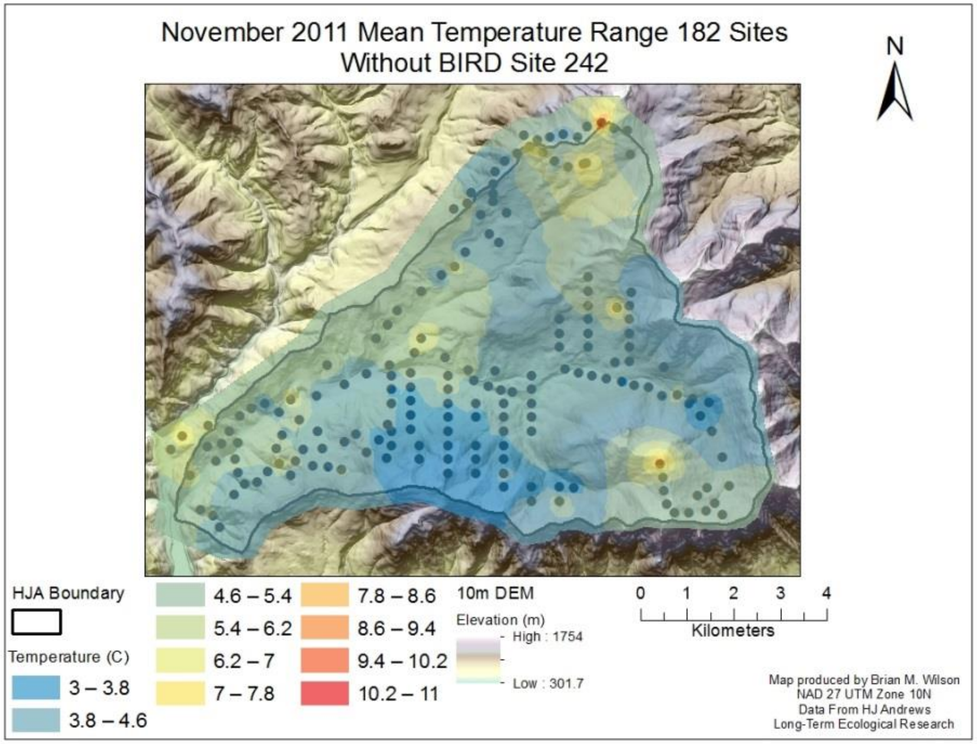




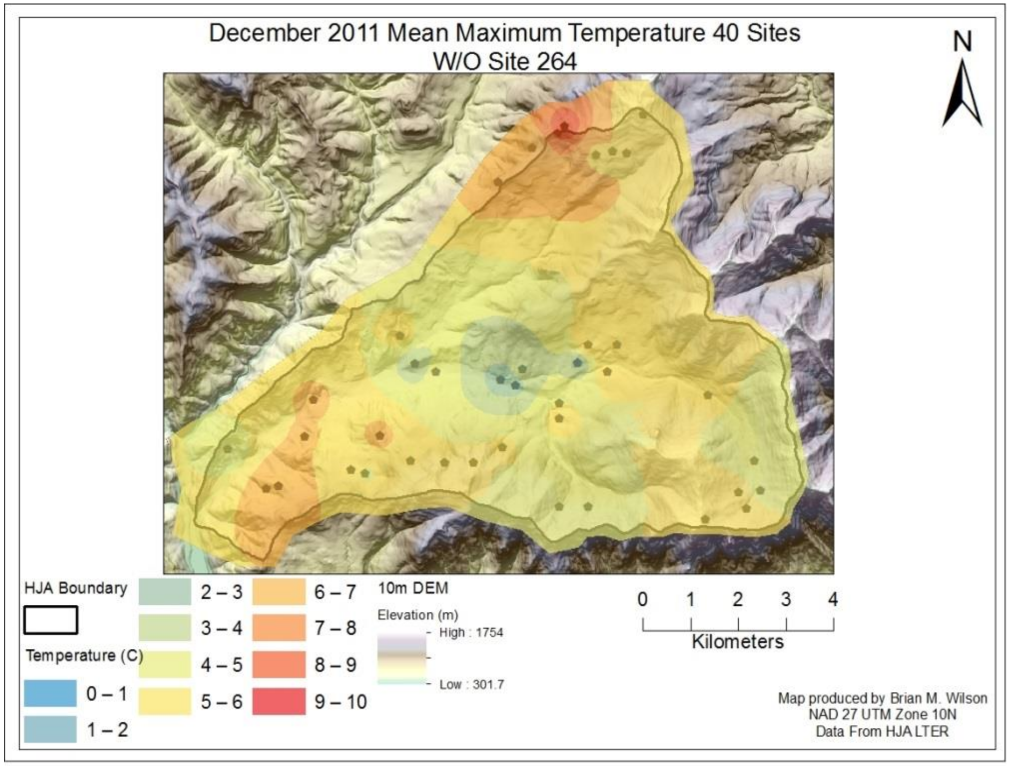
Mean monthly temperature range November 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

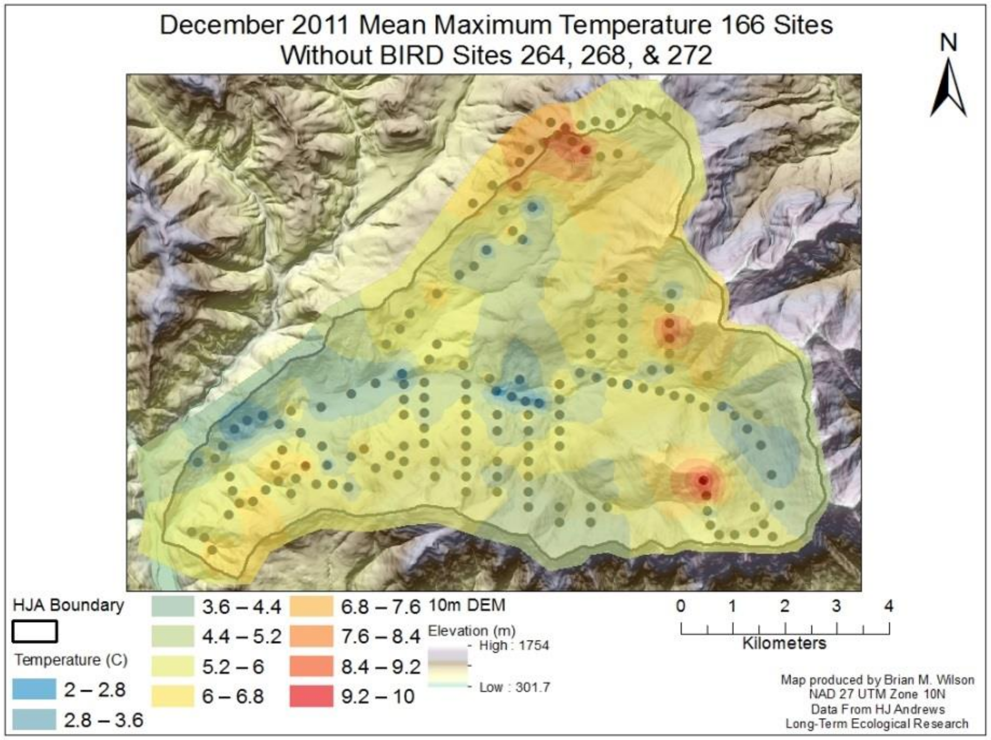


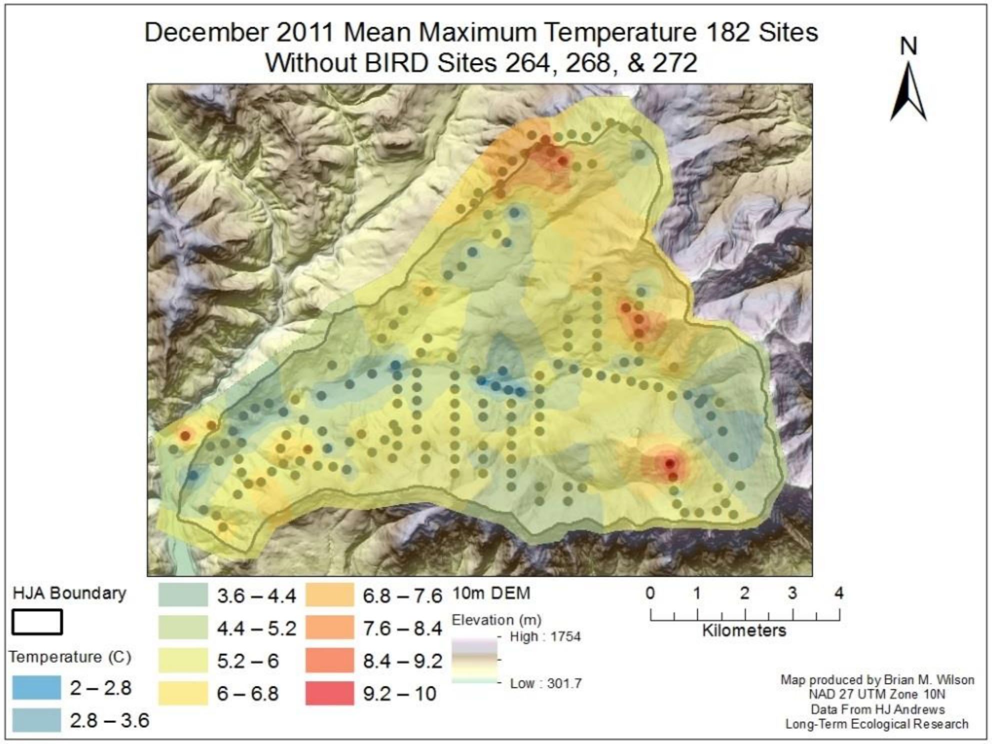




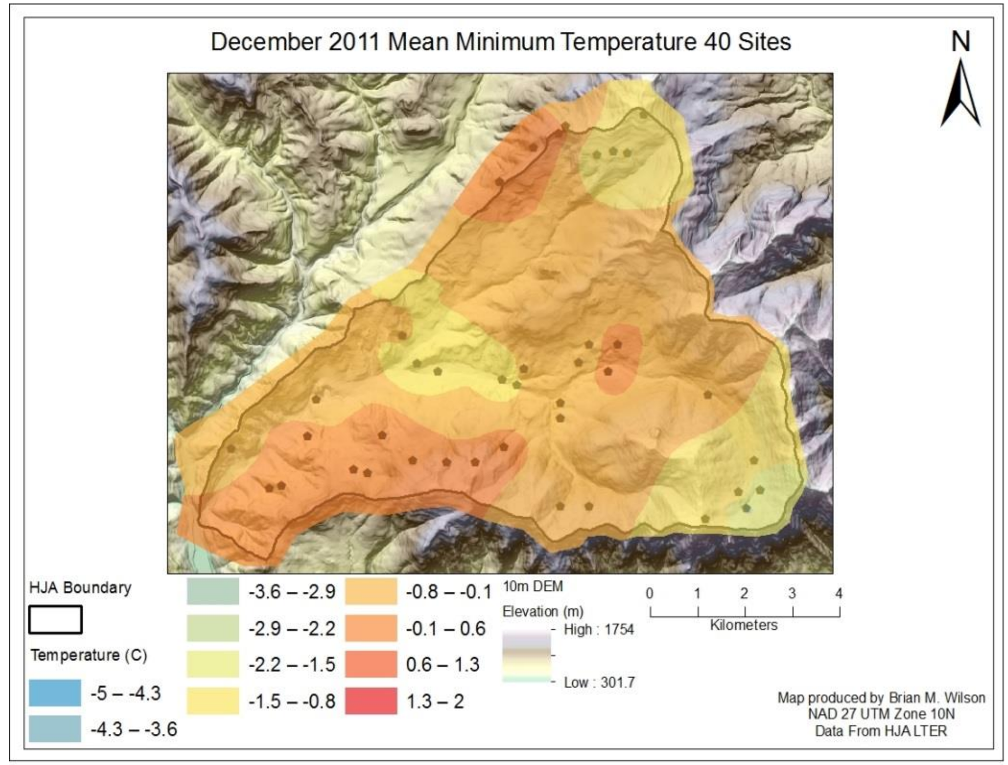
Mean monthly maximum temperature December 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

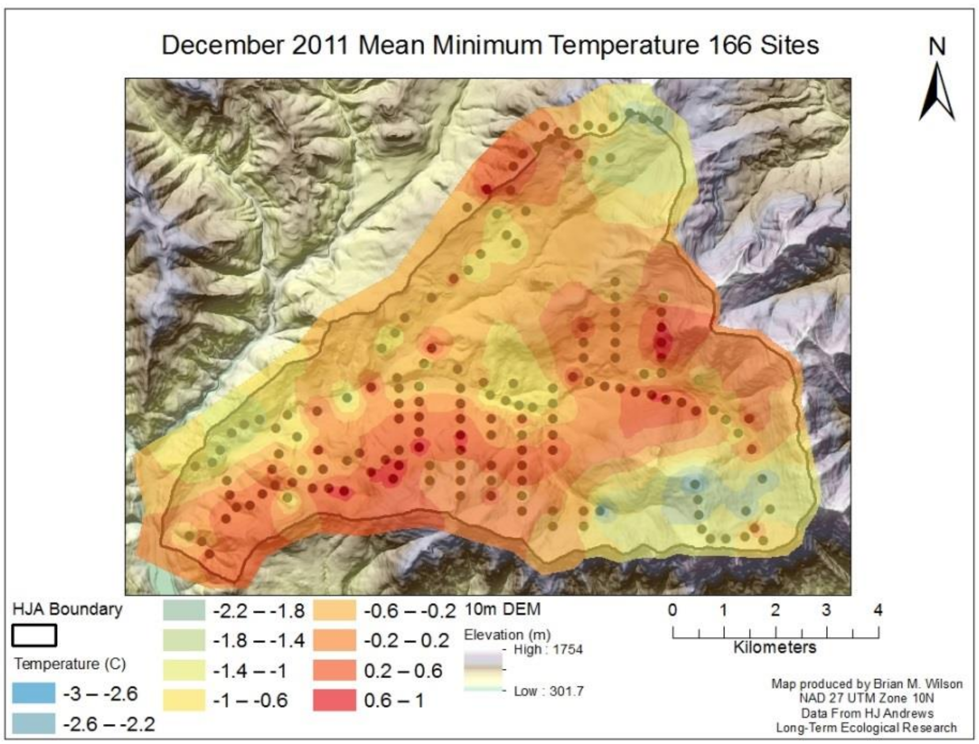


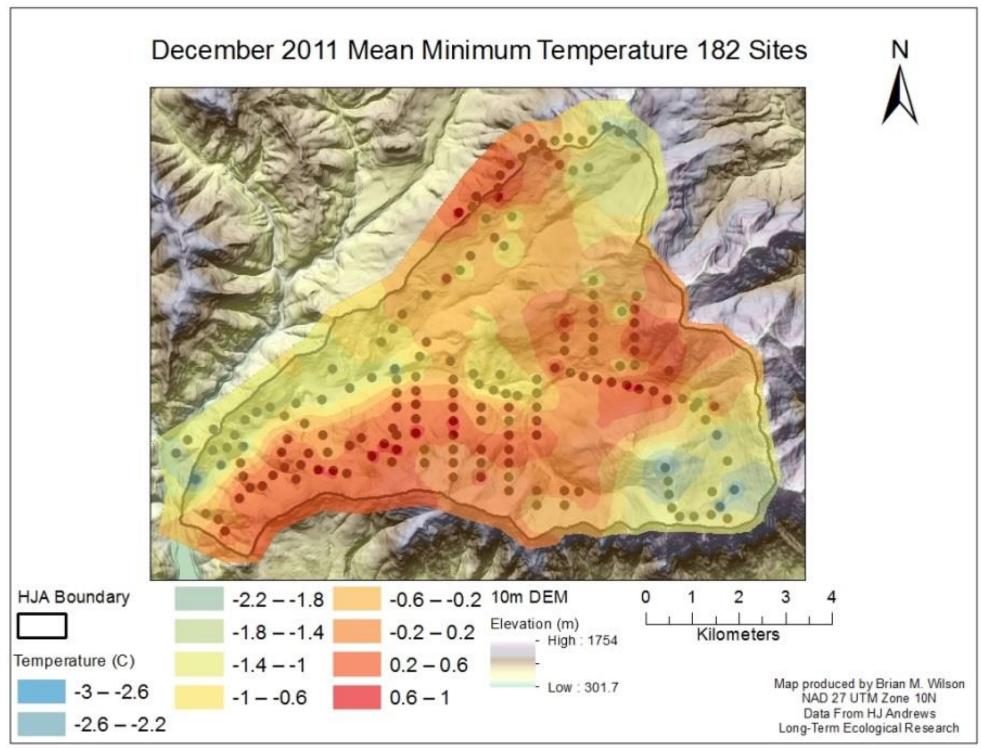




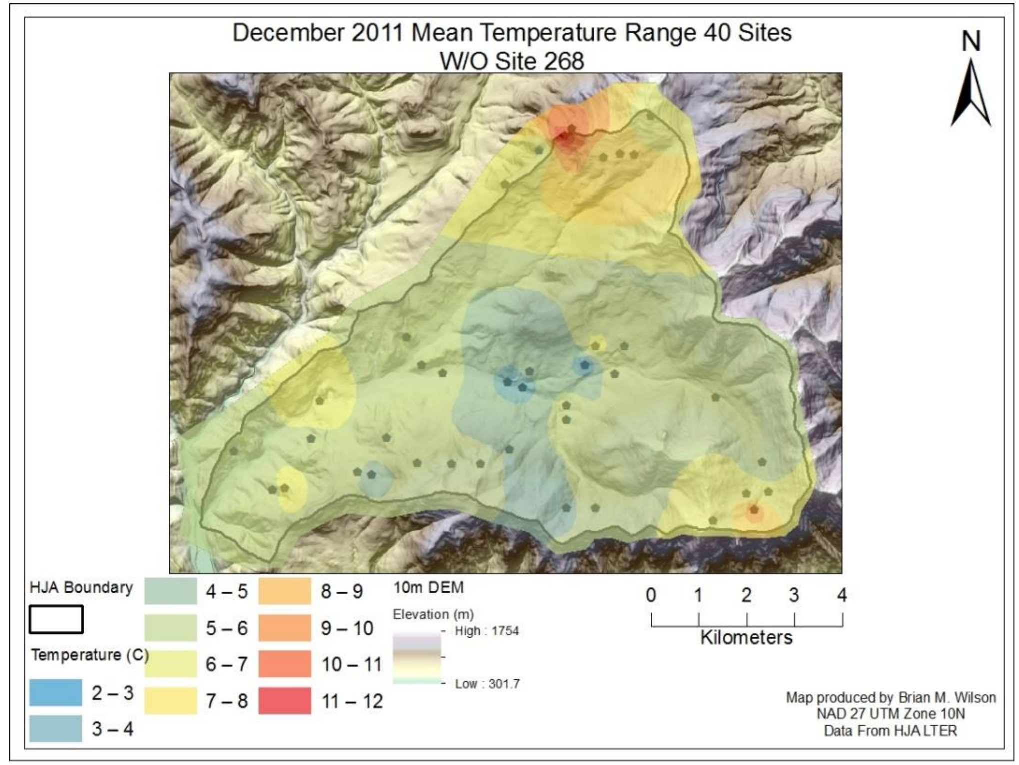
Mean monthly minimum temperature December 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

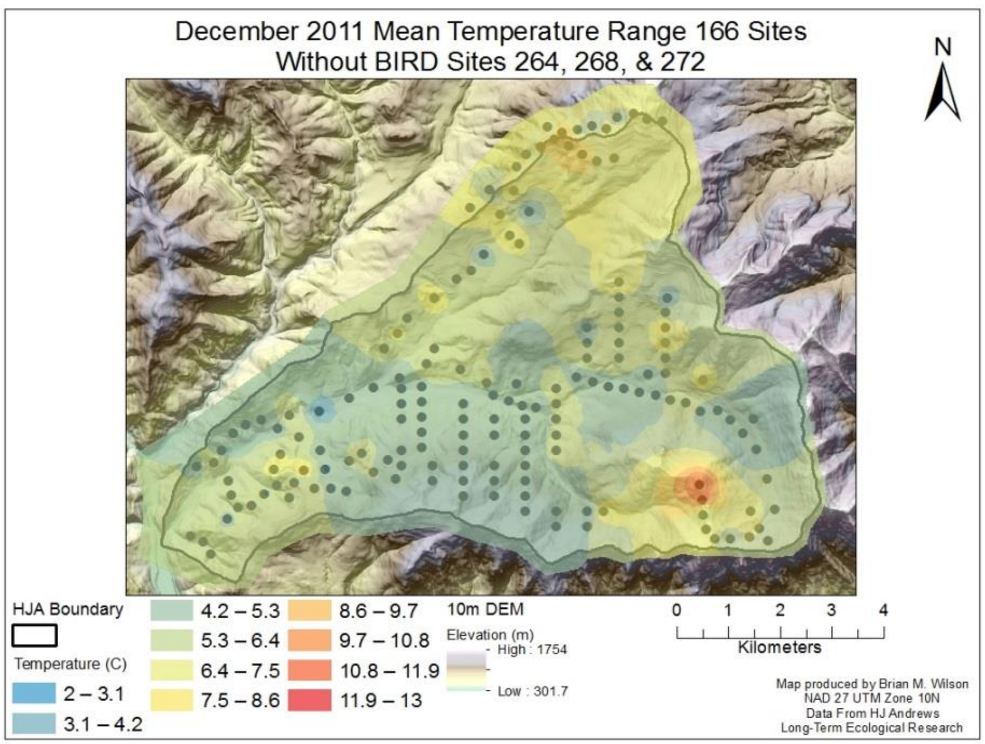


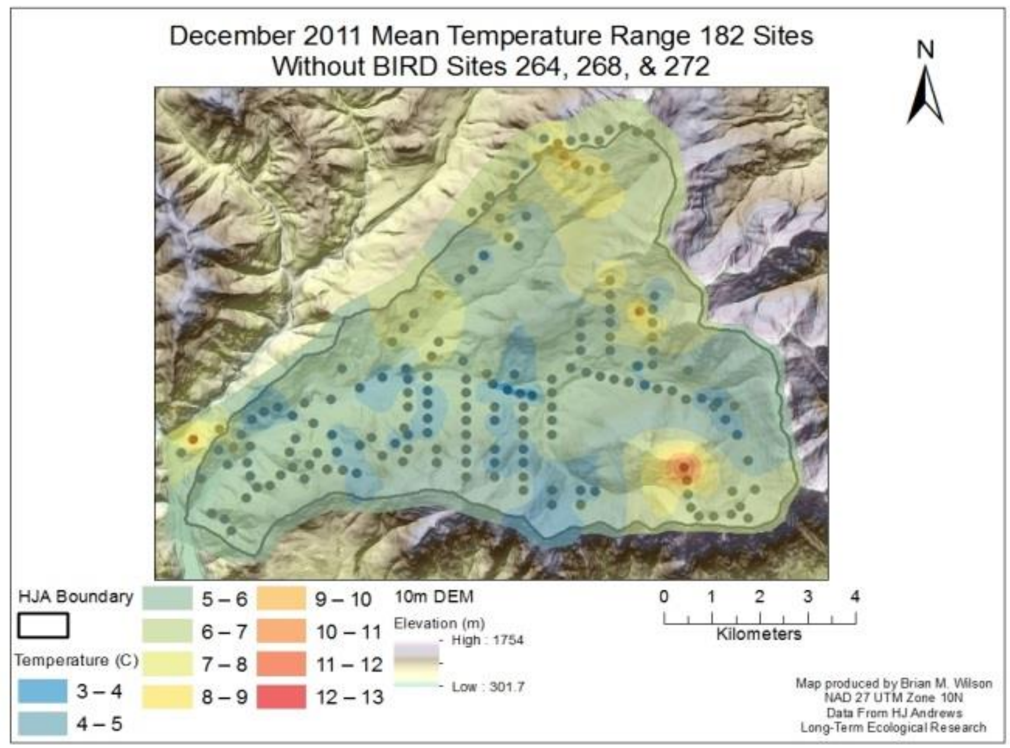




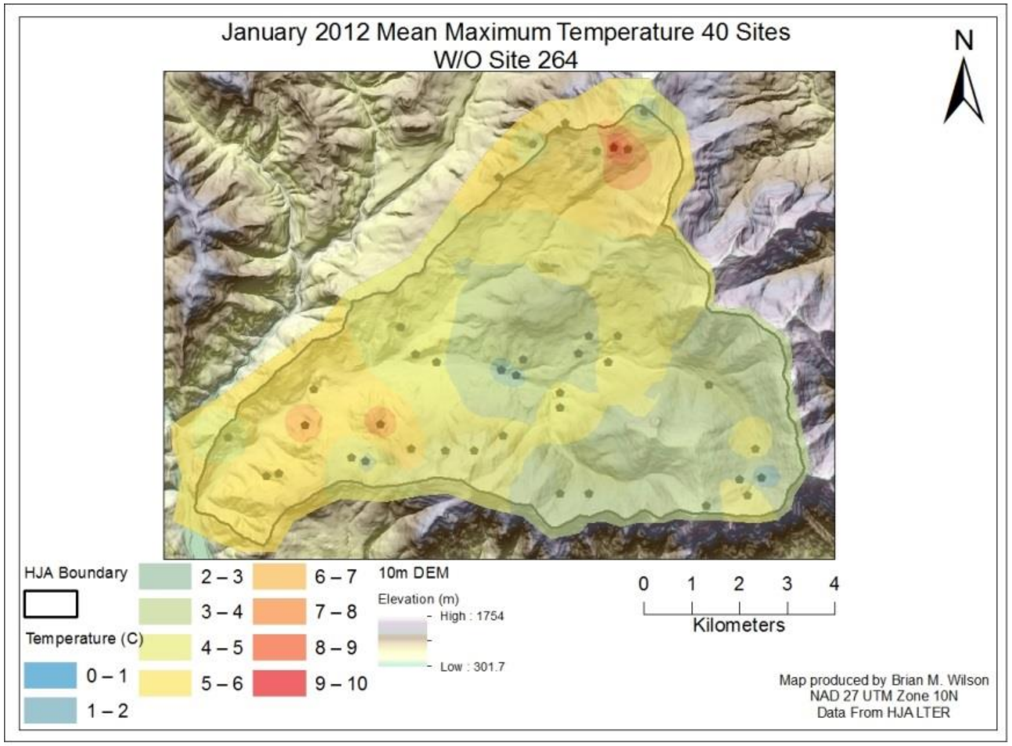
Mean monthly temperature range December 2011 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

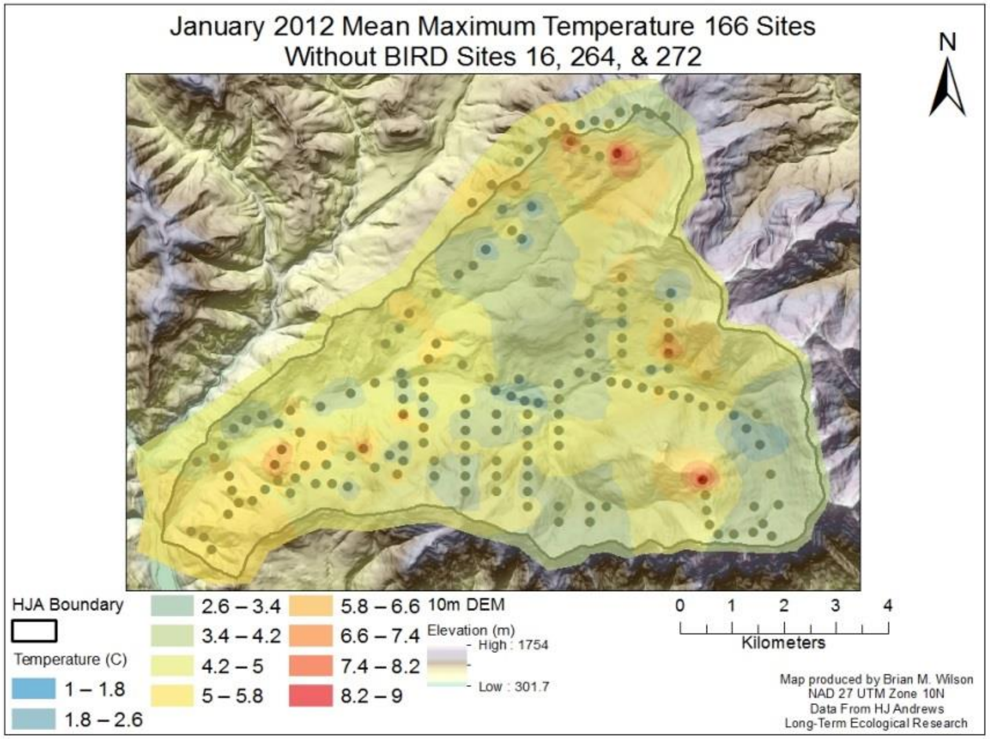


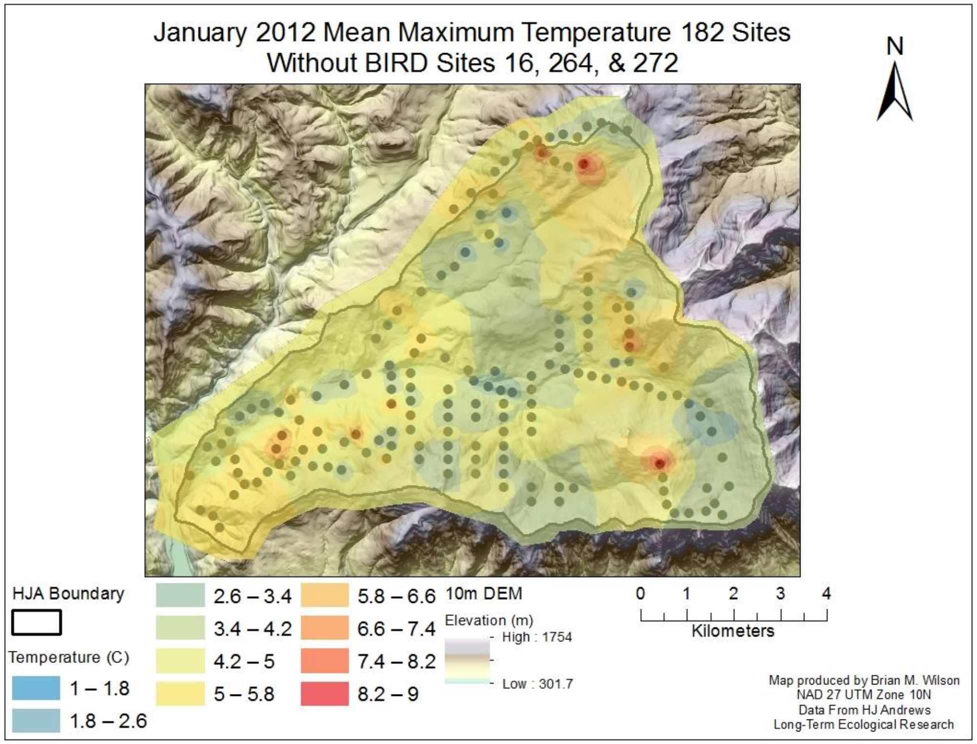




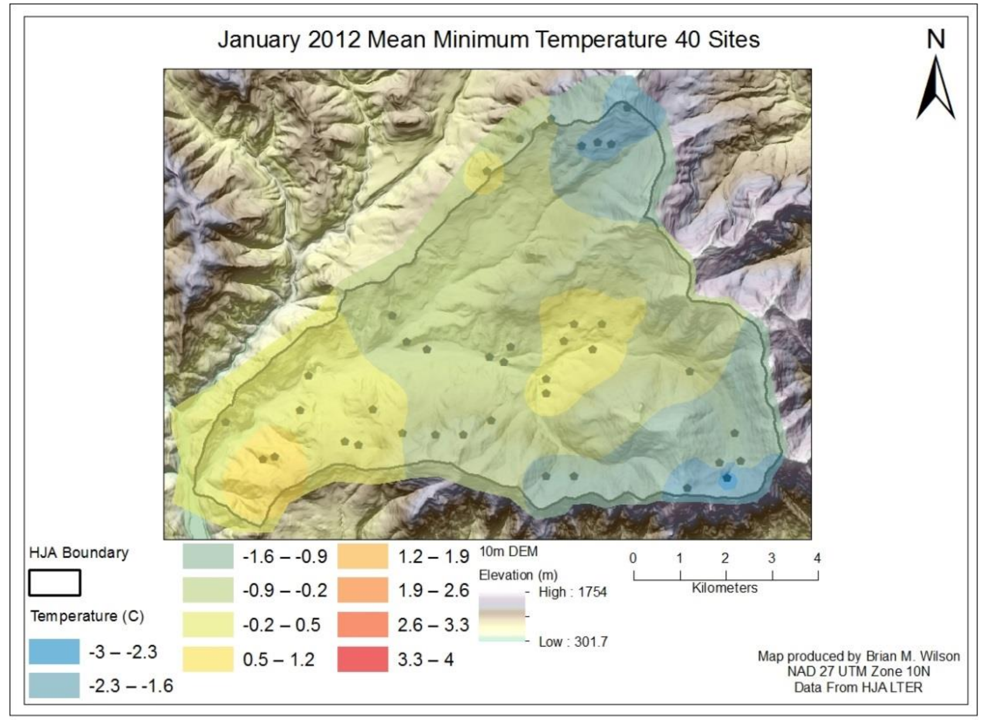
Mean monthly maximum temperature January 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

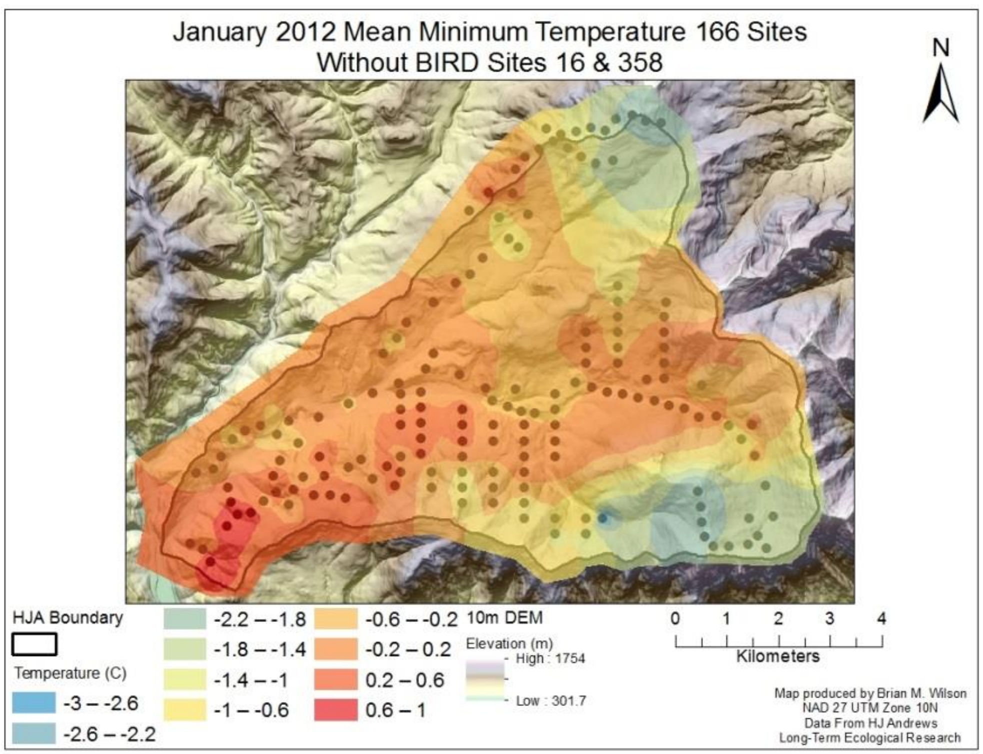


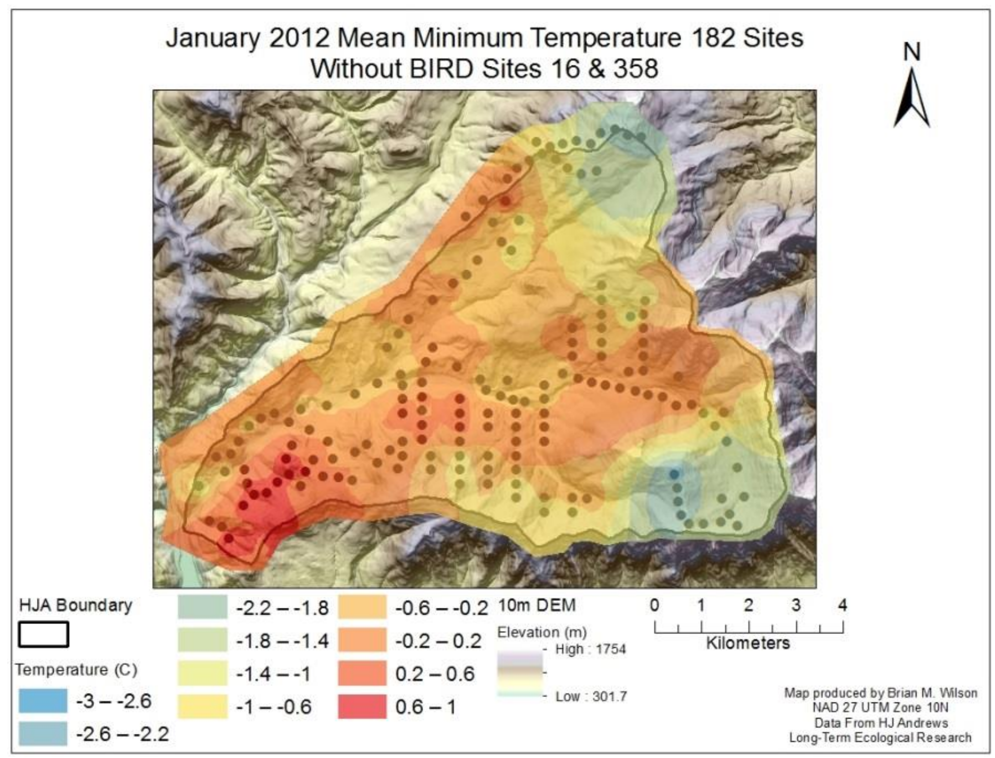




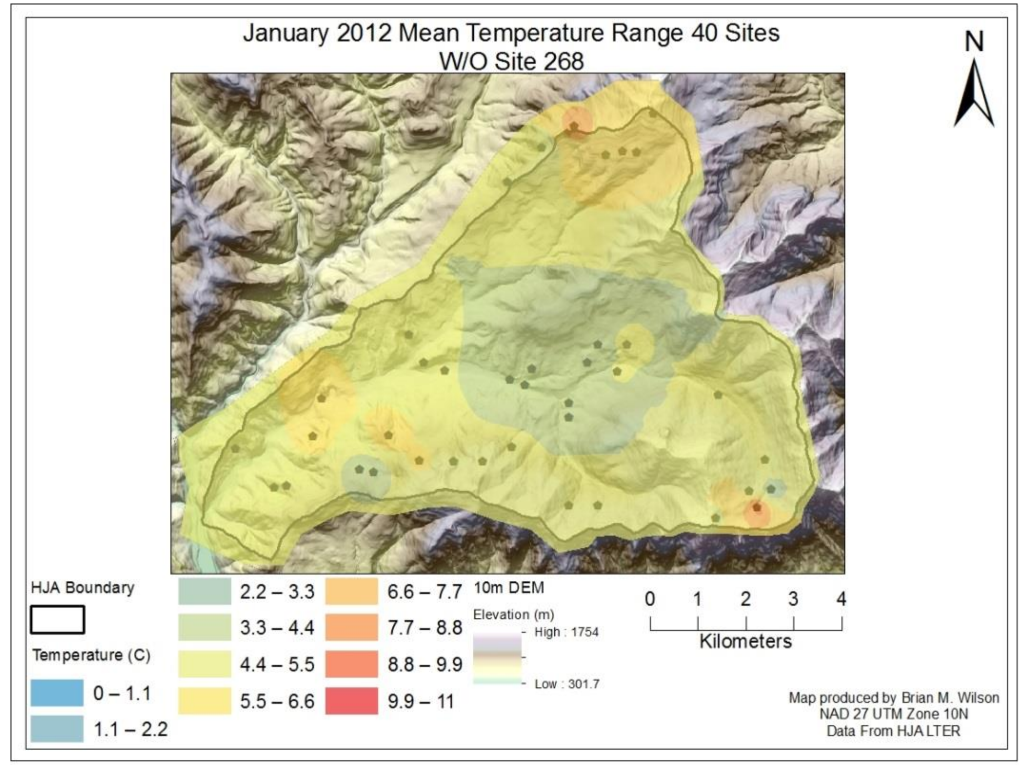
Mean monthly minimum temperature January 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

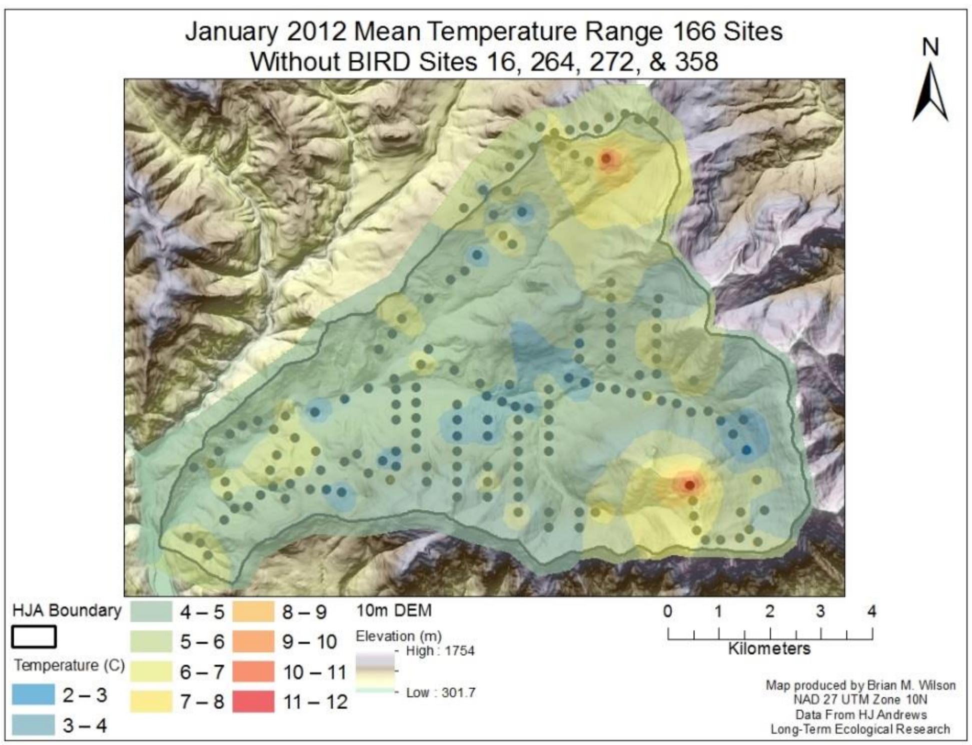


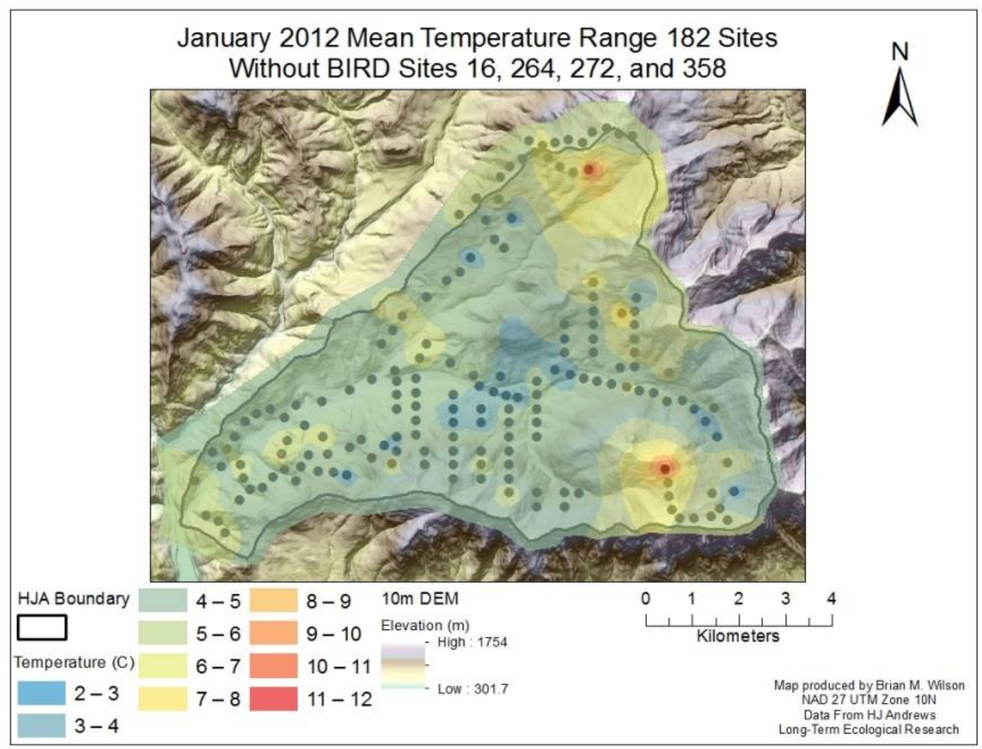




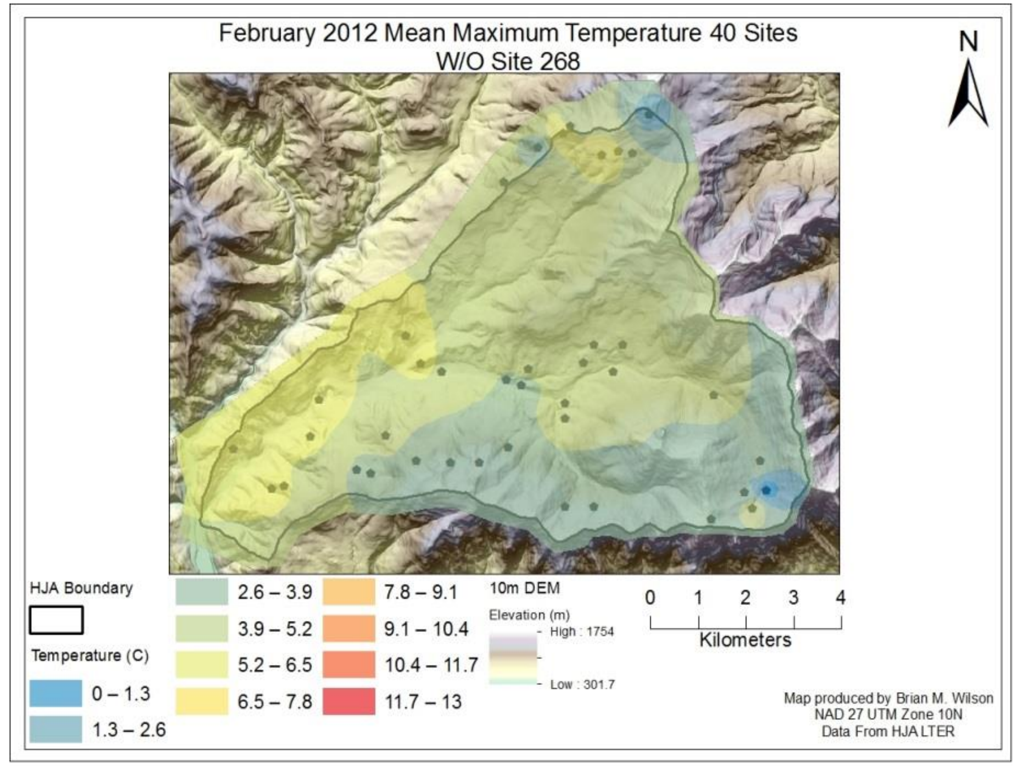
Mean monthly temperature range January 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

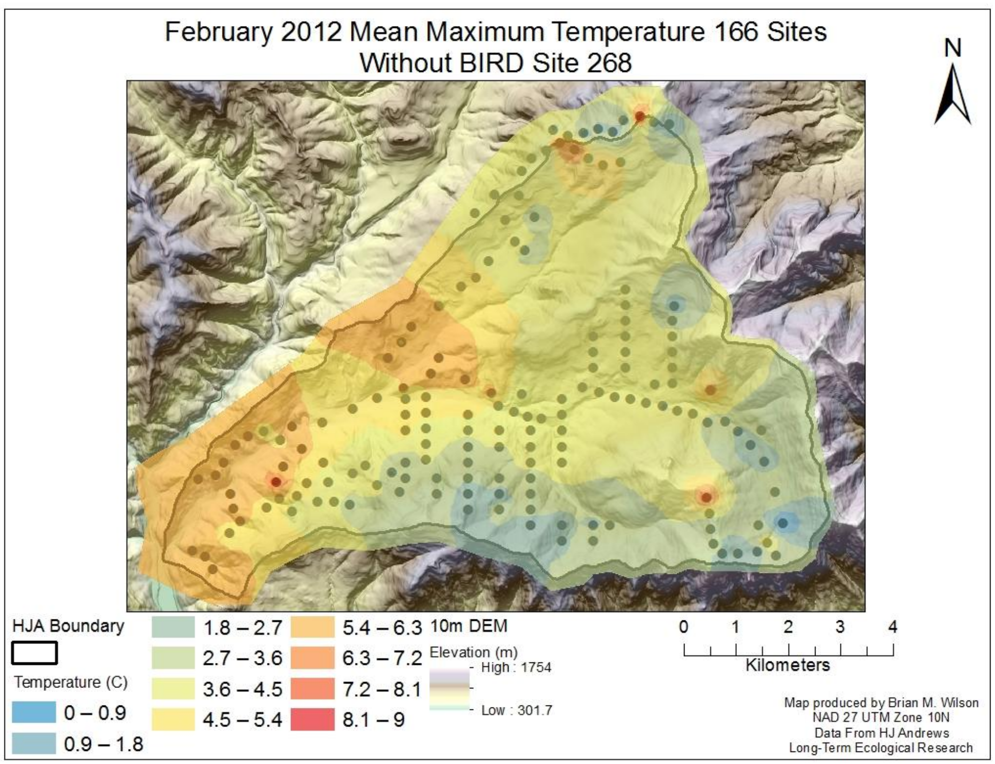


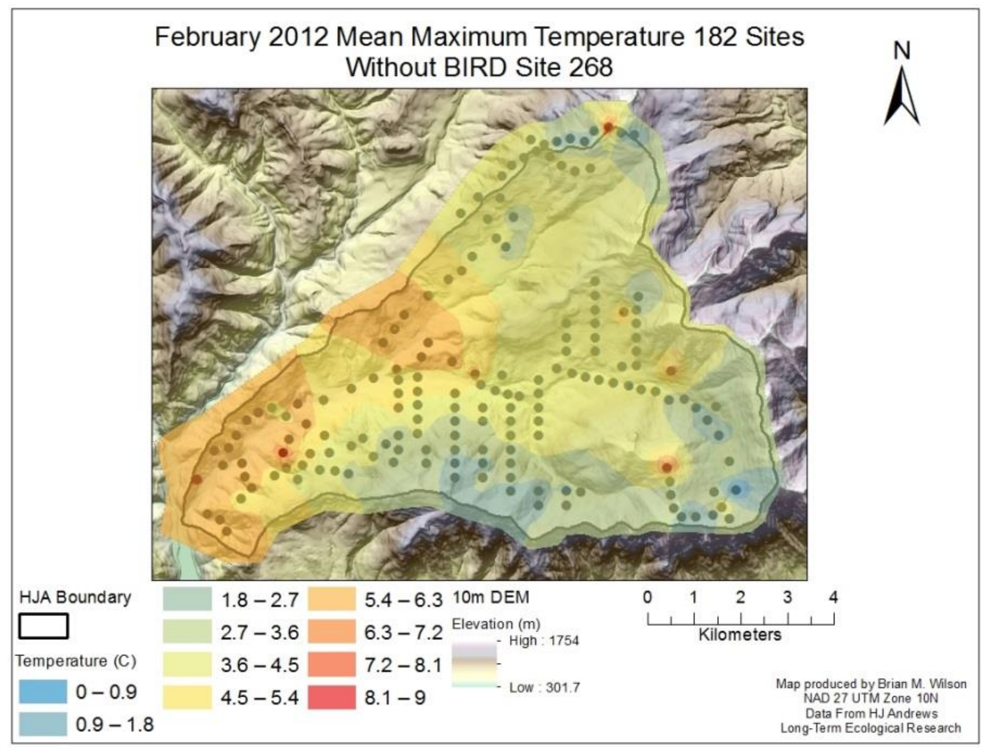




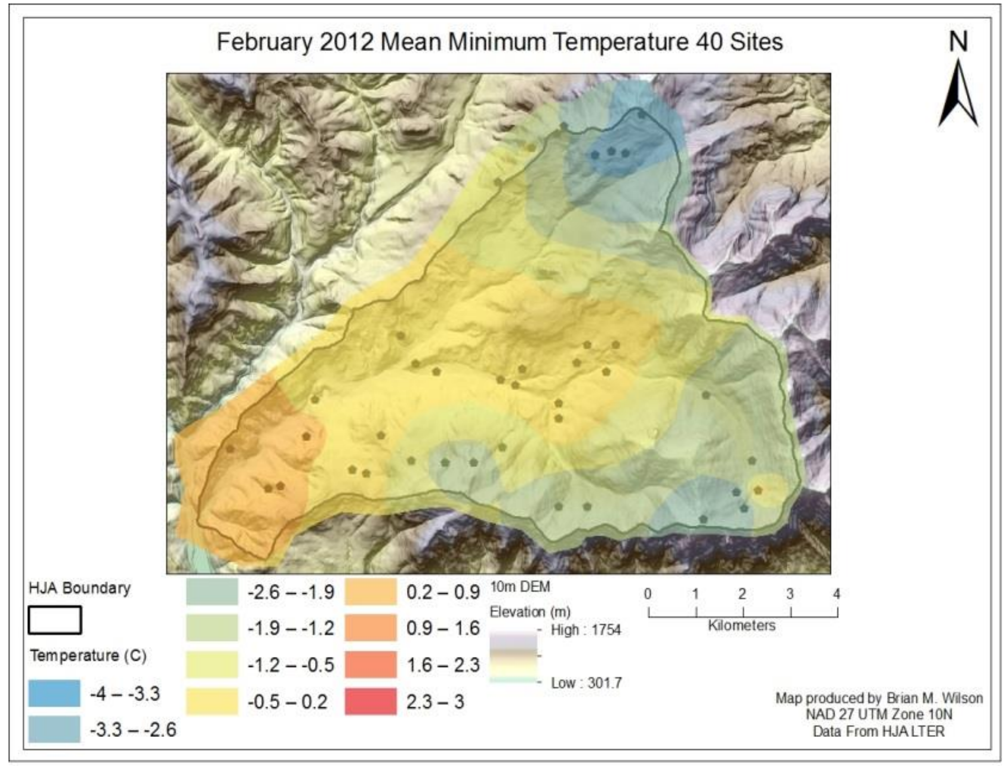
Mean monthly maximum temperature February 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

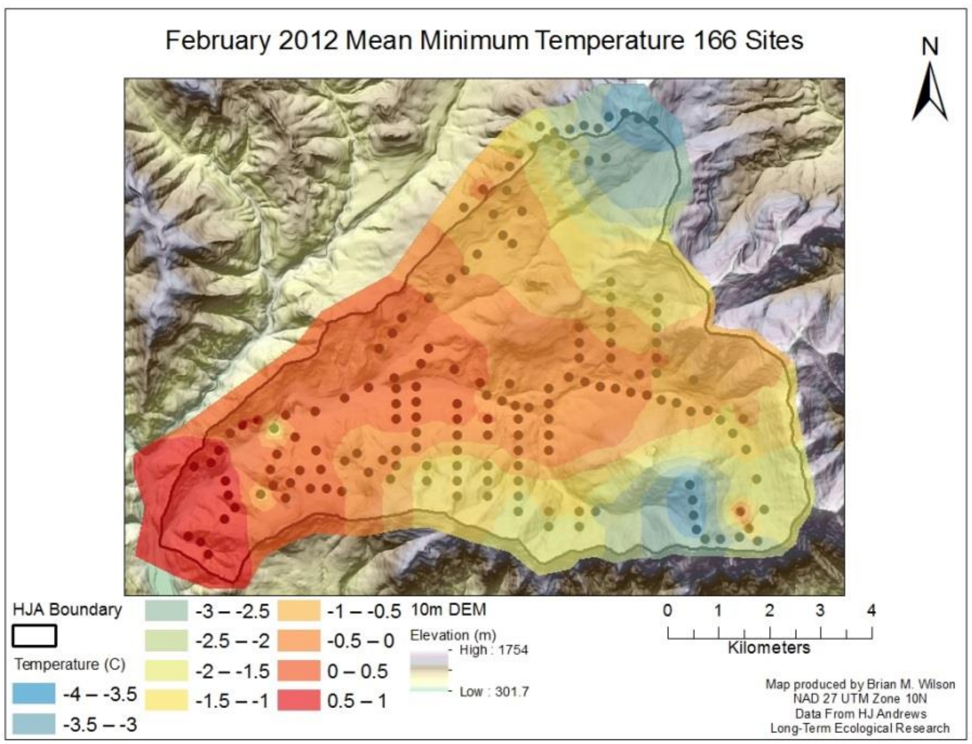


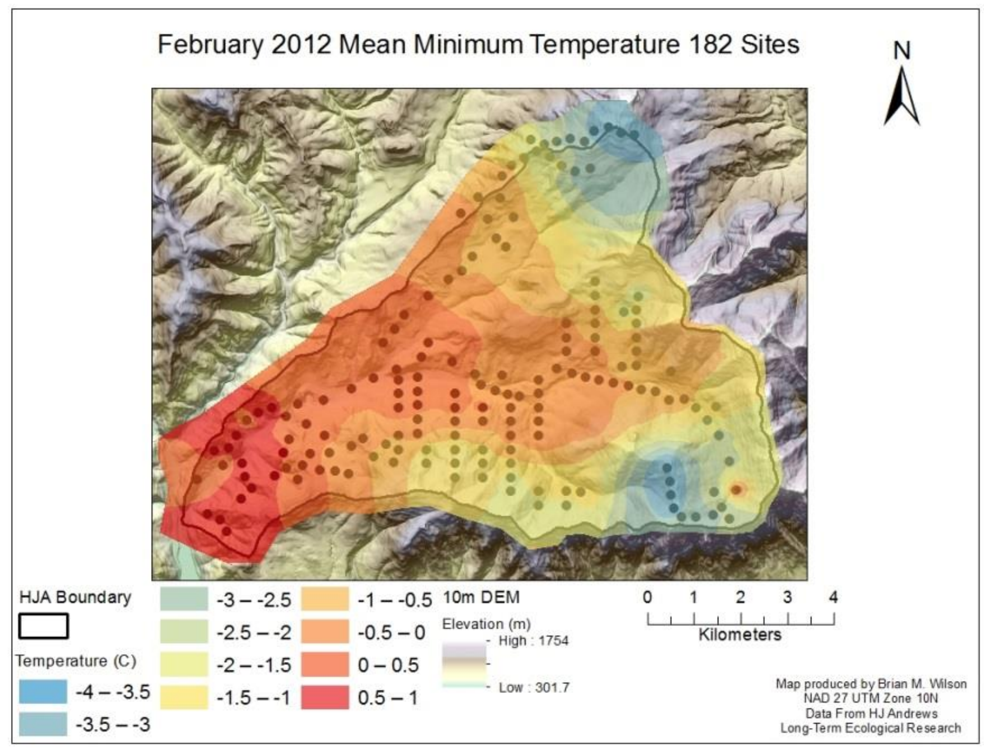




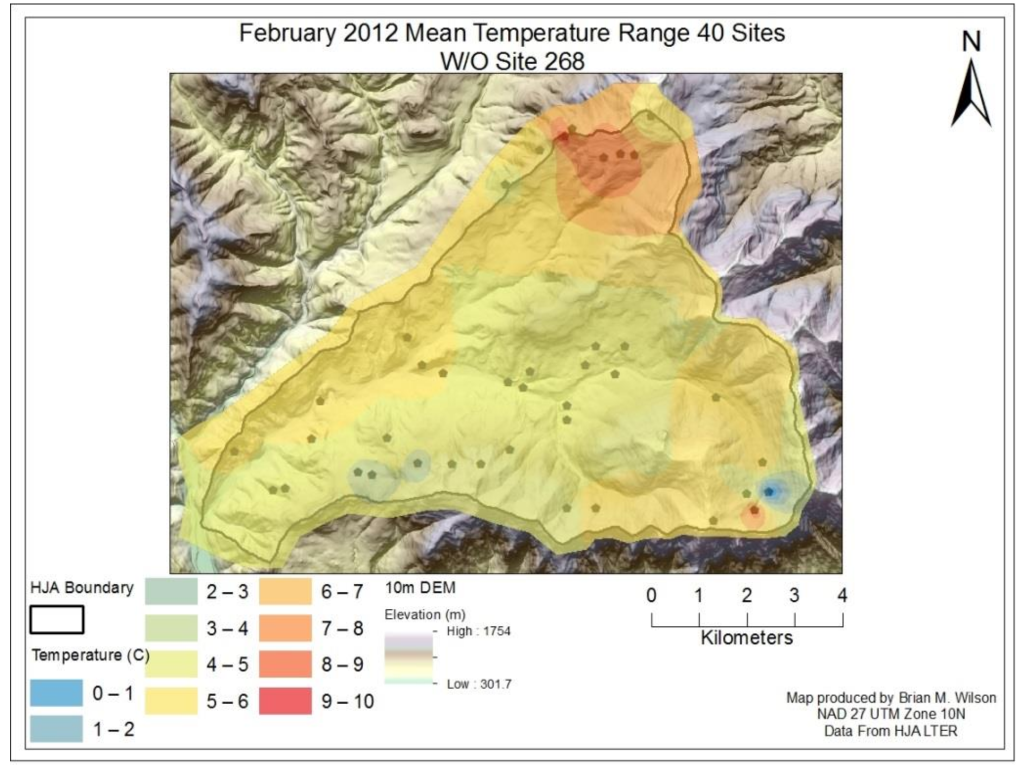
Mean monthly minimum temperature February 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

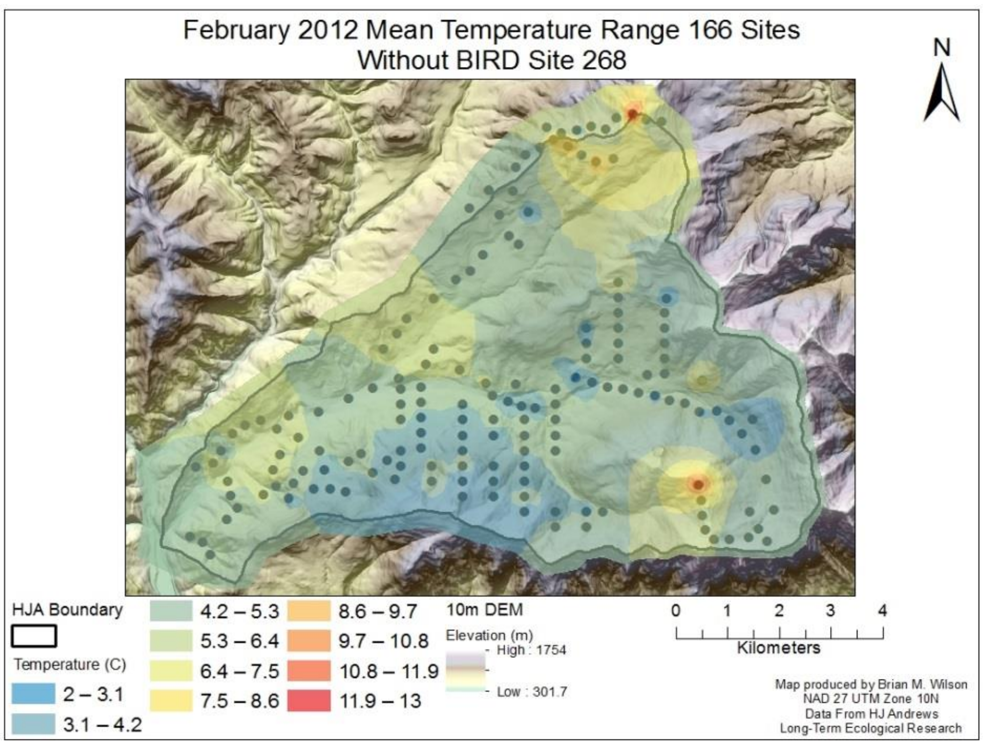


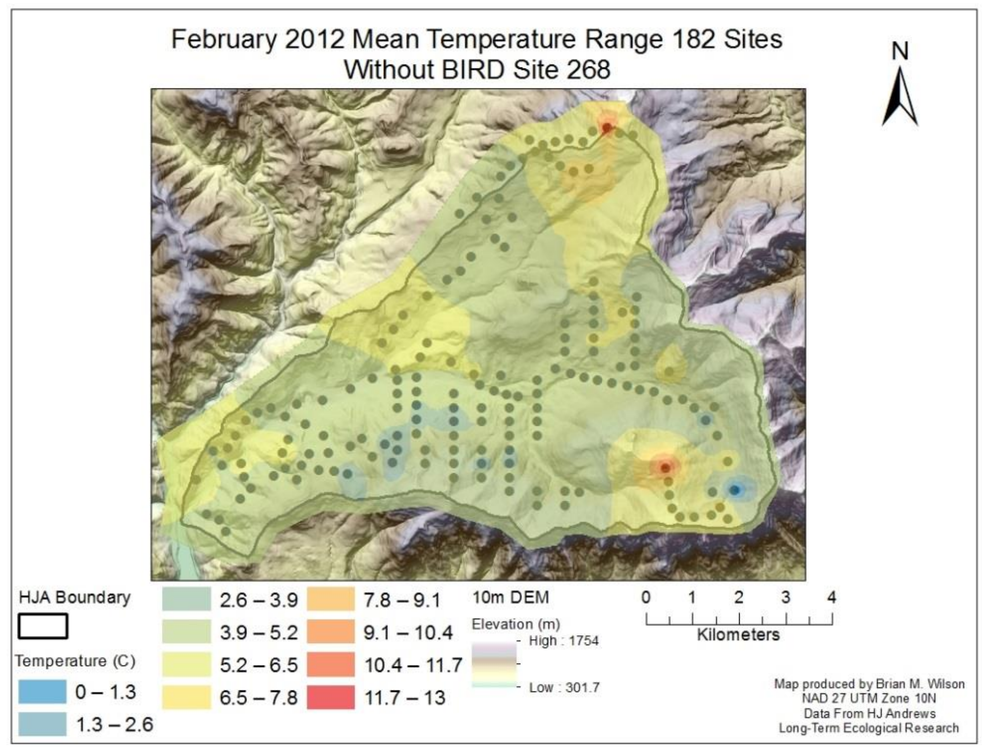




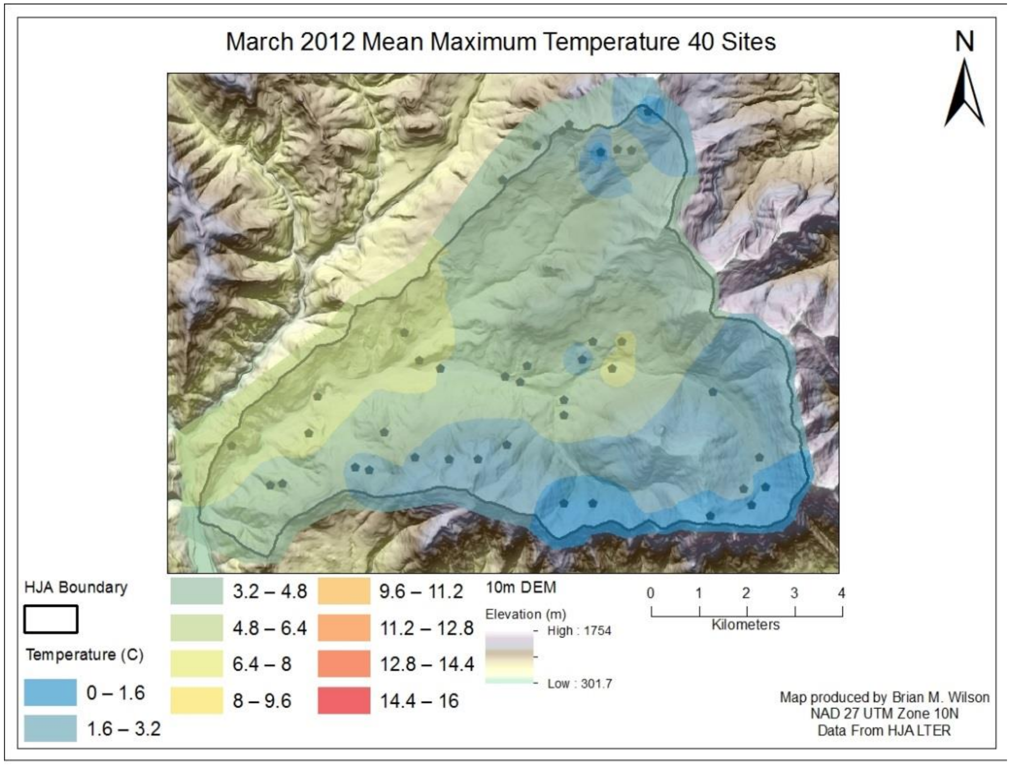
Mean monthly temperature range February 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

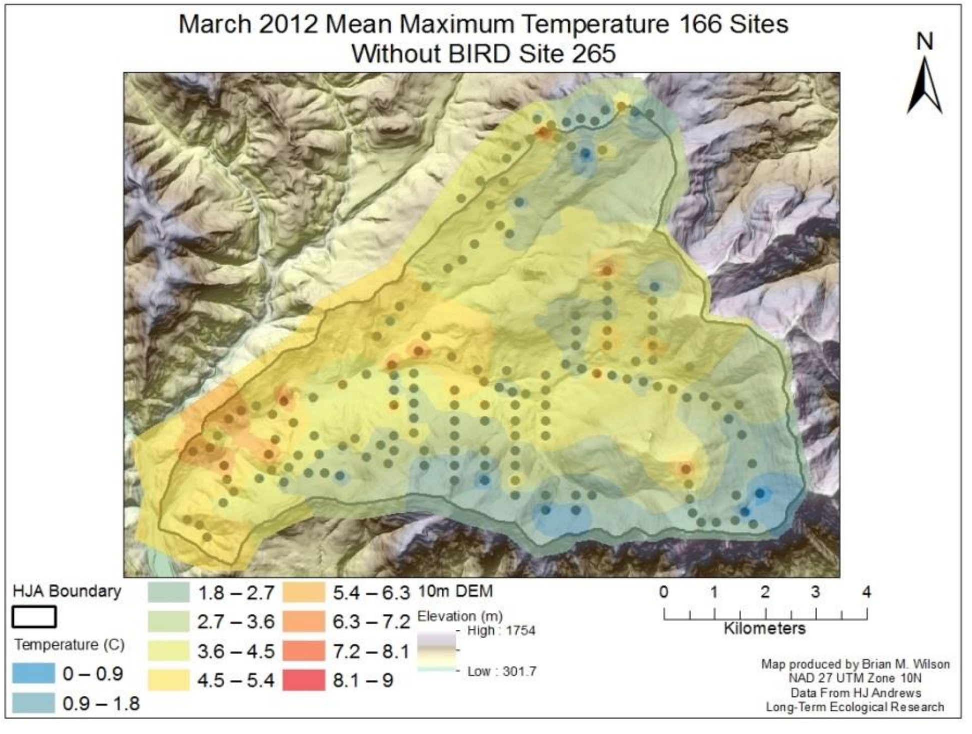


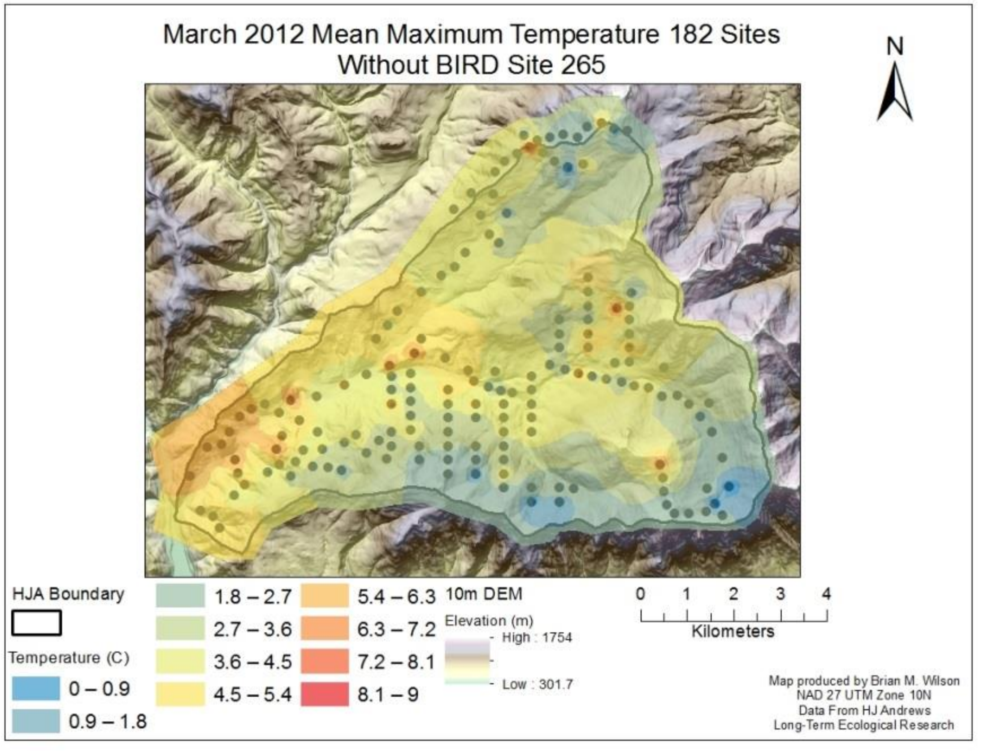




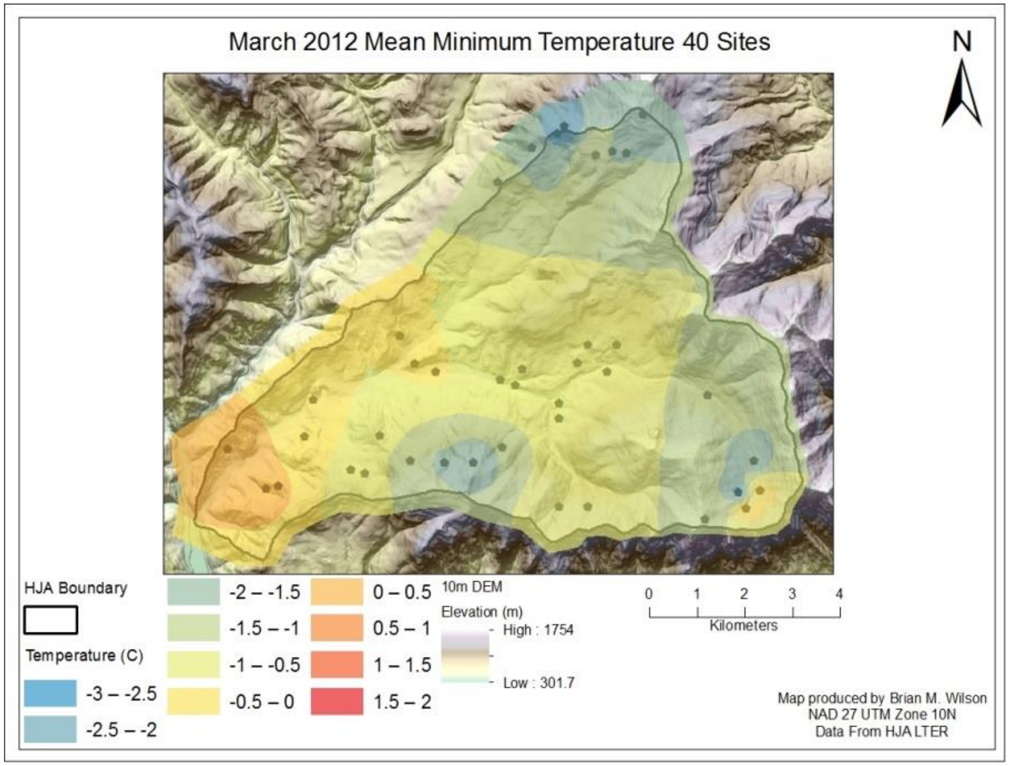
Mean monthly maximum temperature March 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

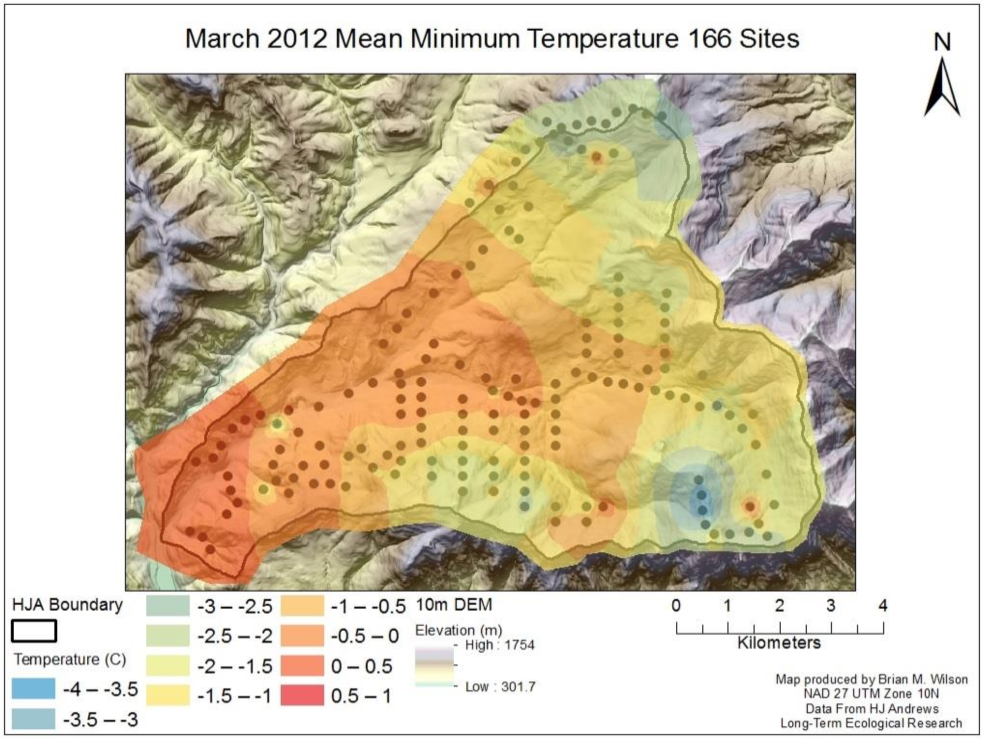


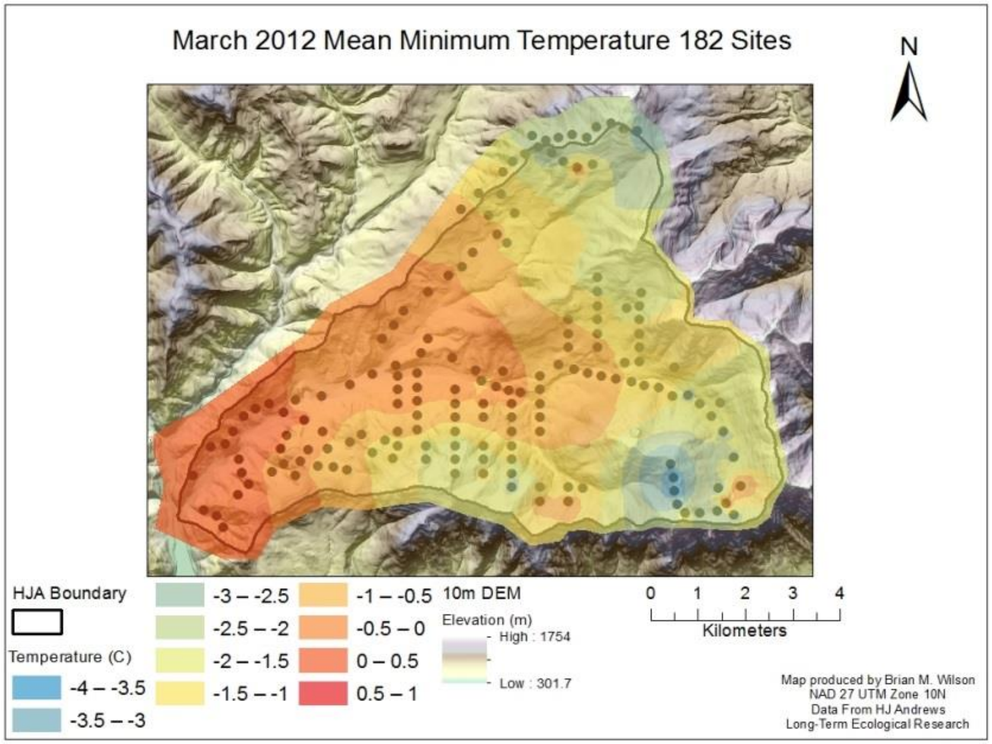




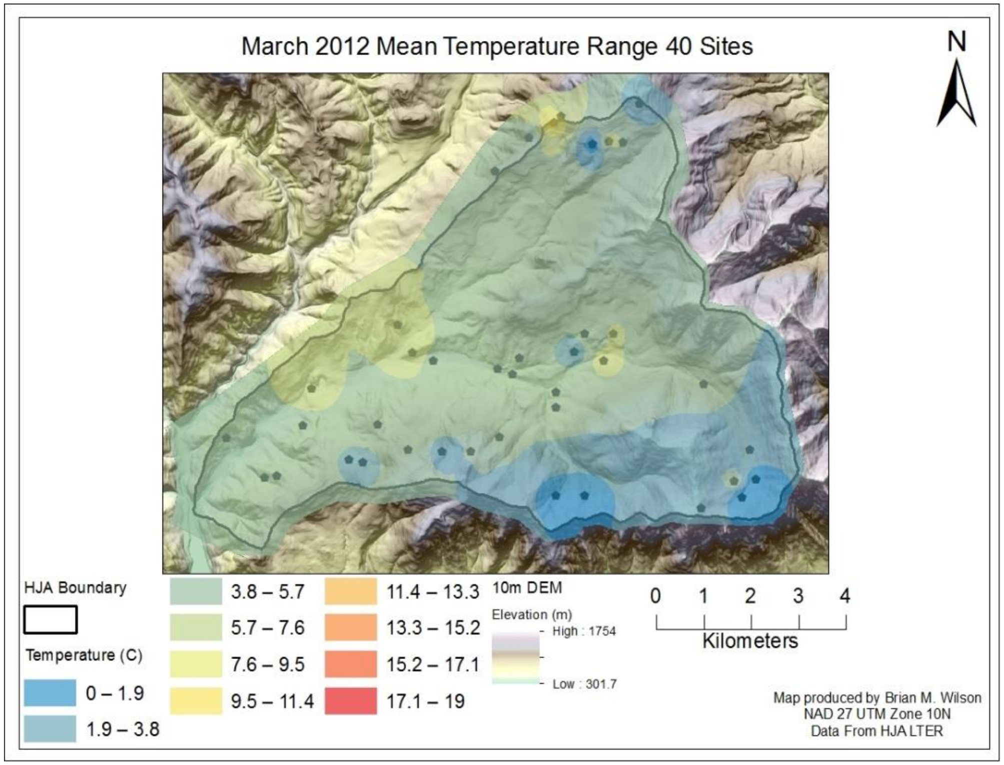
Mean monthly minimum temperature March 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

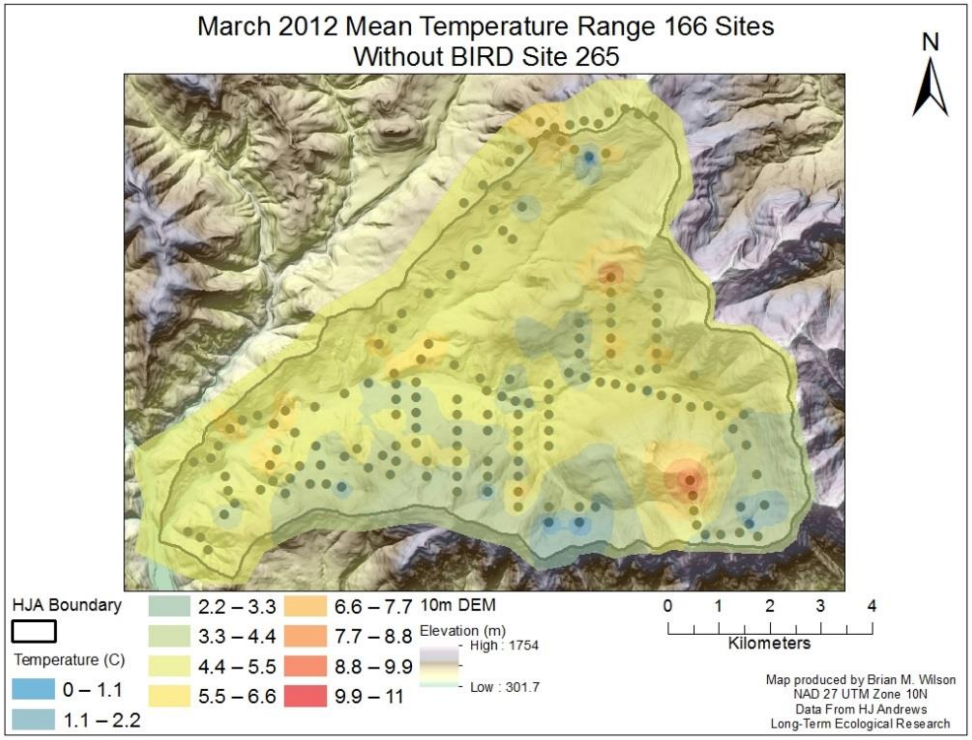


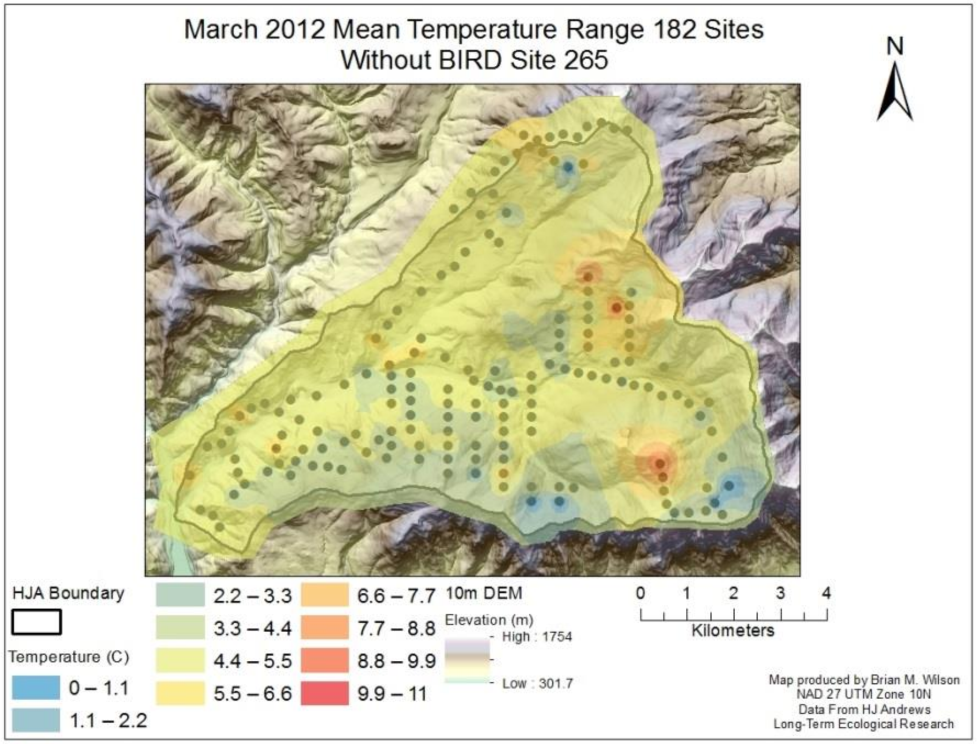




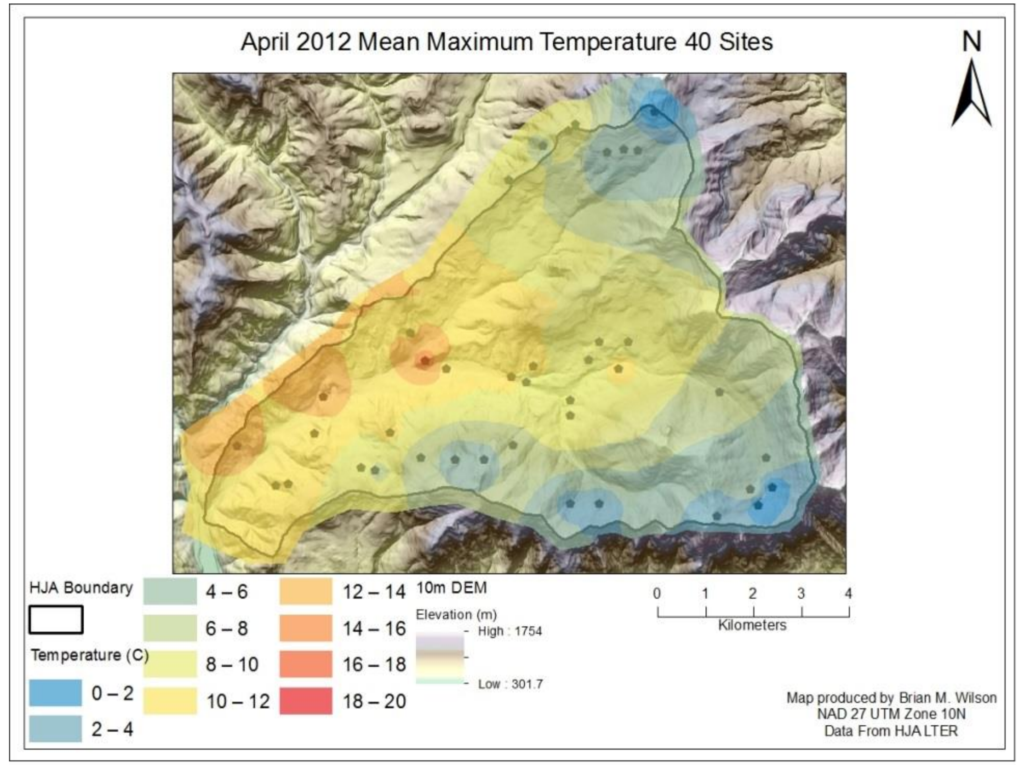
Mean monthly temperature range March 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

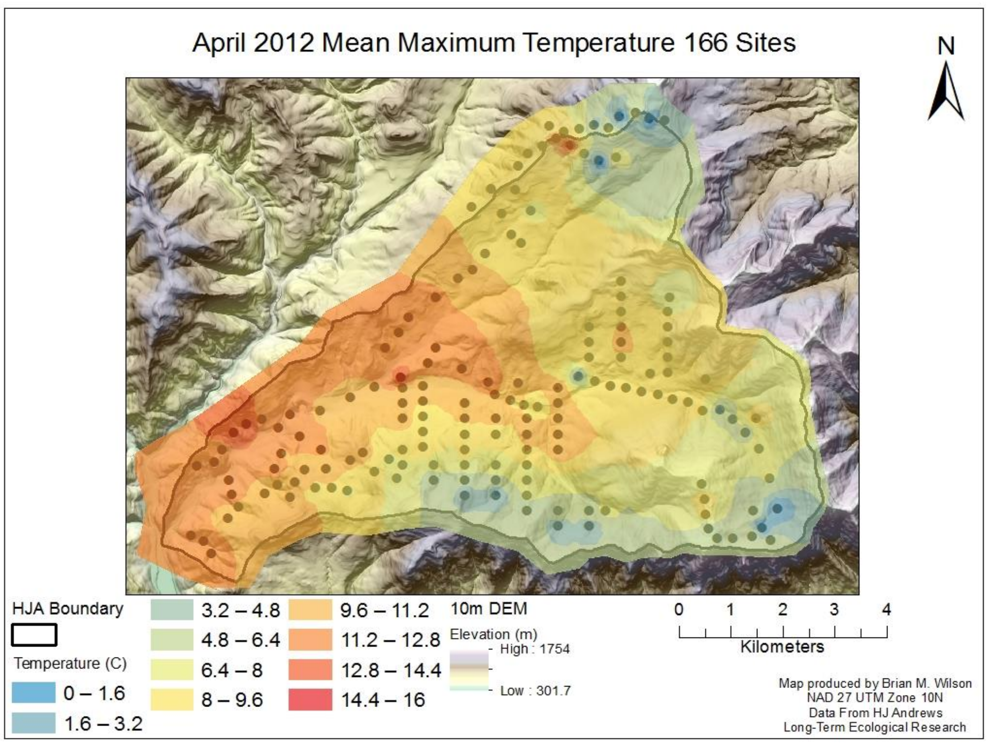


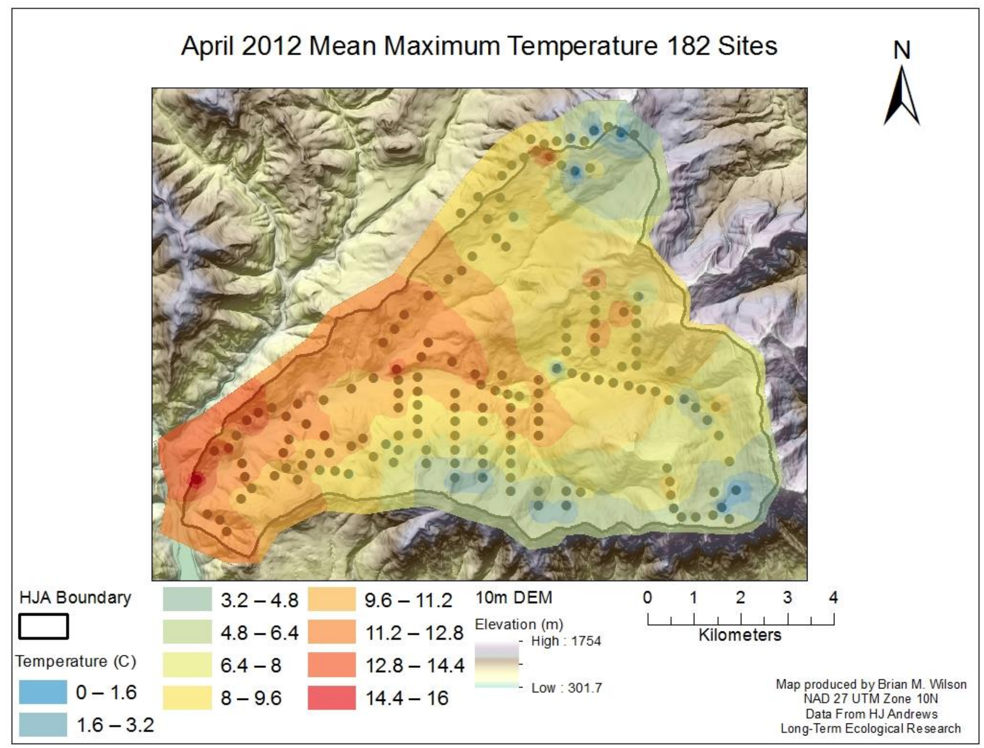




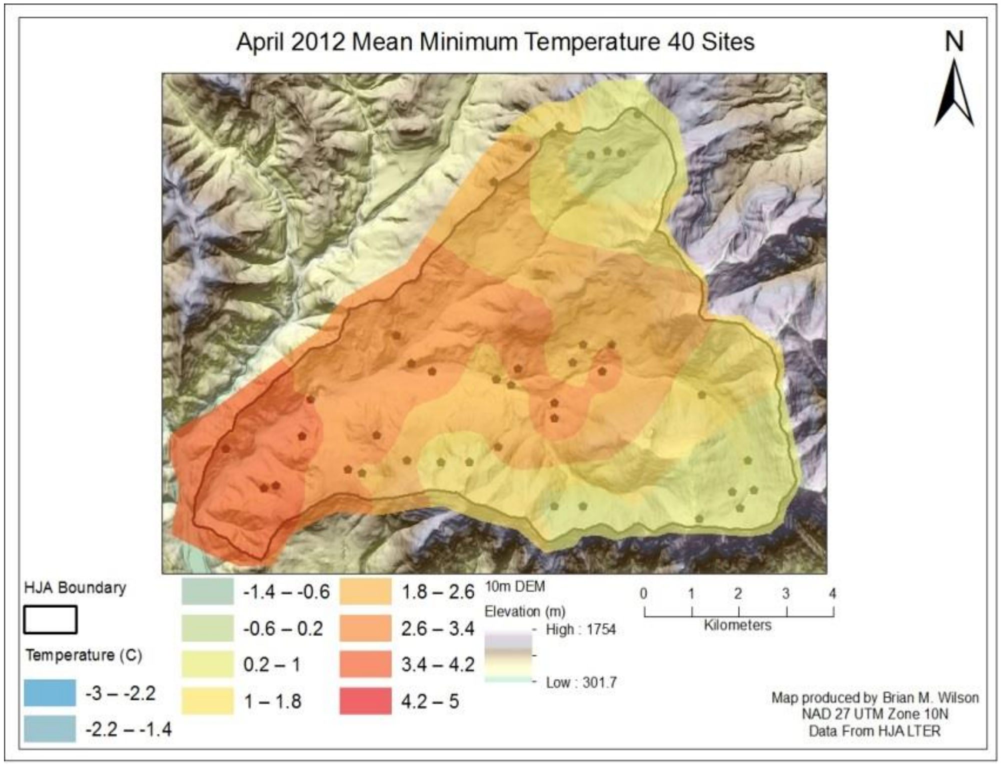
Mean monthly maximum temperature April 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

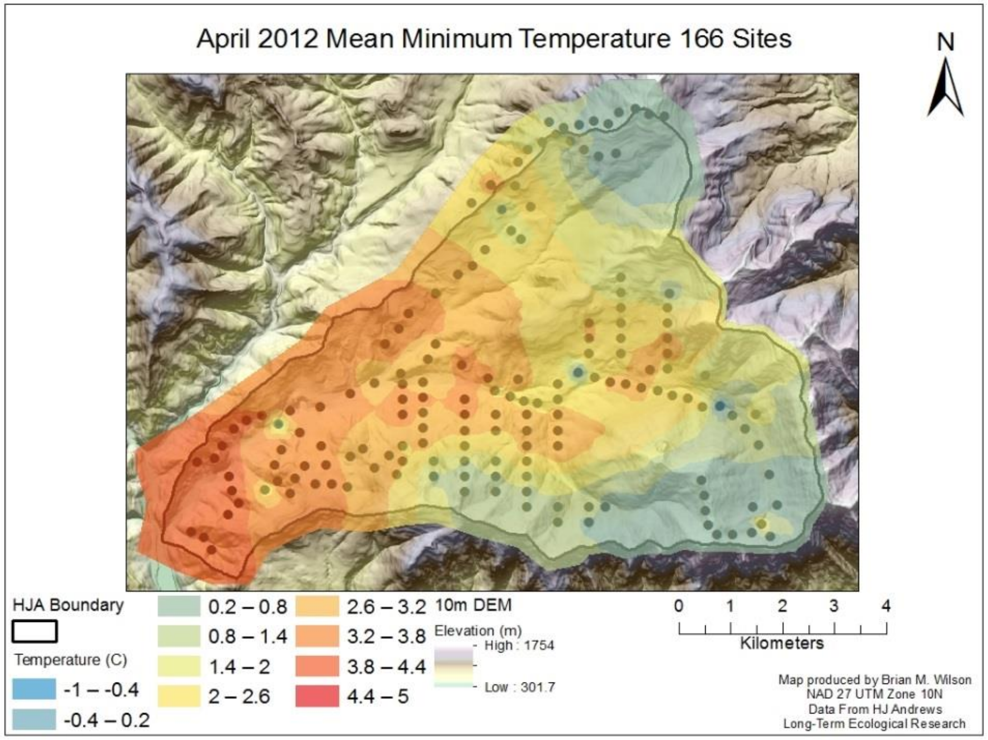


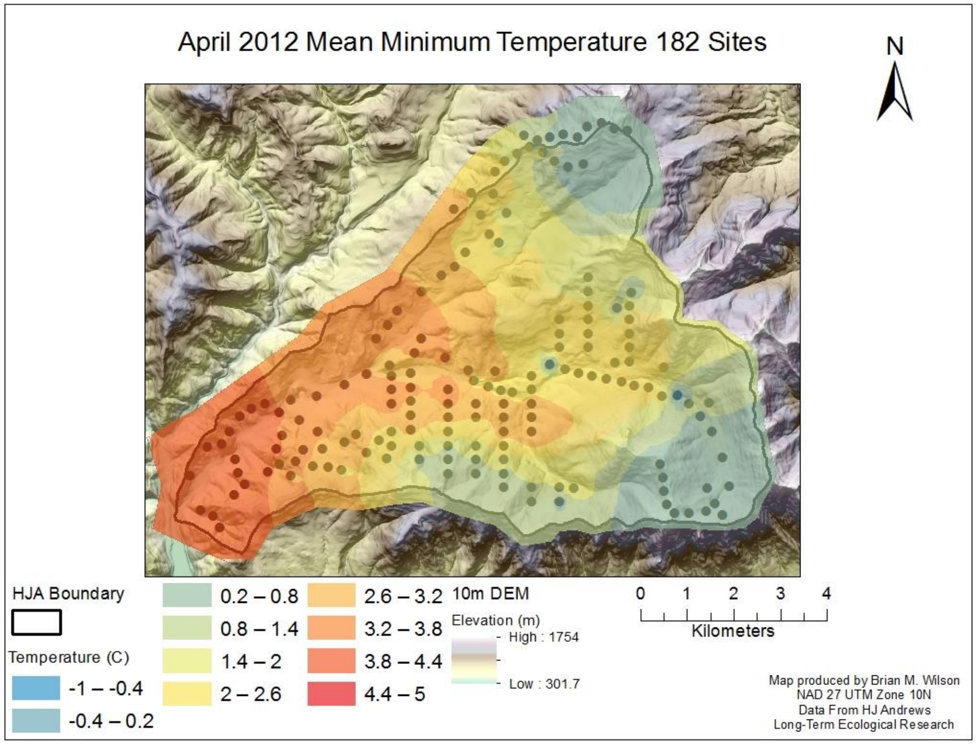




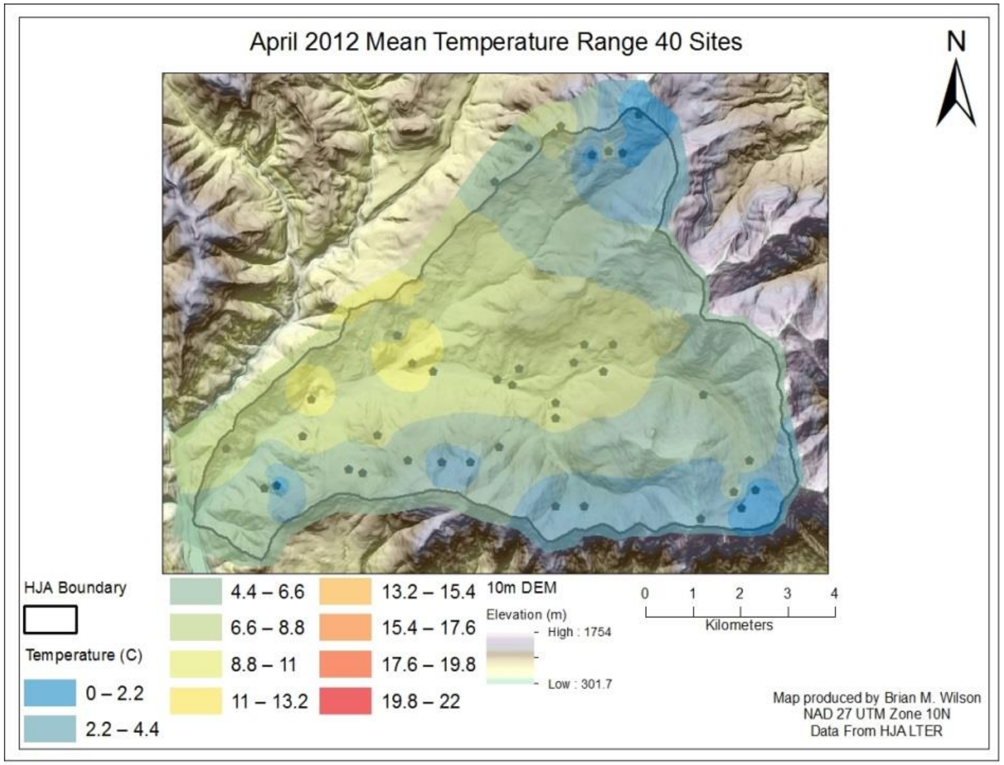
Mean monthly minimum temperature April 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

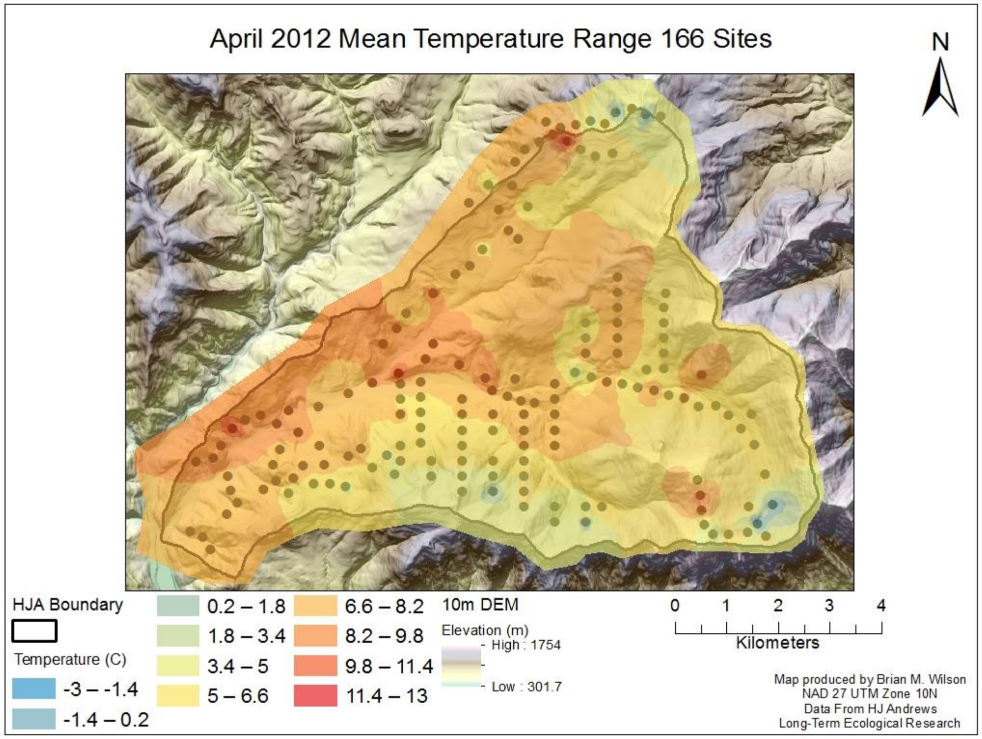


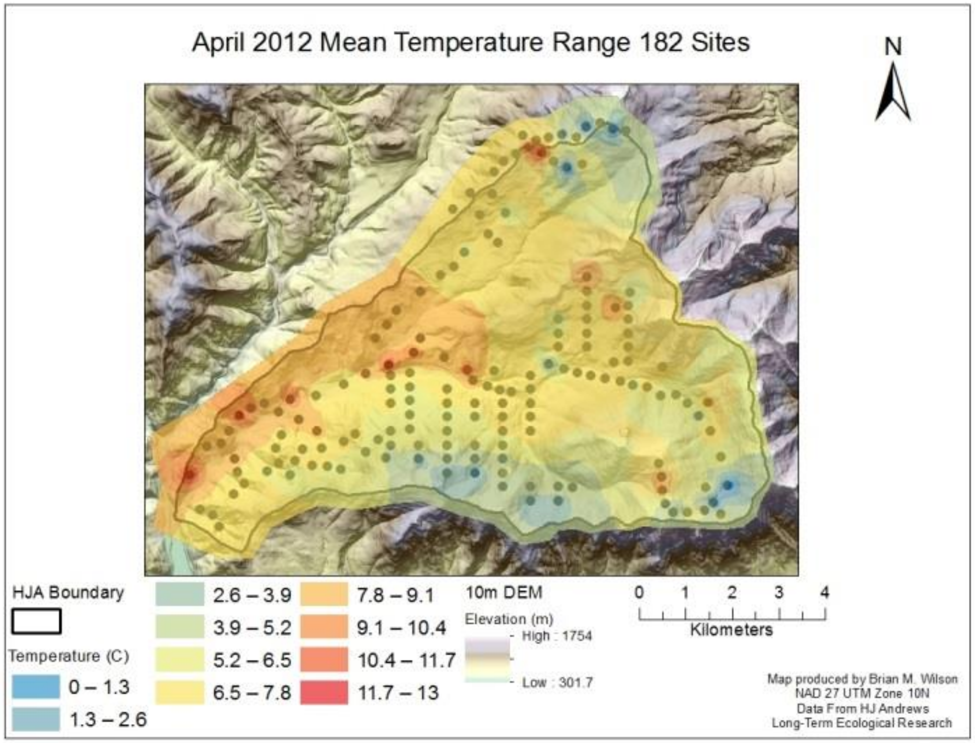




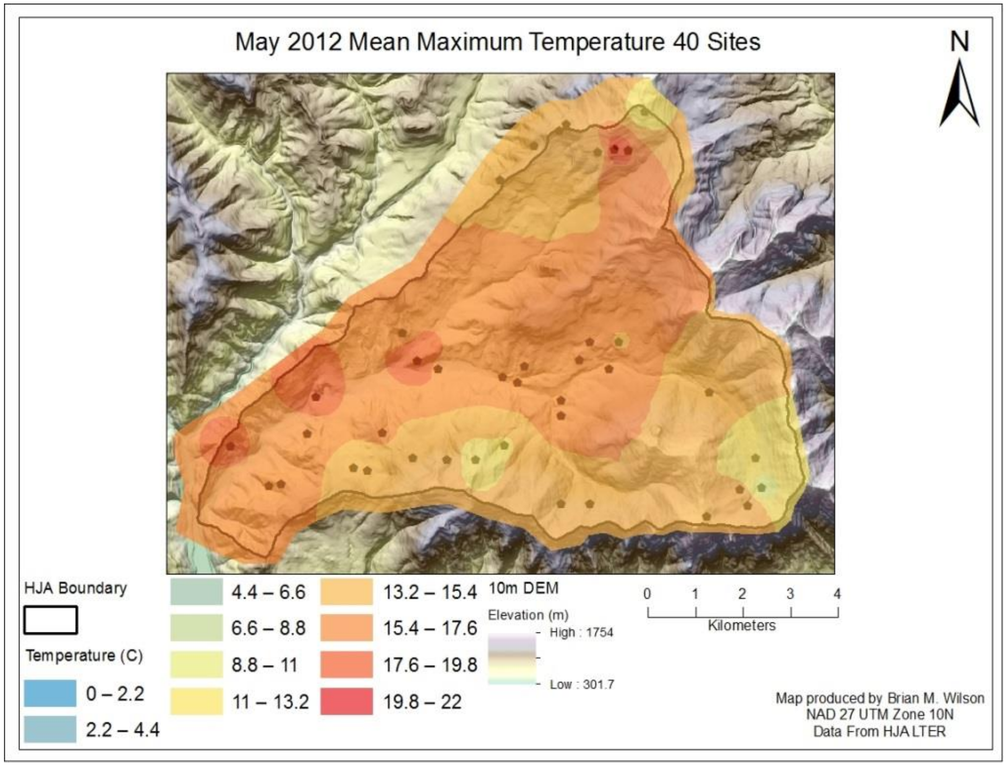
Mean monthly temperature range April 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

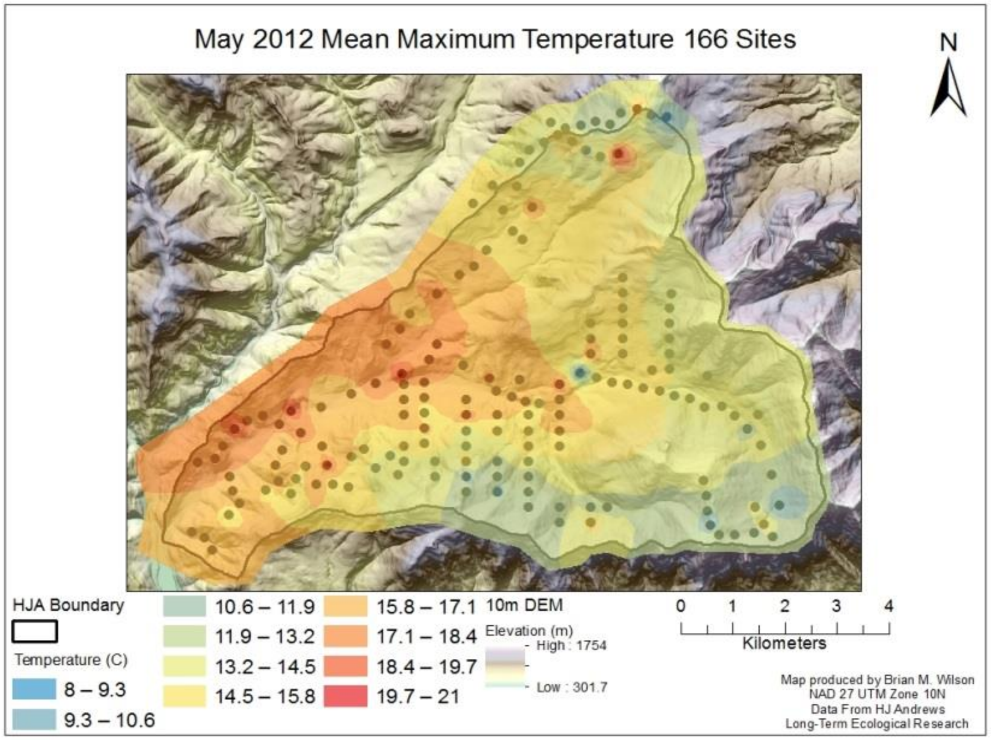


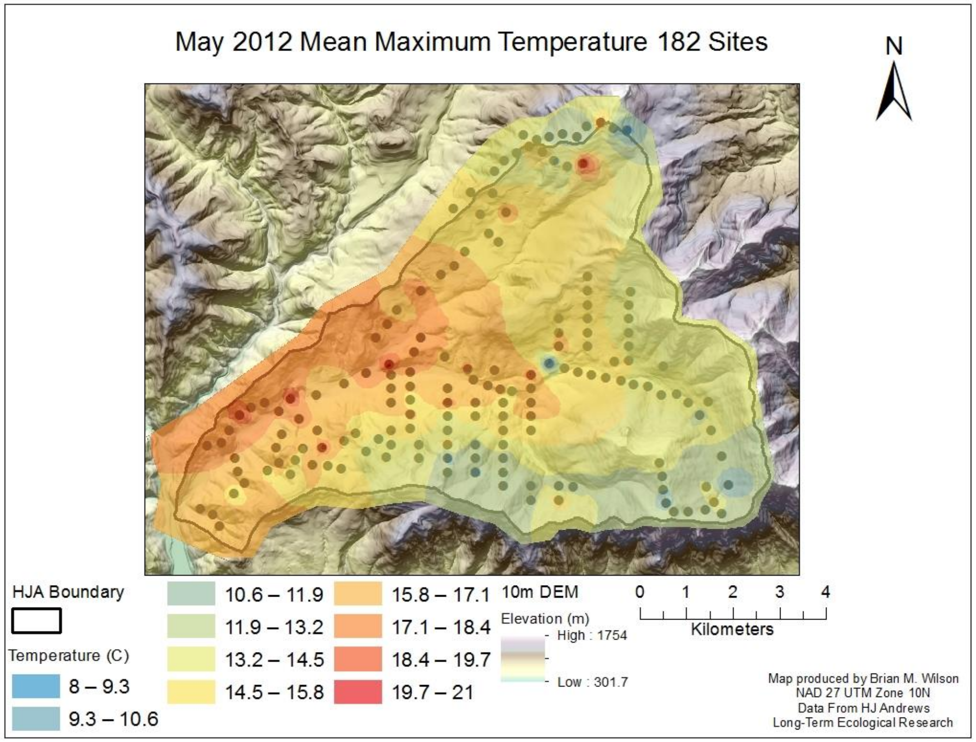




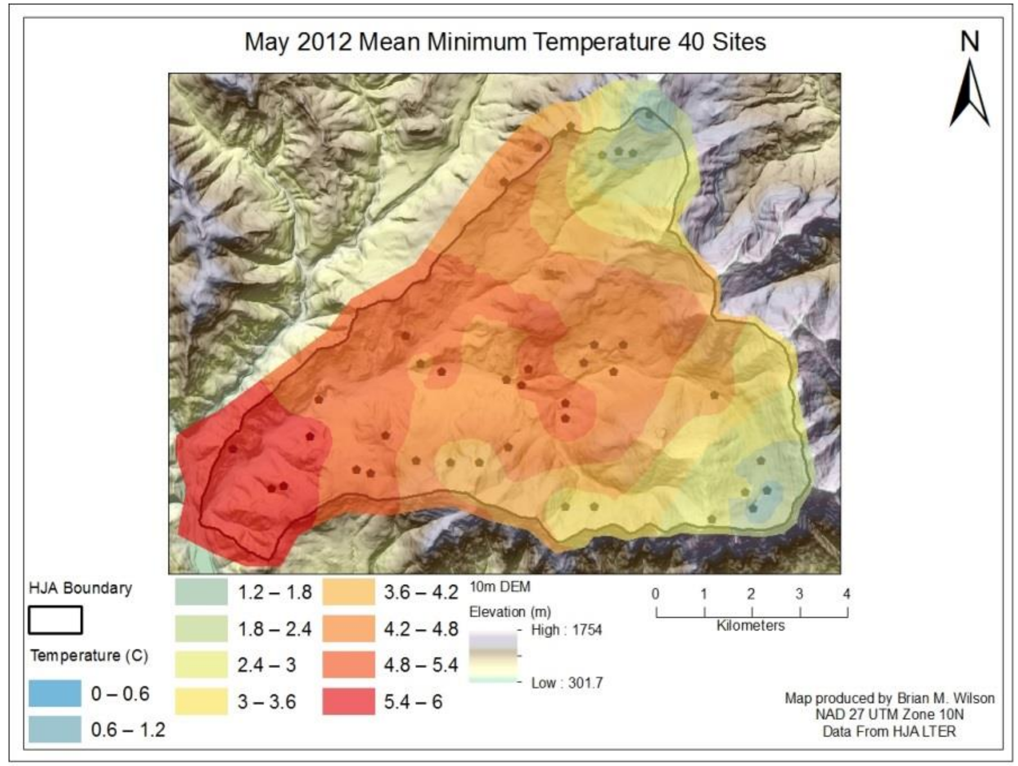
Mean monthly maximum temperature May 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

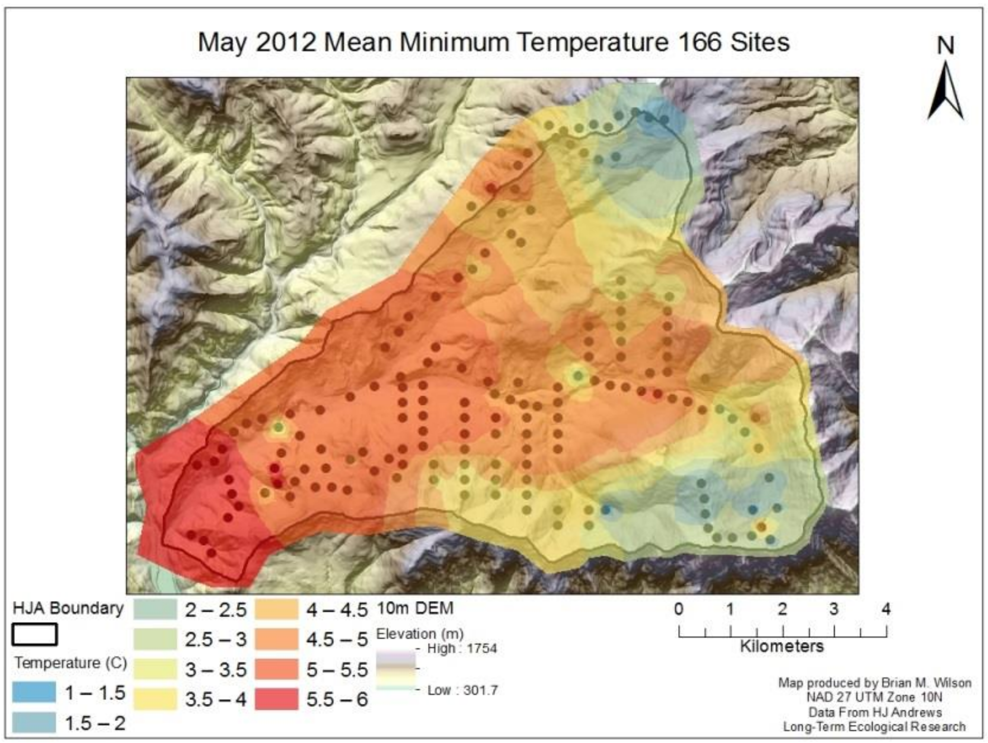


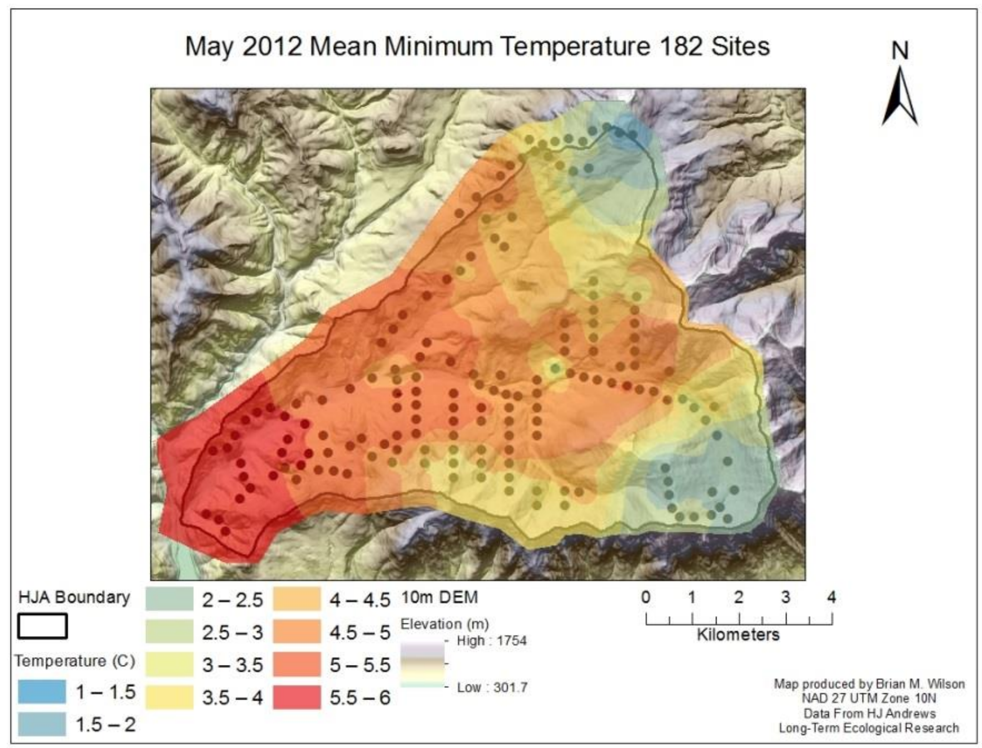




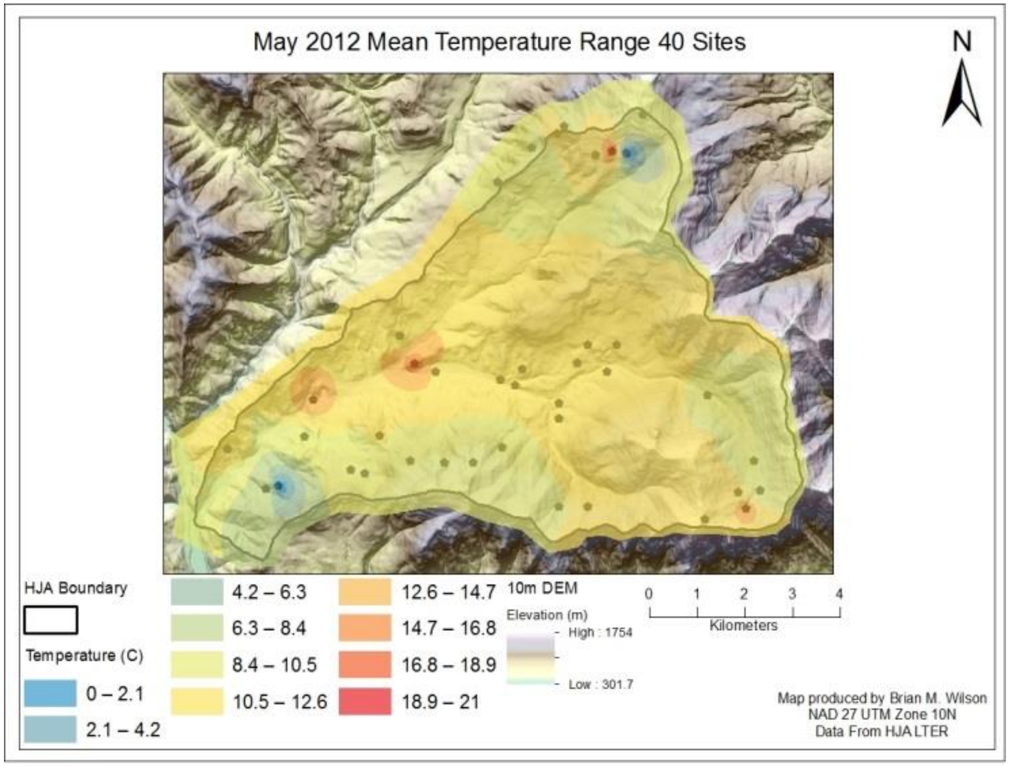
Mean monthly minimum temperature May 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

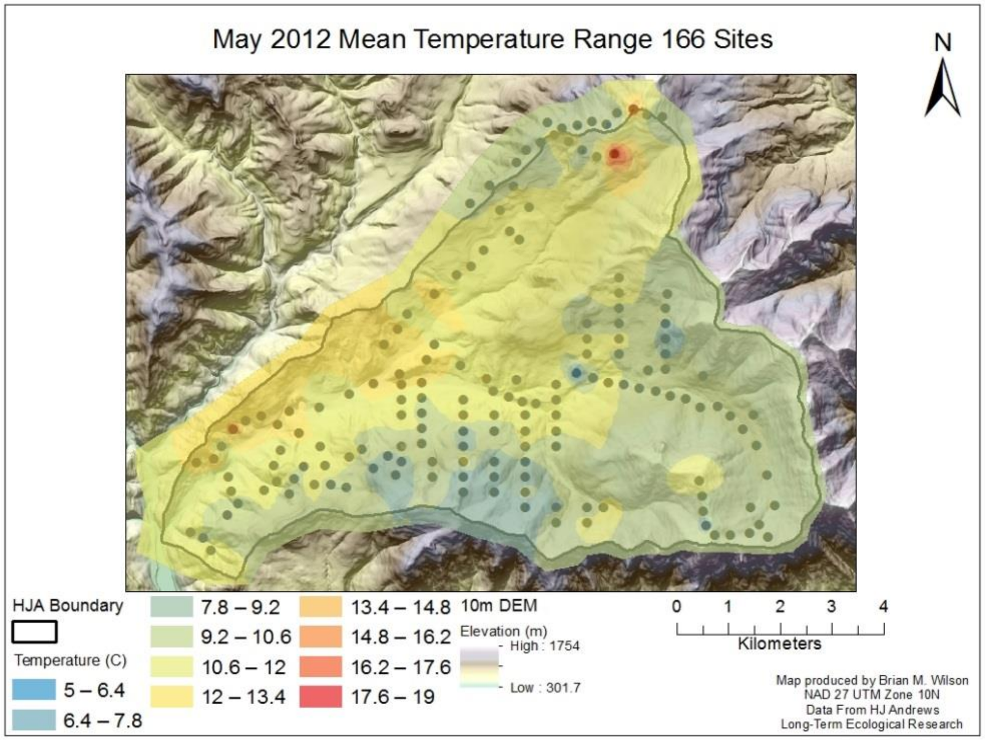


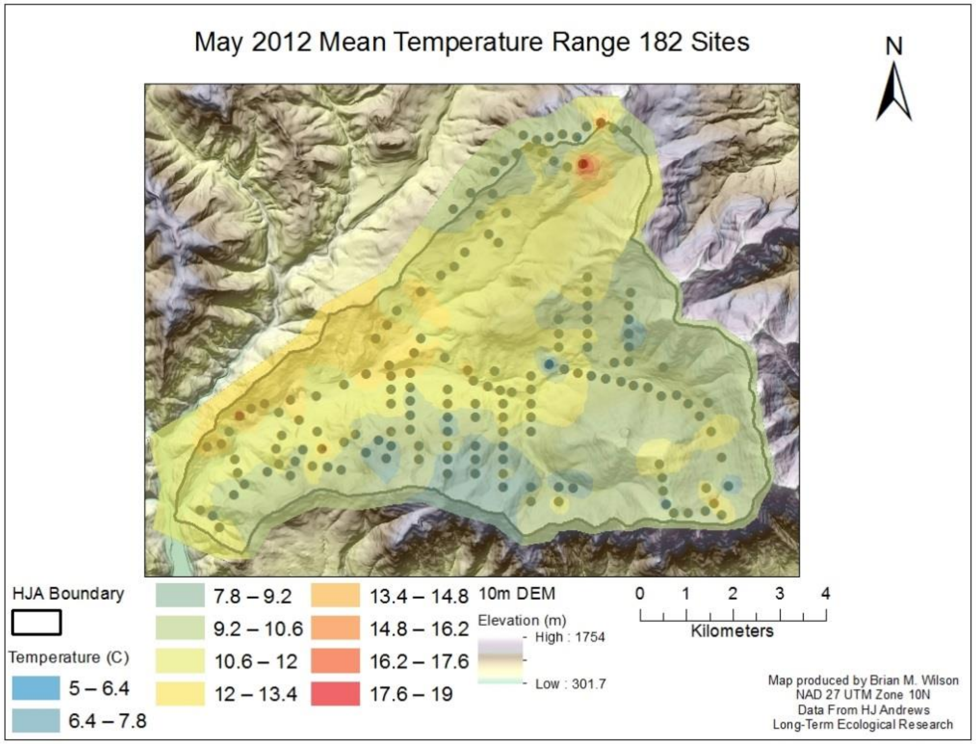




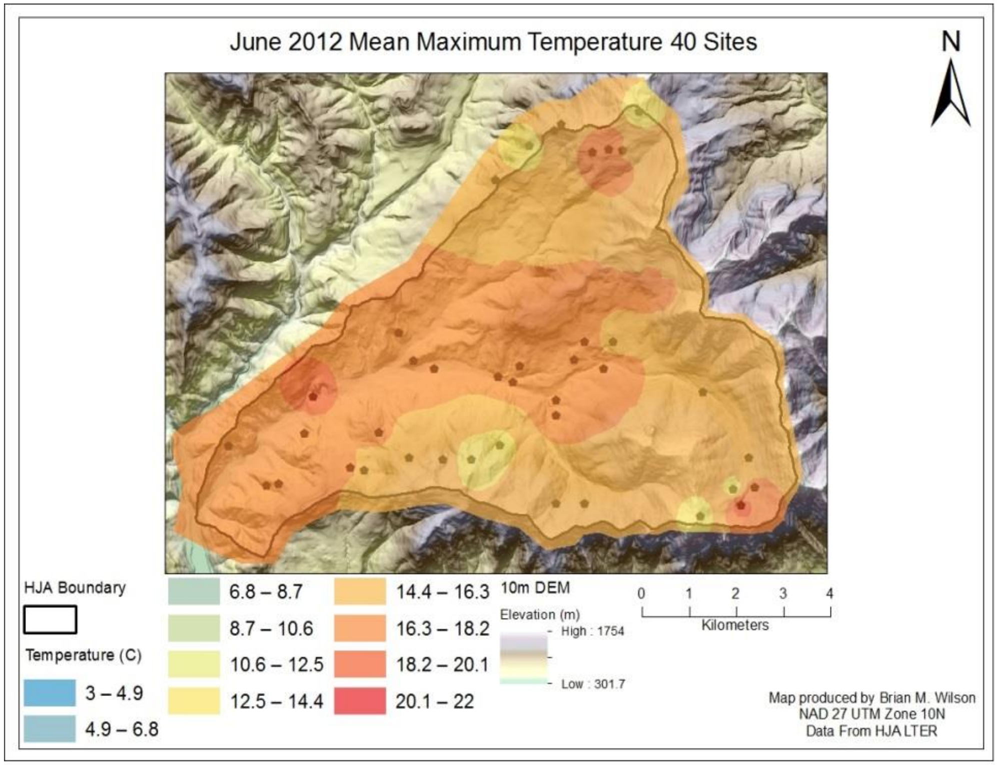
Mean monthly temperature range May 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

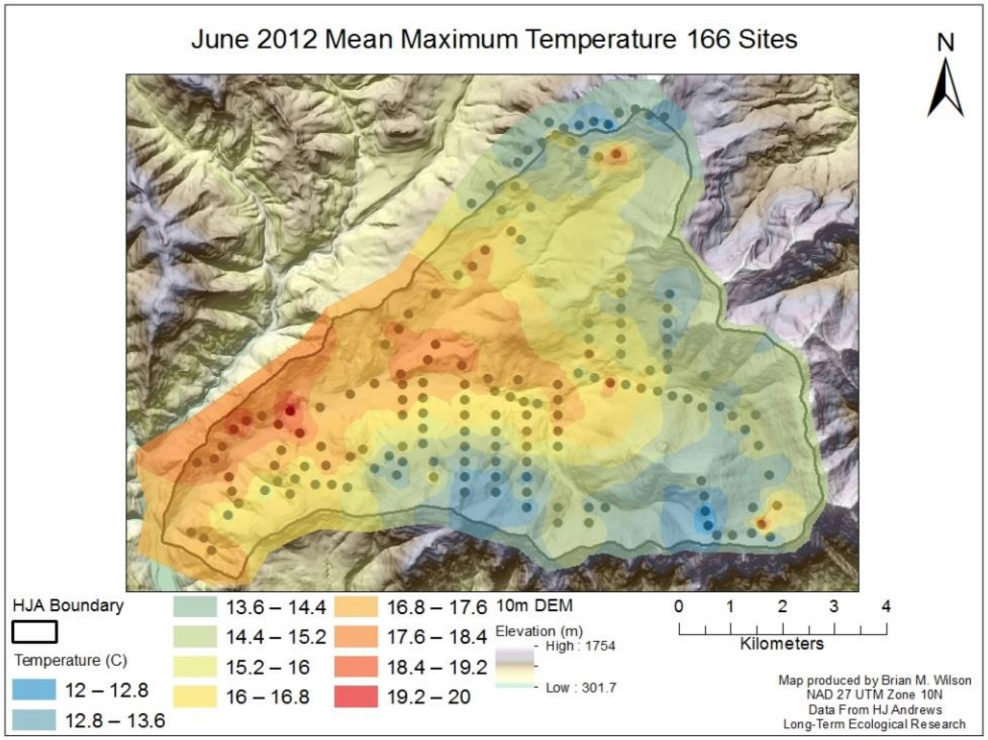


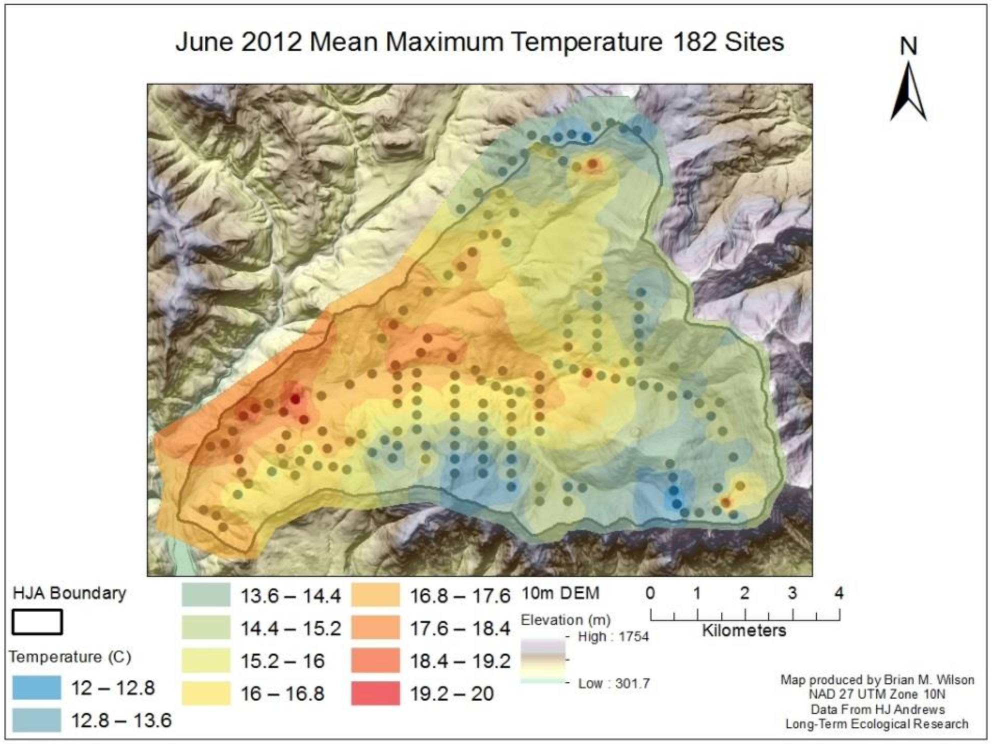




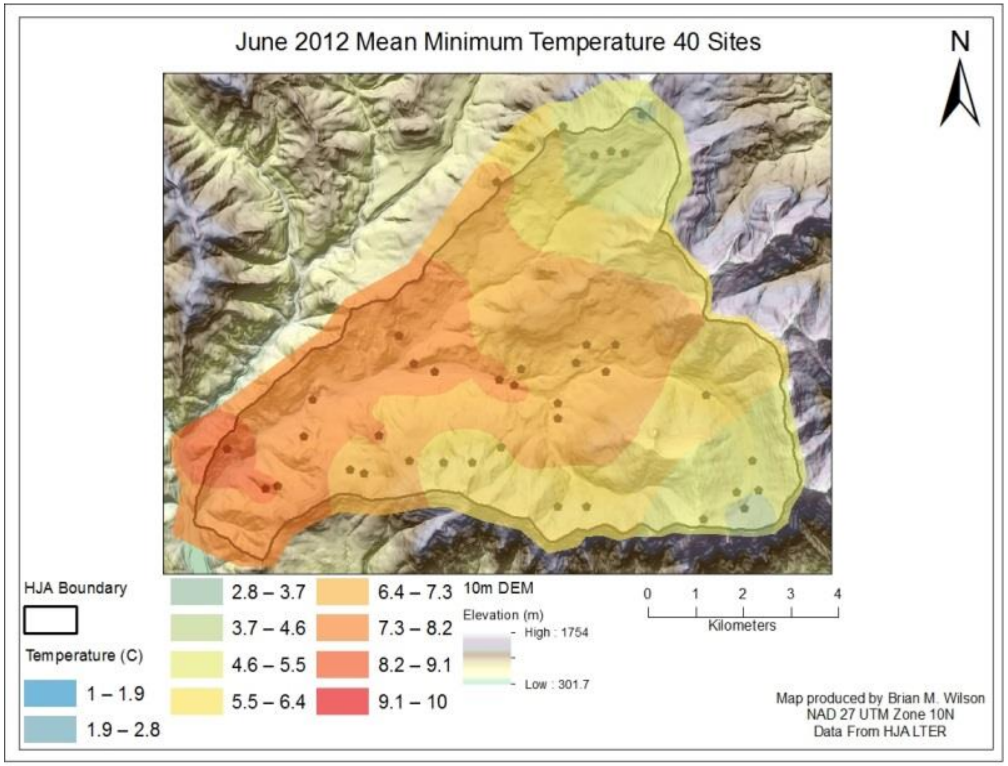
Mean monthly maximum temperature June 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

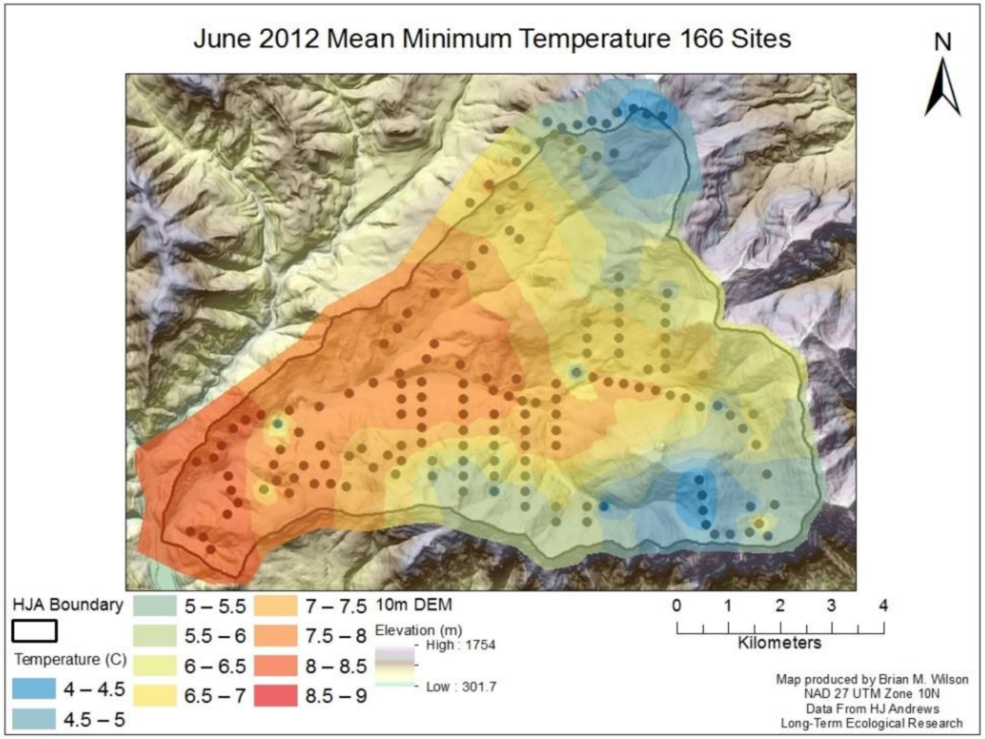


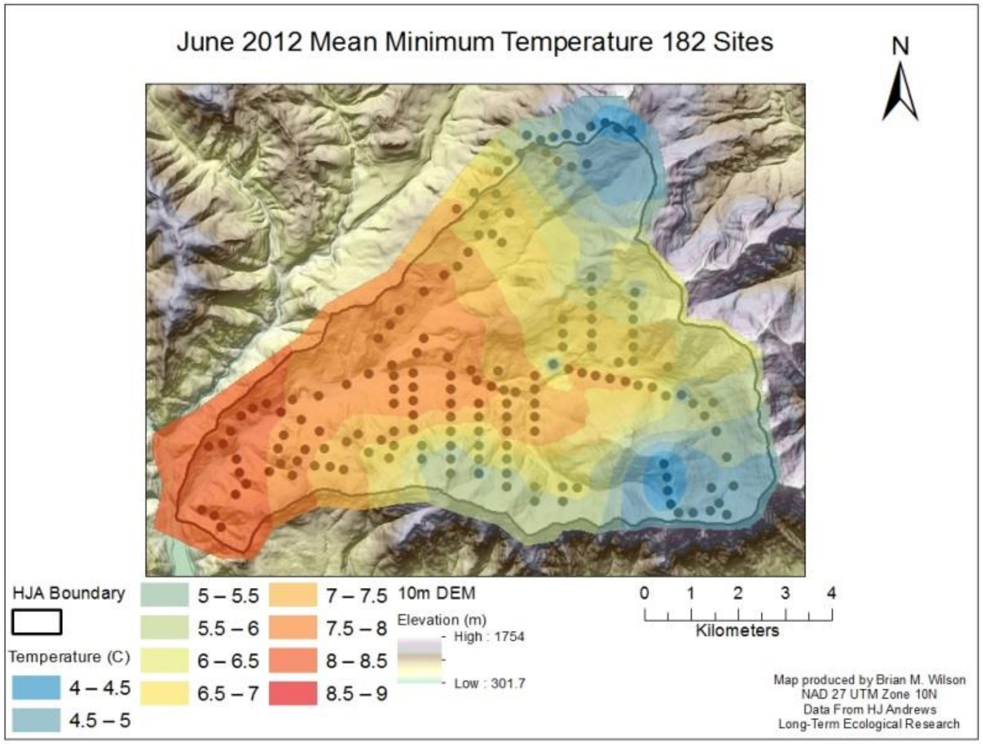




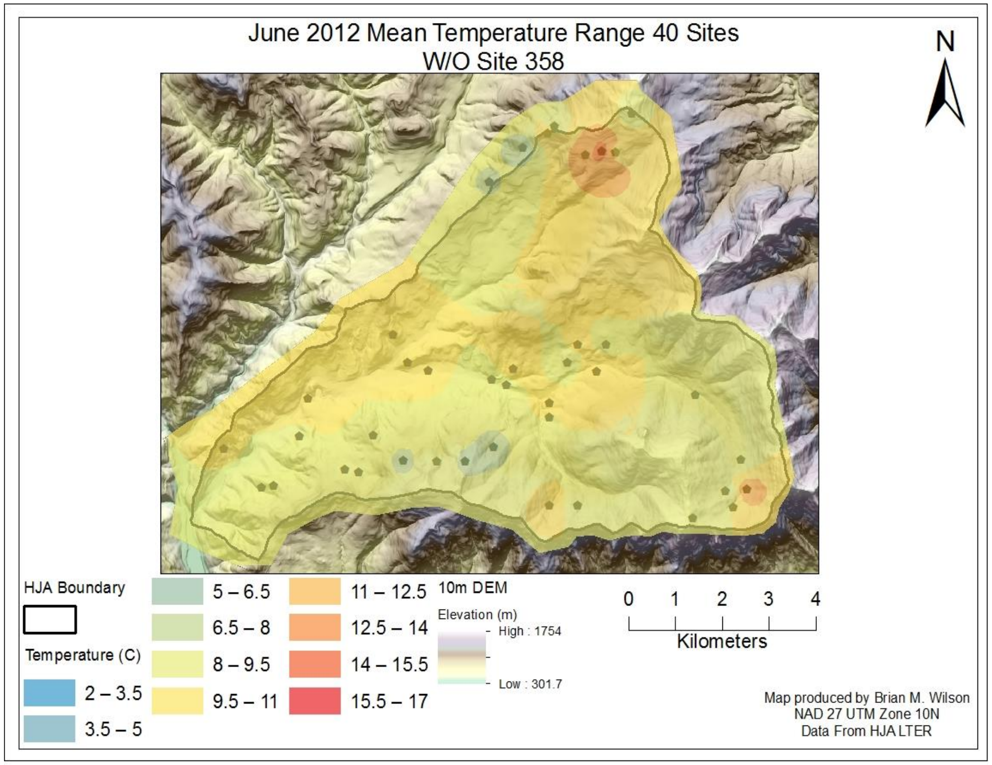
Mean monthly minimum temperature June 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.

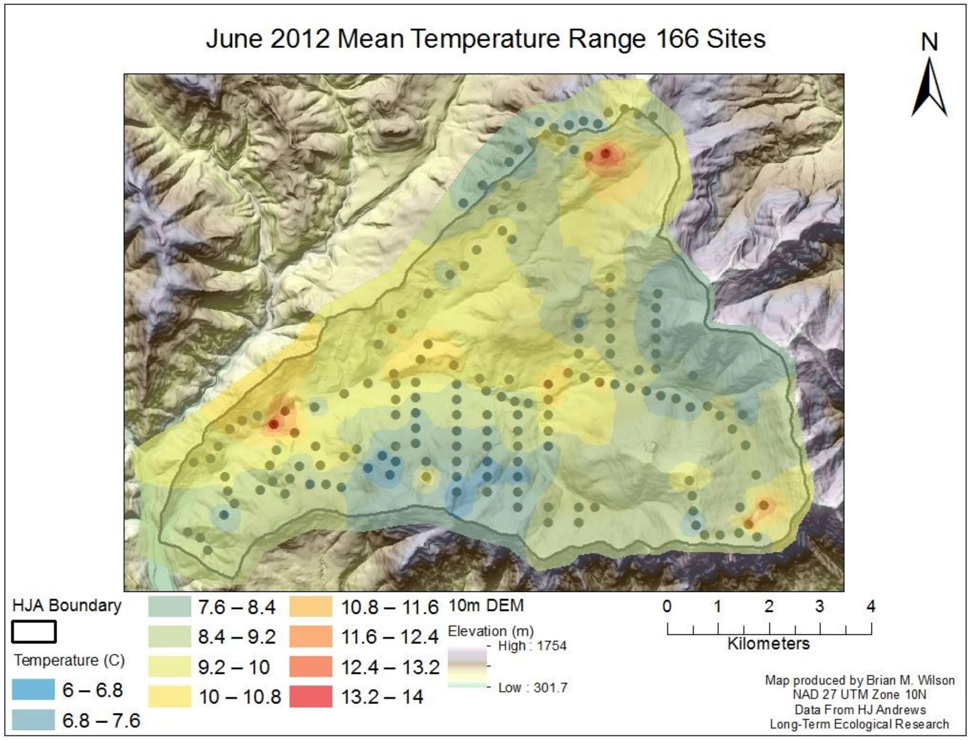






Mean monthly temperature range June 2012 using 40 BIRD sites, 166 BIRD sites, and 166 BIRD sites plus 16 Reference and Benchmark stand sites for 182 total sites.





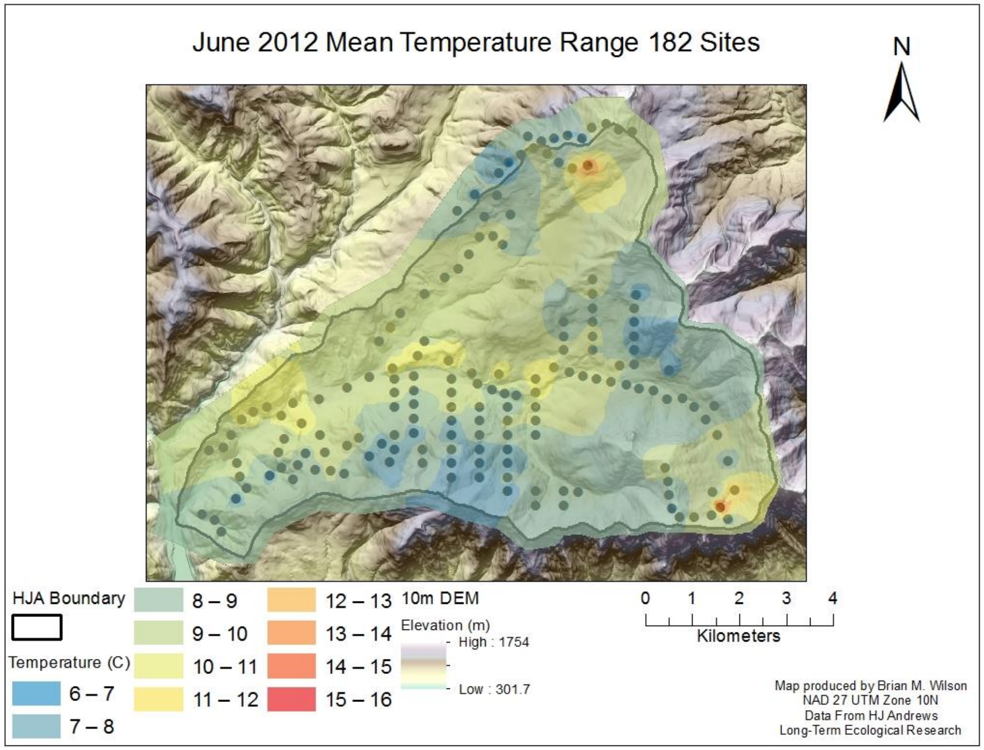
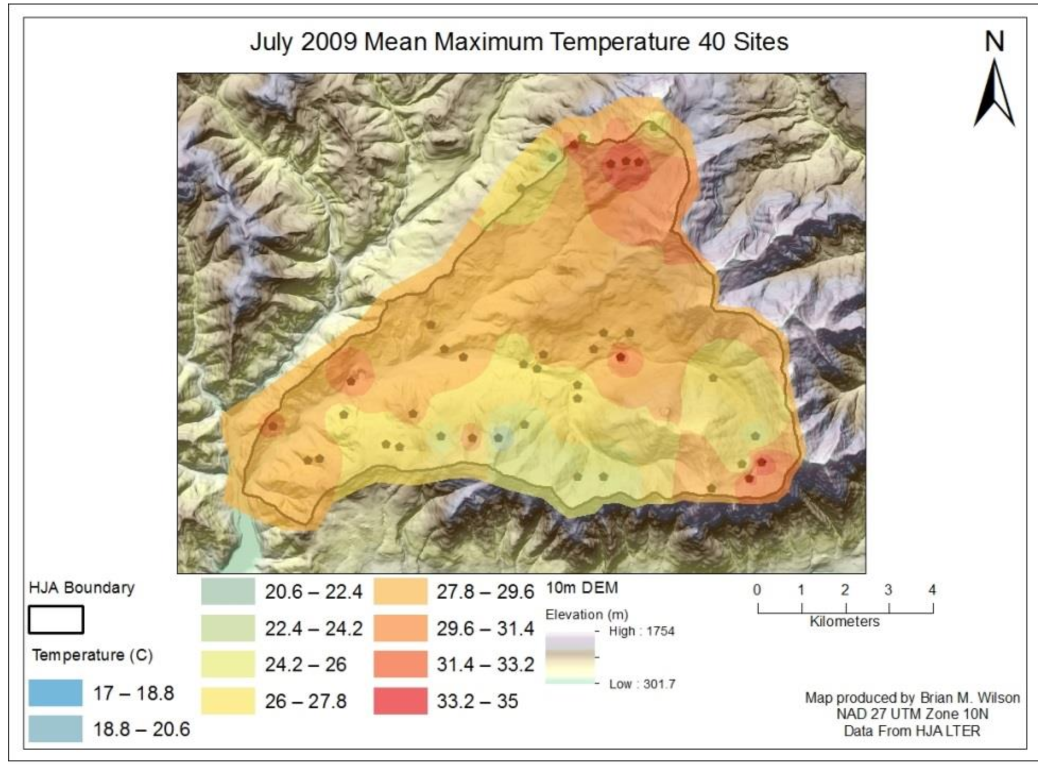
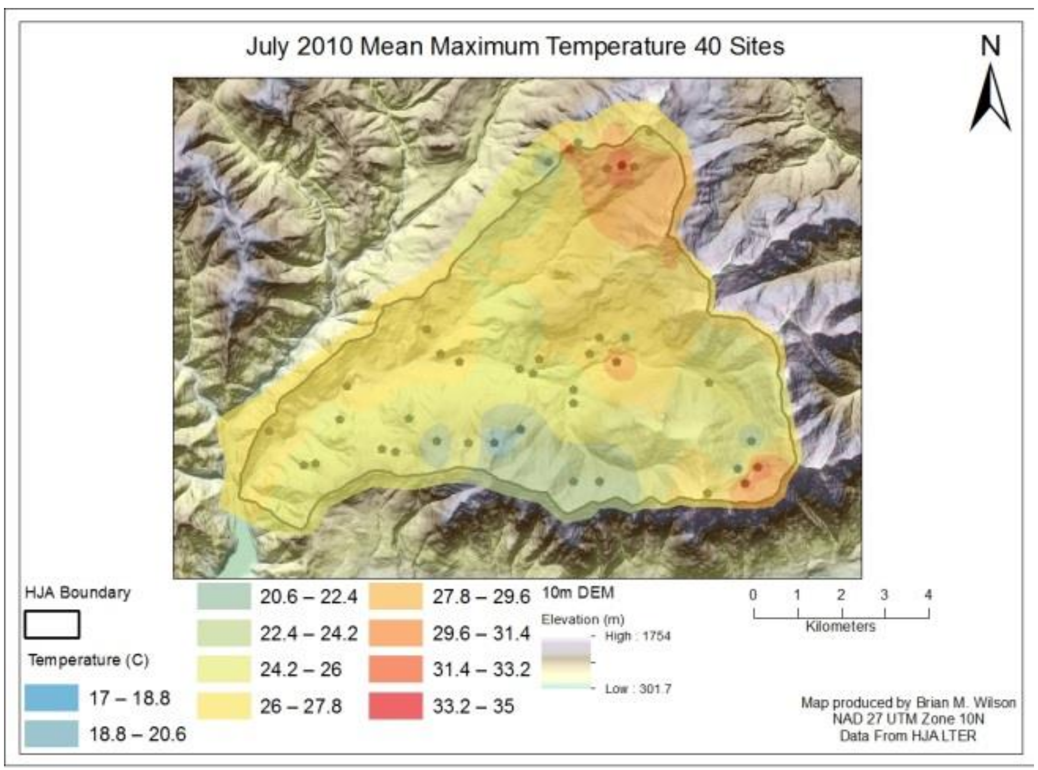
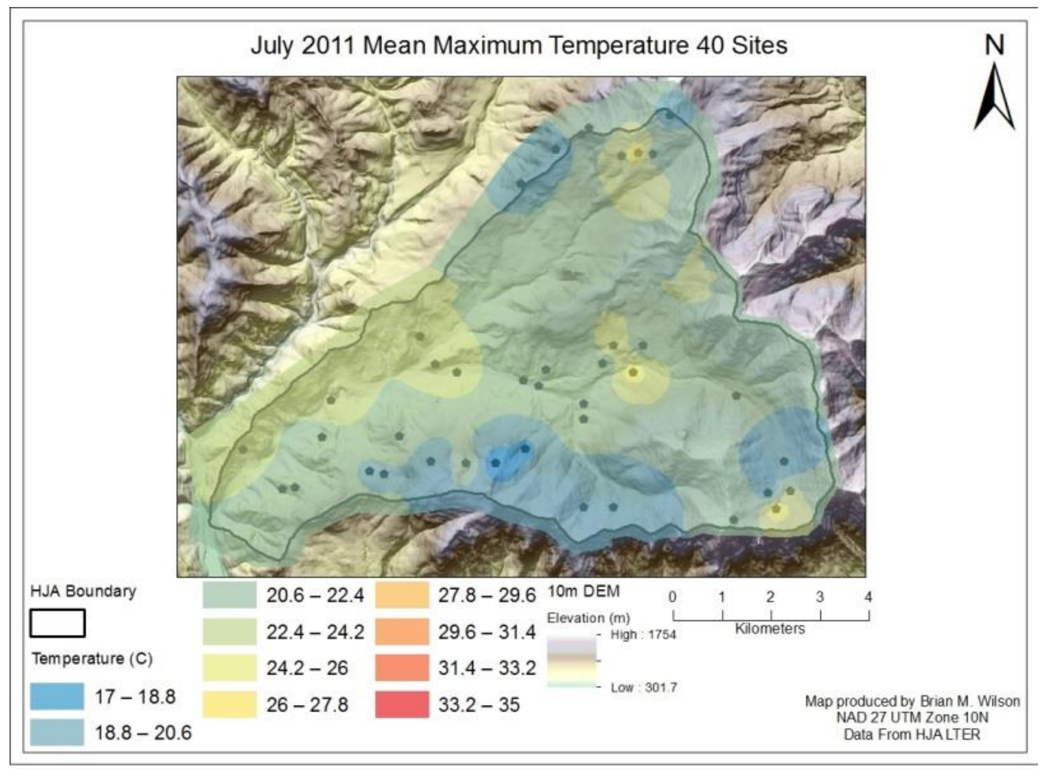


Figure 17.

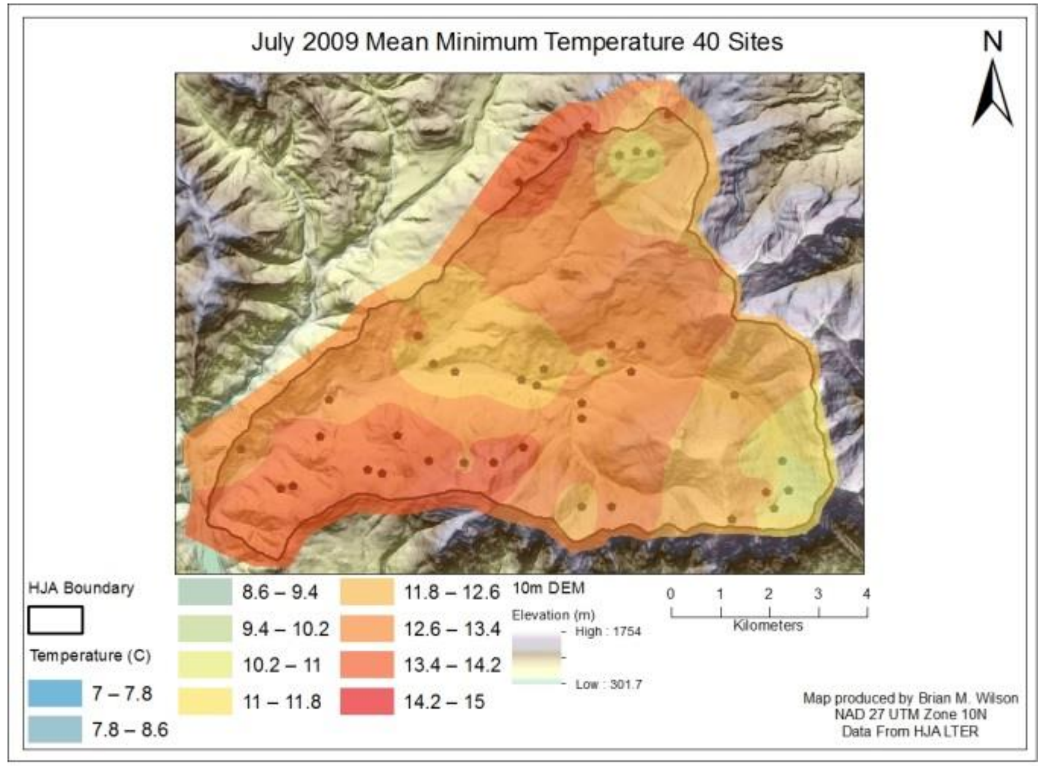
Mean Monthly Maximum Temperature 3 Consecutive Years July 2009 to July 2011 using 40 BIRD Sites.

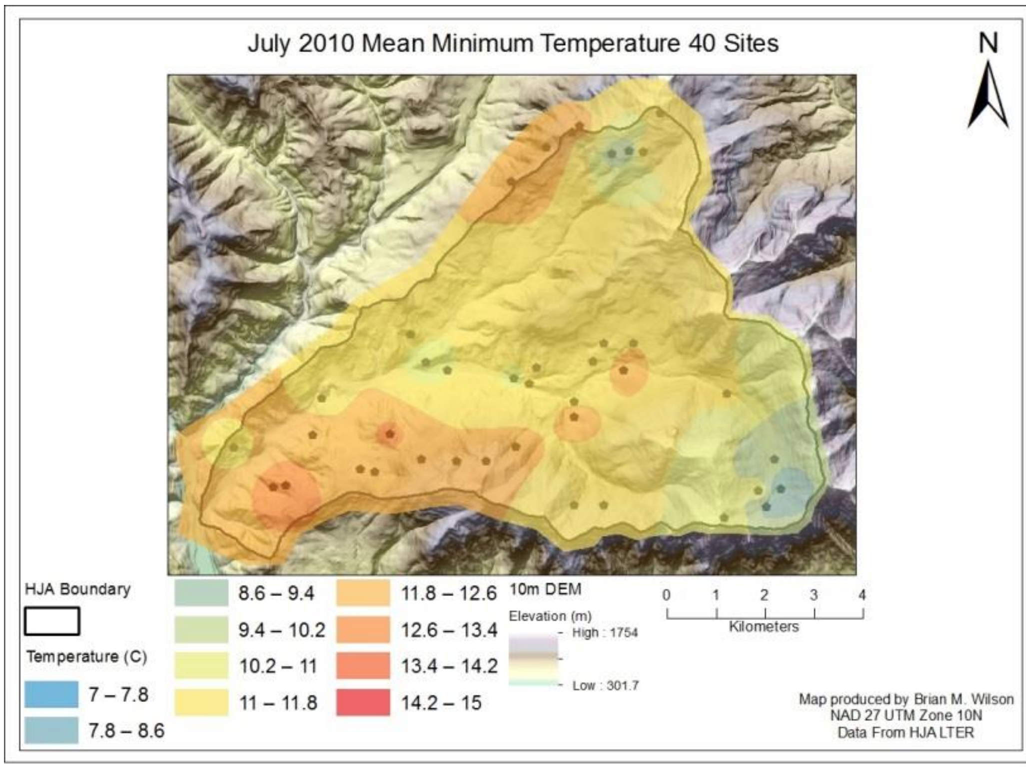


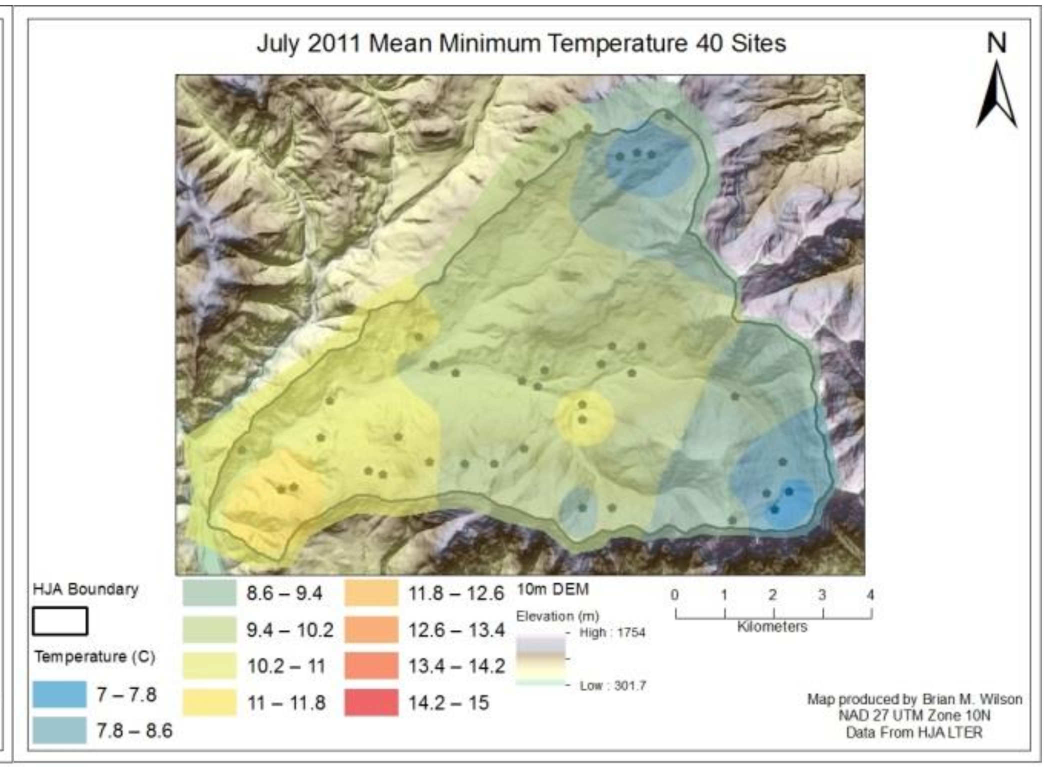




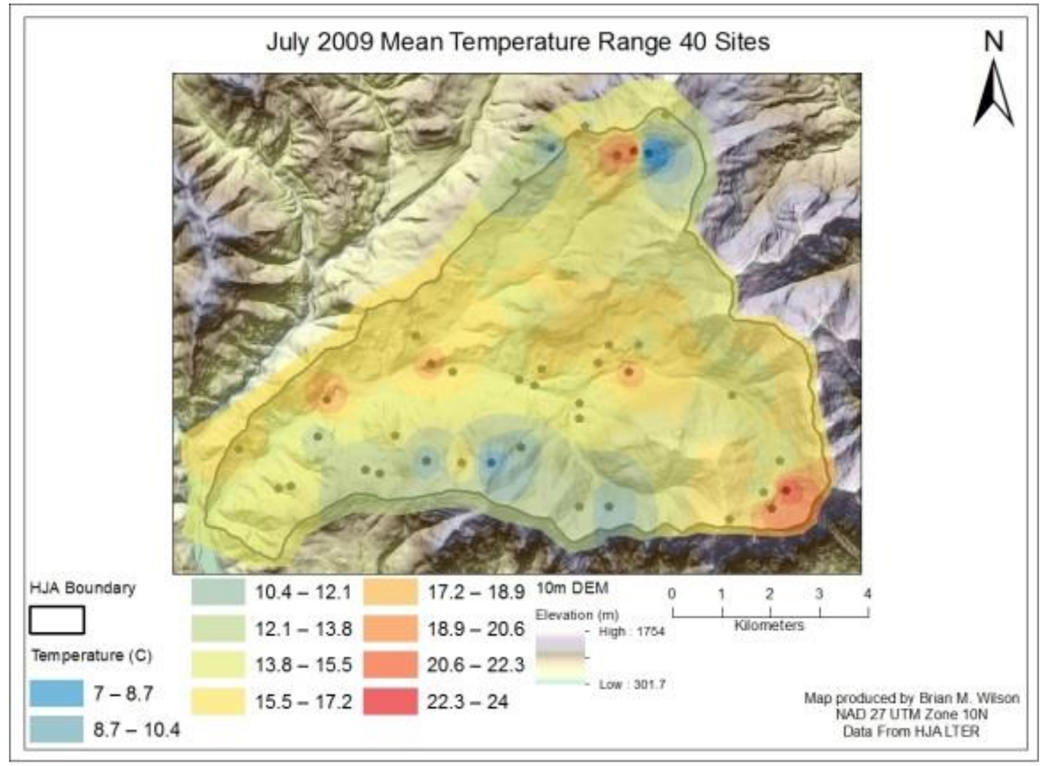
Mean Monthly Minimum Temperature 3 Consecutive Years July 2009 to July 2011 using 40 BIRD Sites.

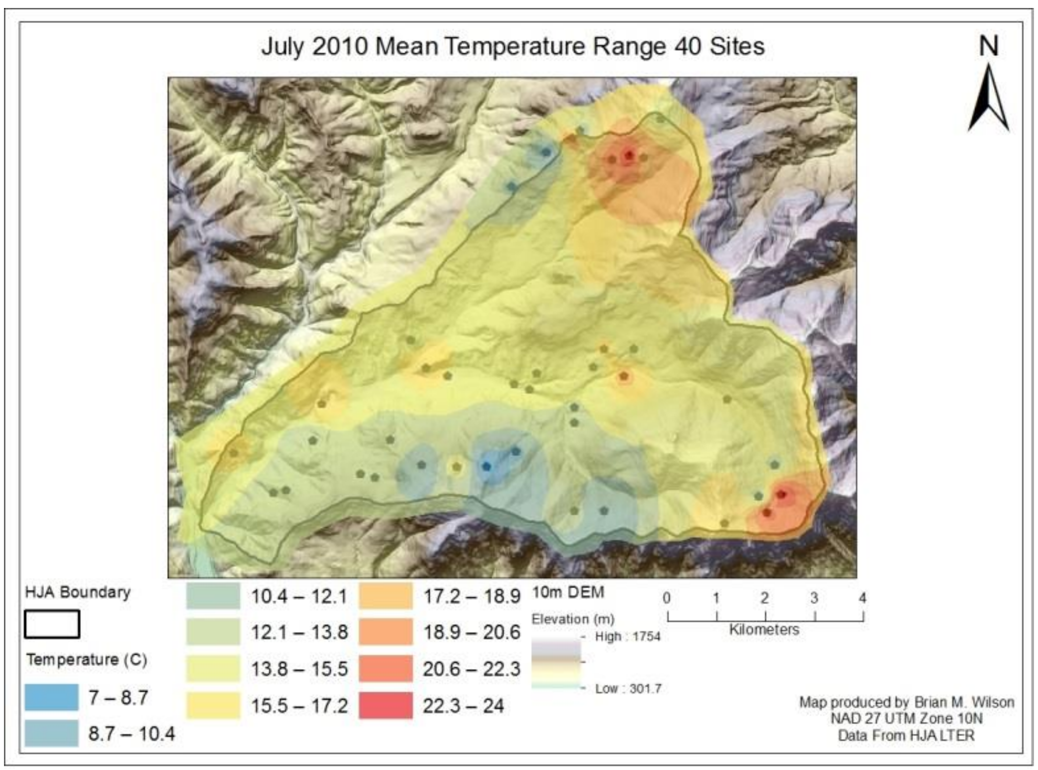


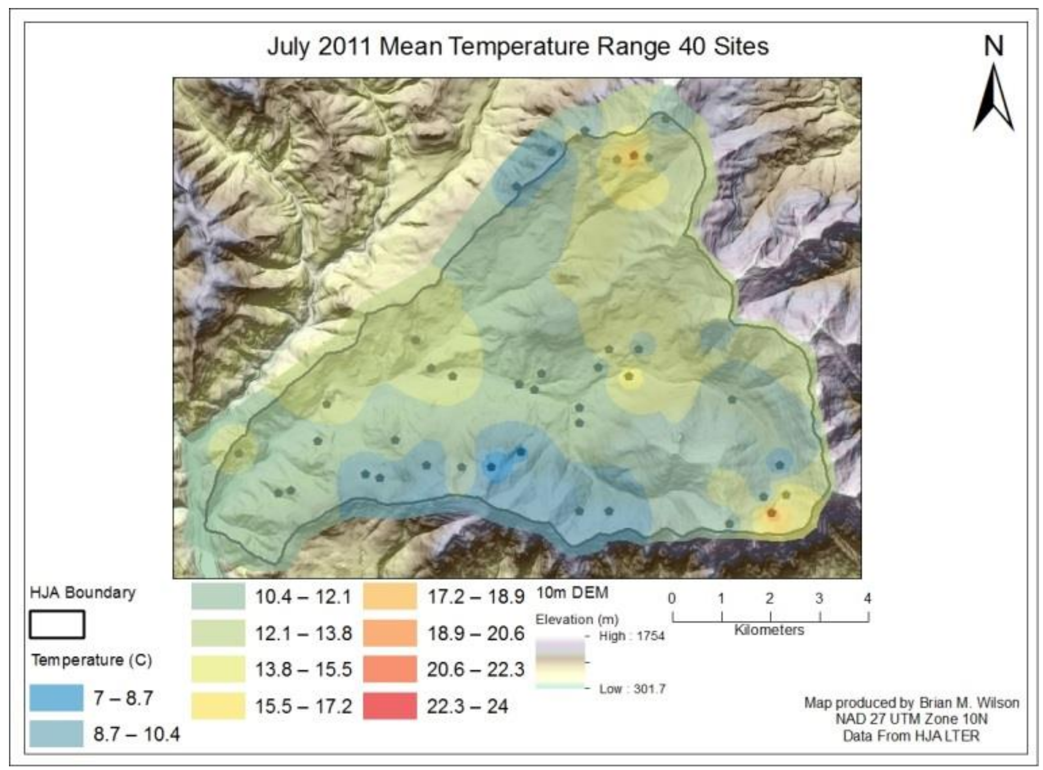




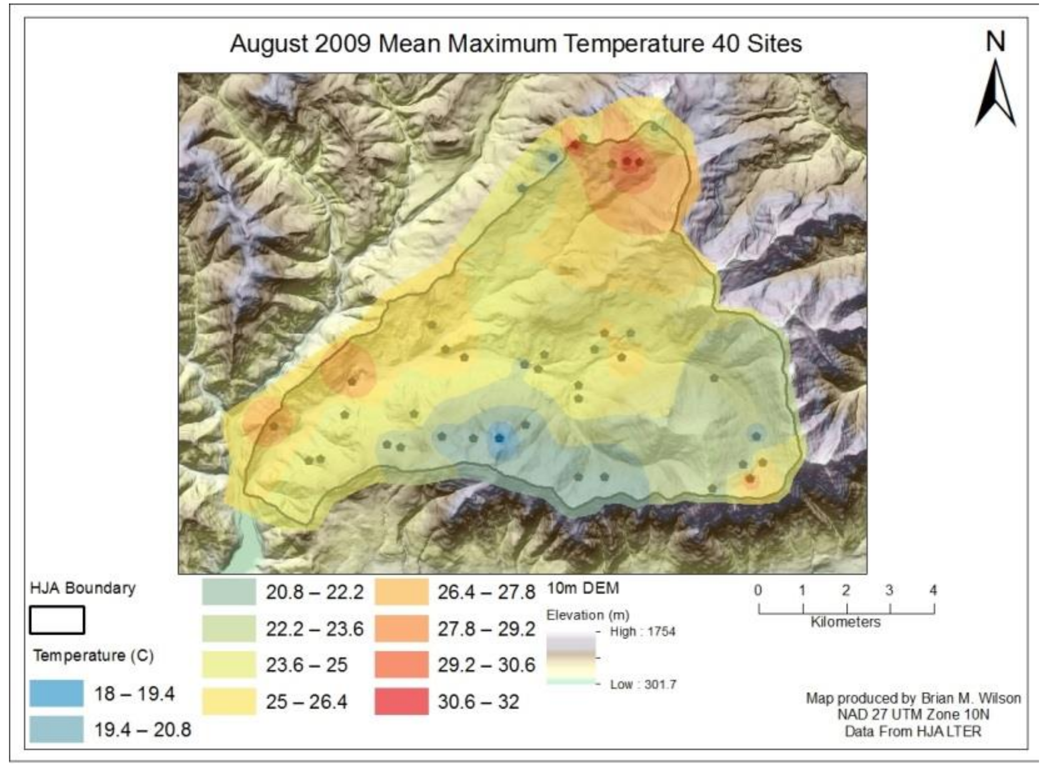
Mean Monthly Temperature Range 3 Consecutive Years July 2009 to June 2011 using 40 BIRD Sites.

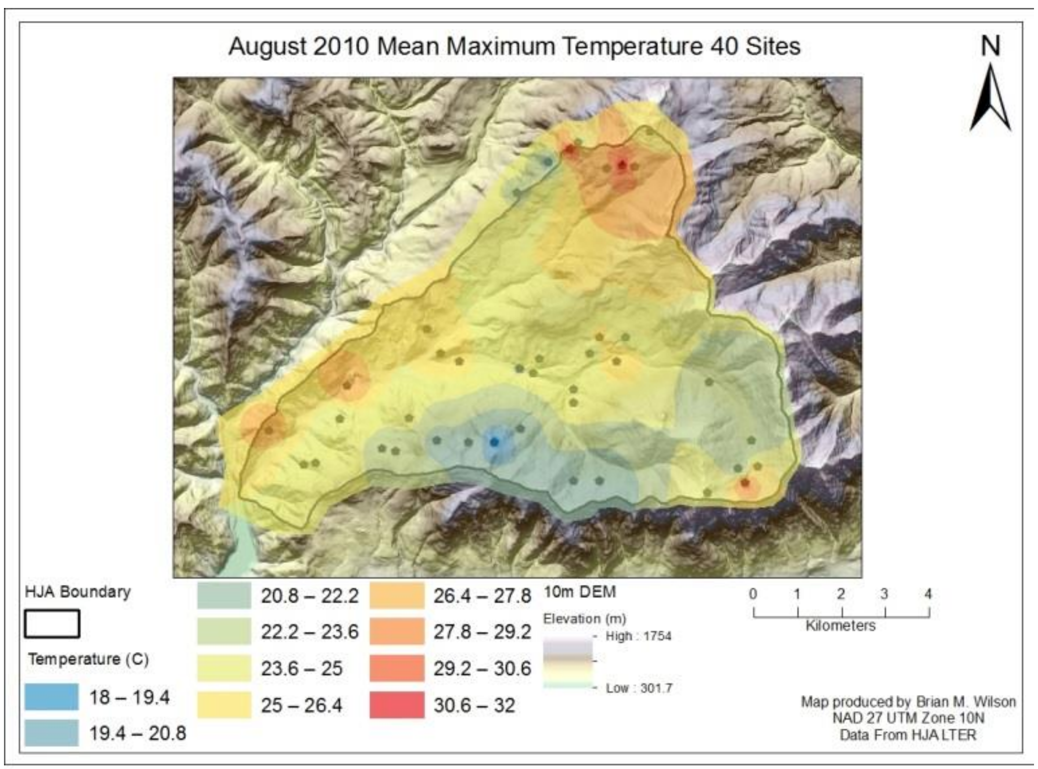


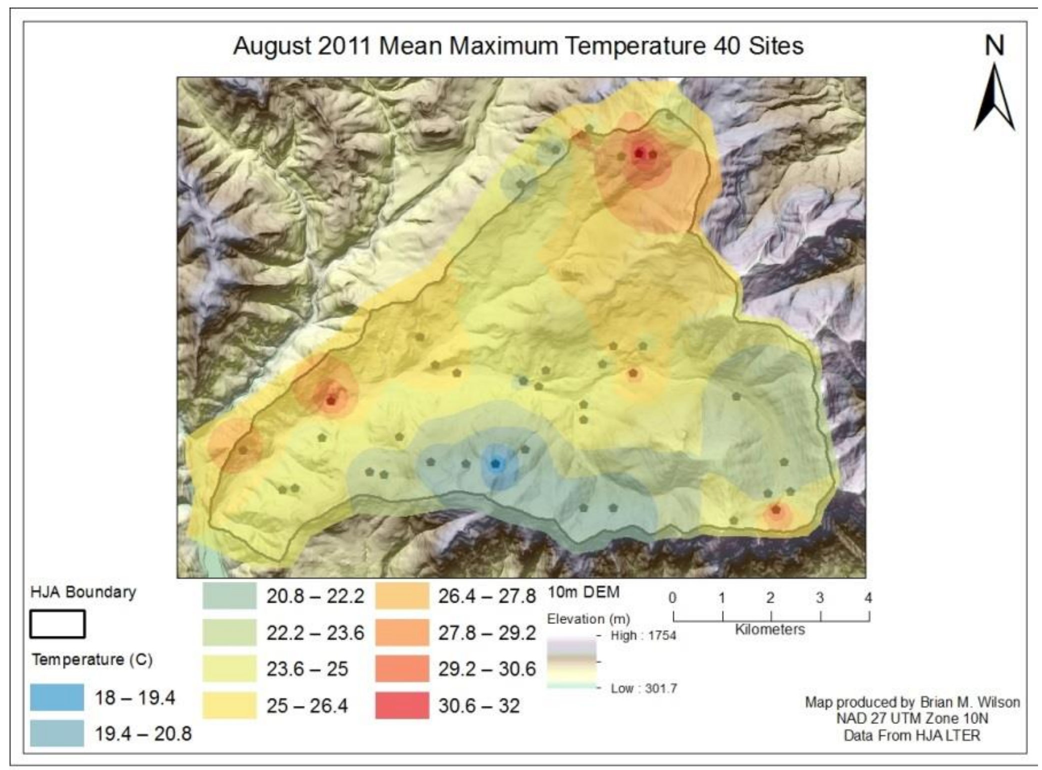




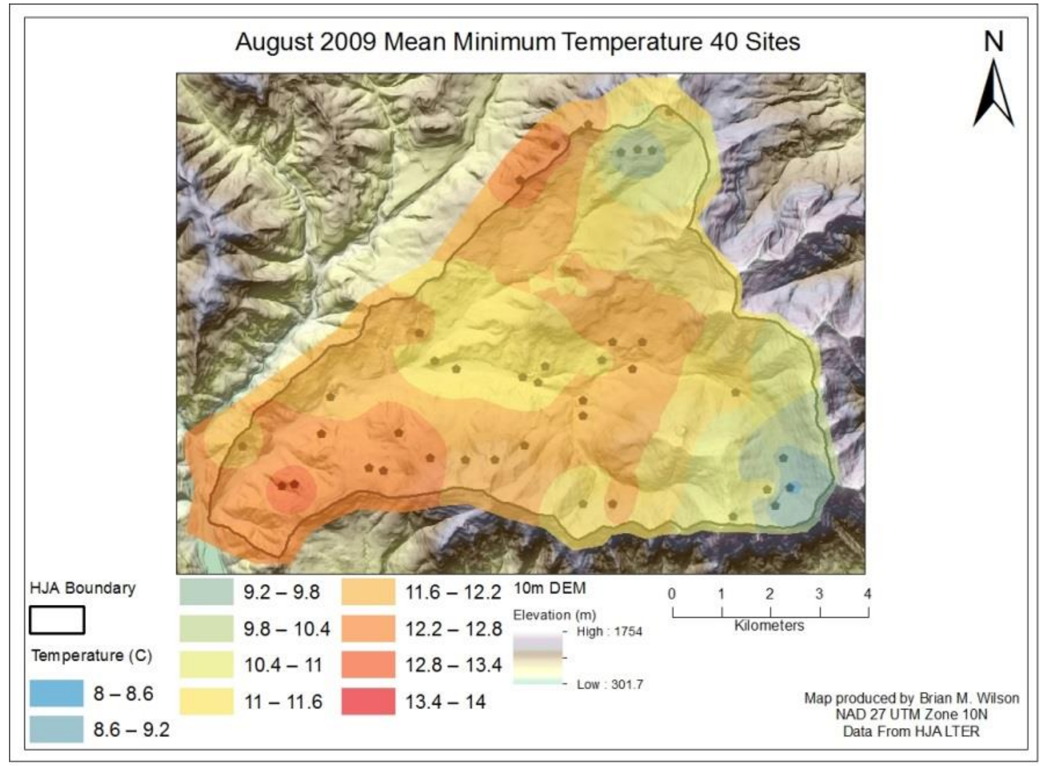
Mean Monthly Maximum Temperature 3 Consecutive Years August 2009 to August 2011 using 40 BIRD Sites.

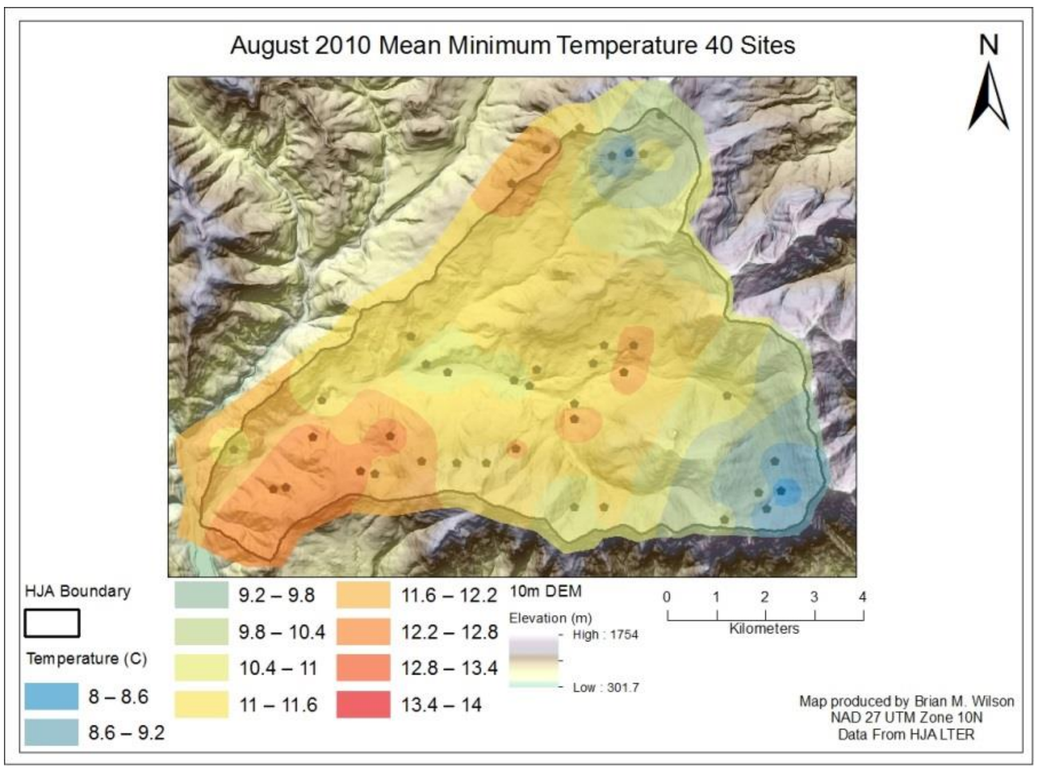


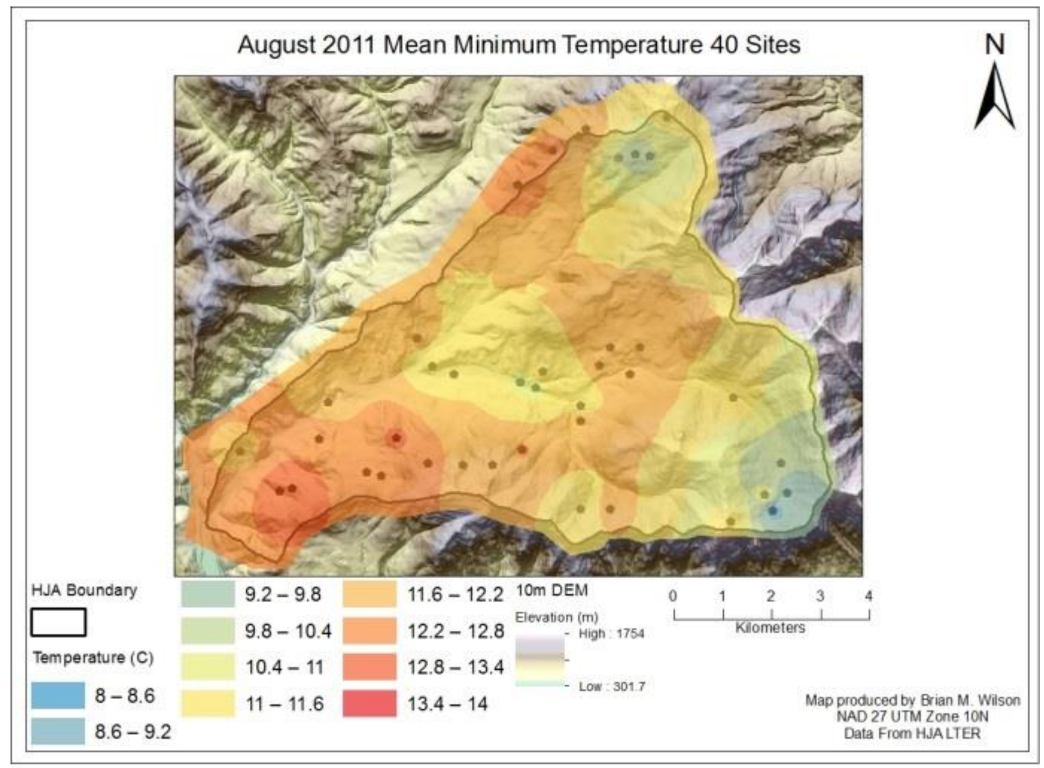




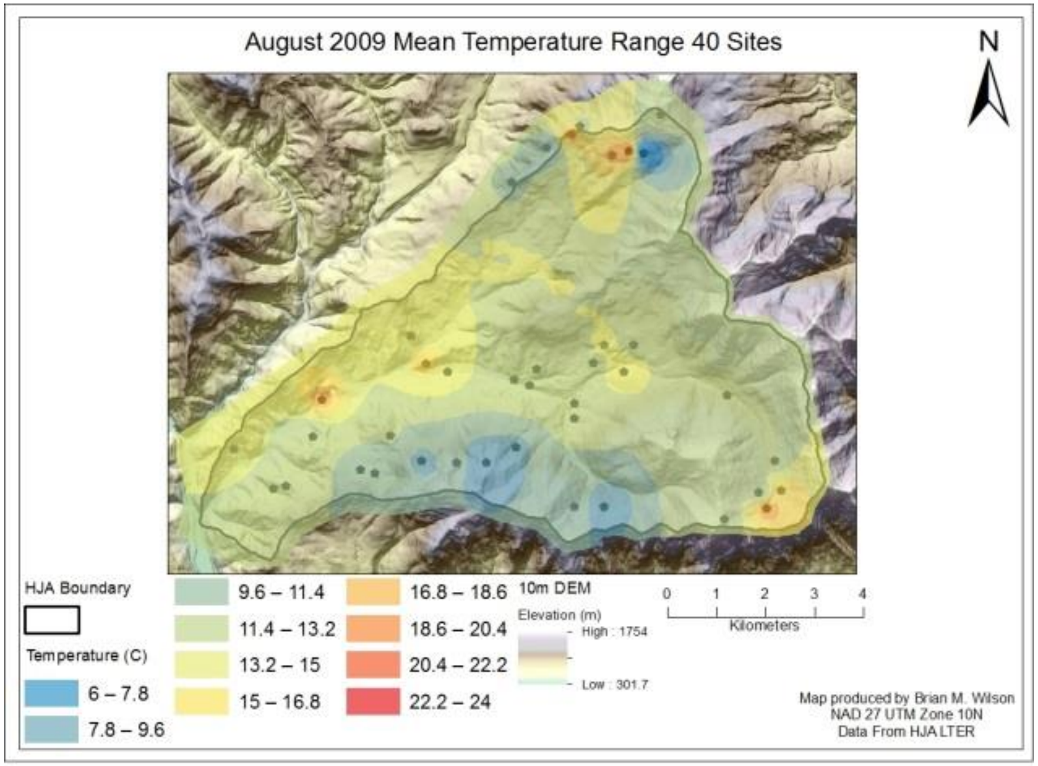
Mean Monthly Minimum Temperature 3 Consecutive Years August 2009 to August 2011 using 40 BIRD Sites.

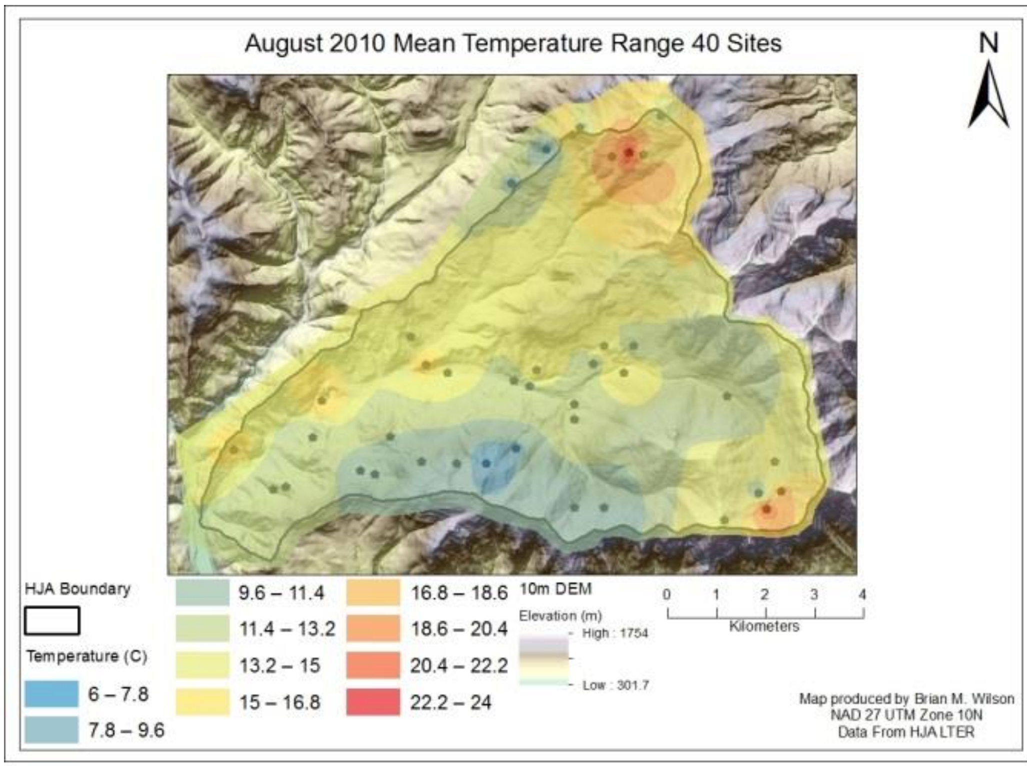


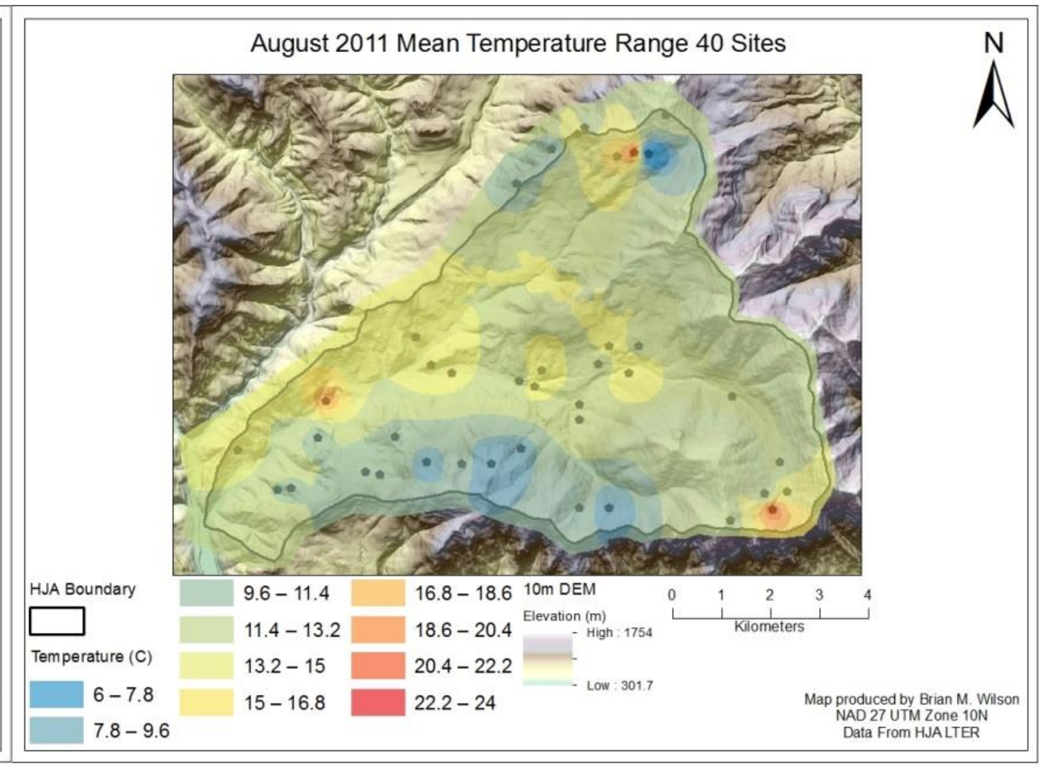




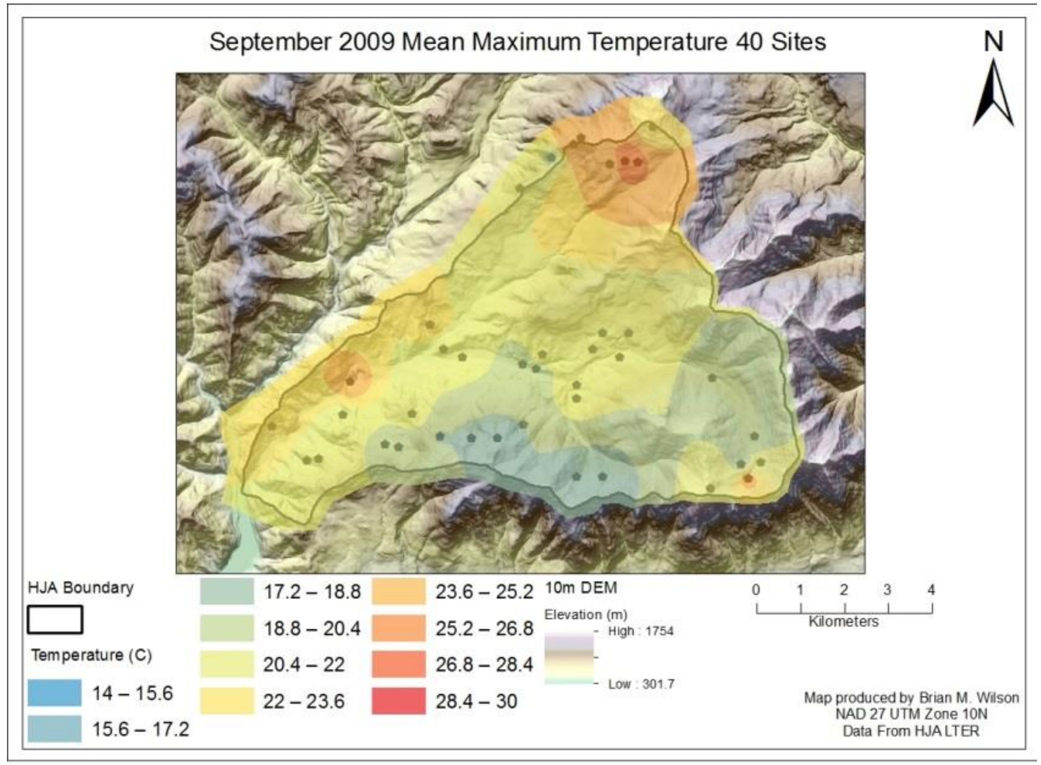
Mean Monthly Temperature Range 3 Consecutive Years August 2009 to August 2011 using 40 BIRD Sites.

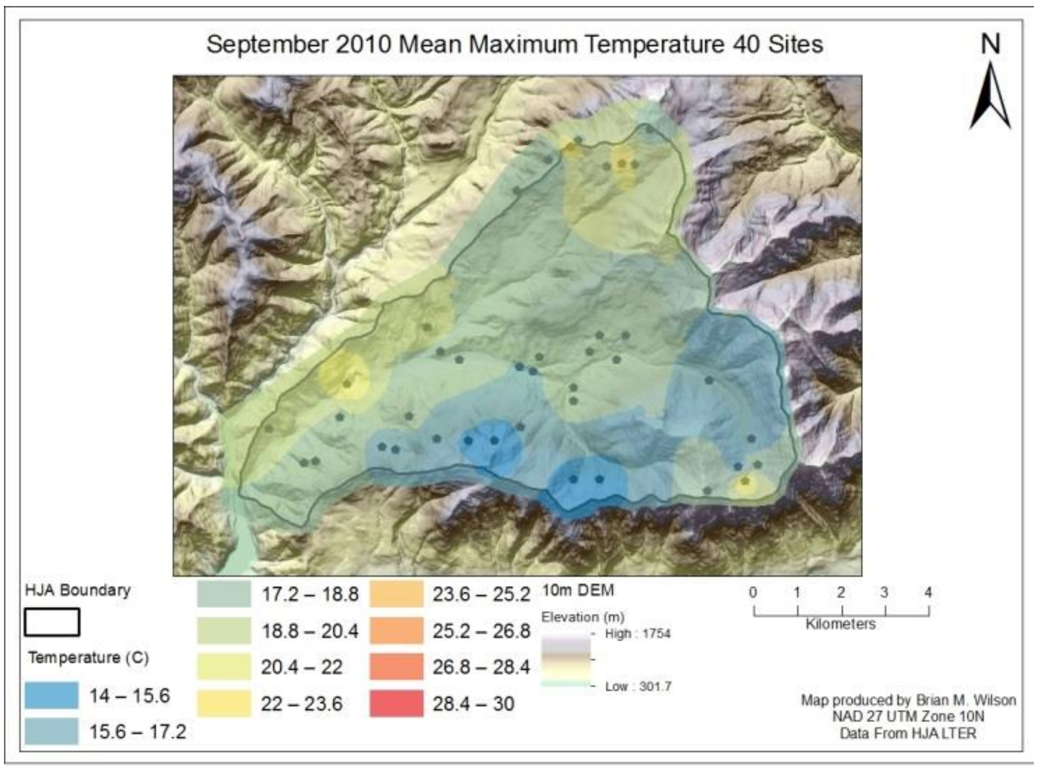


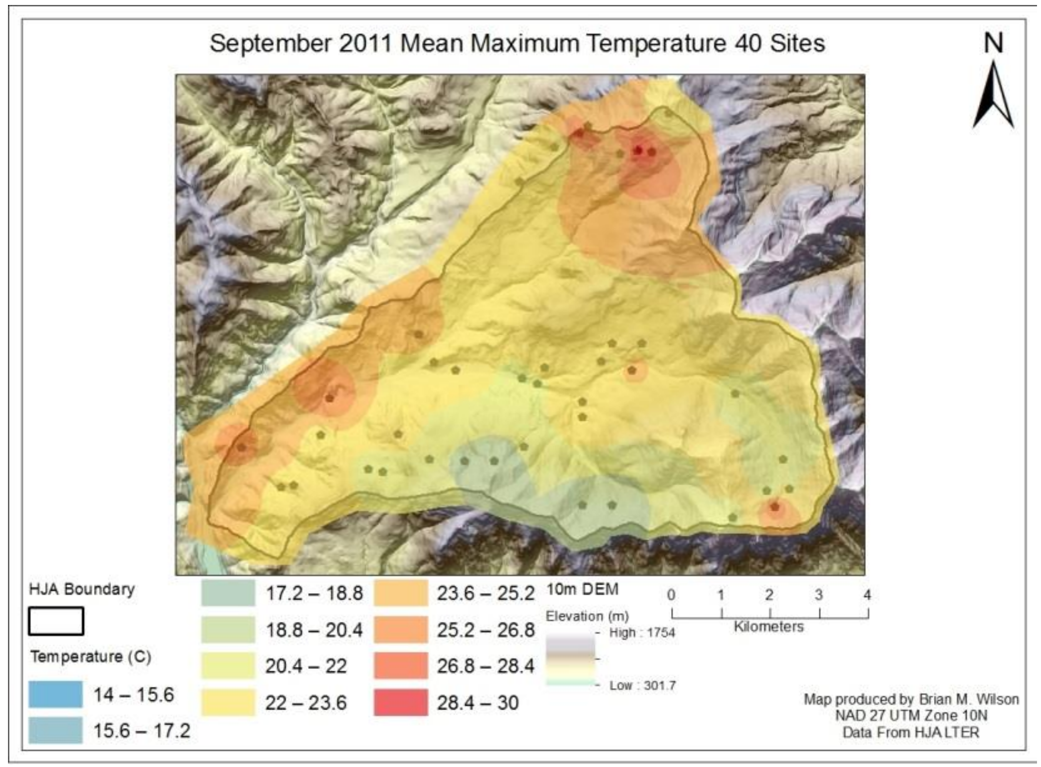




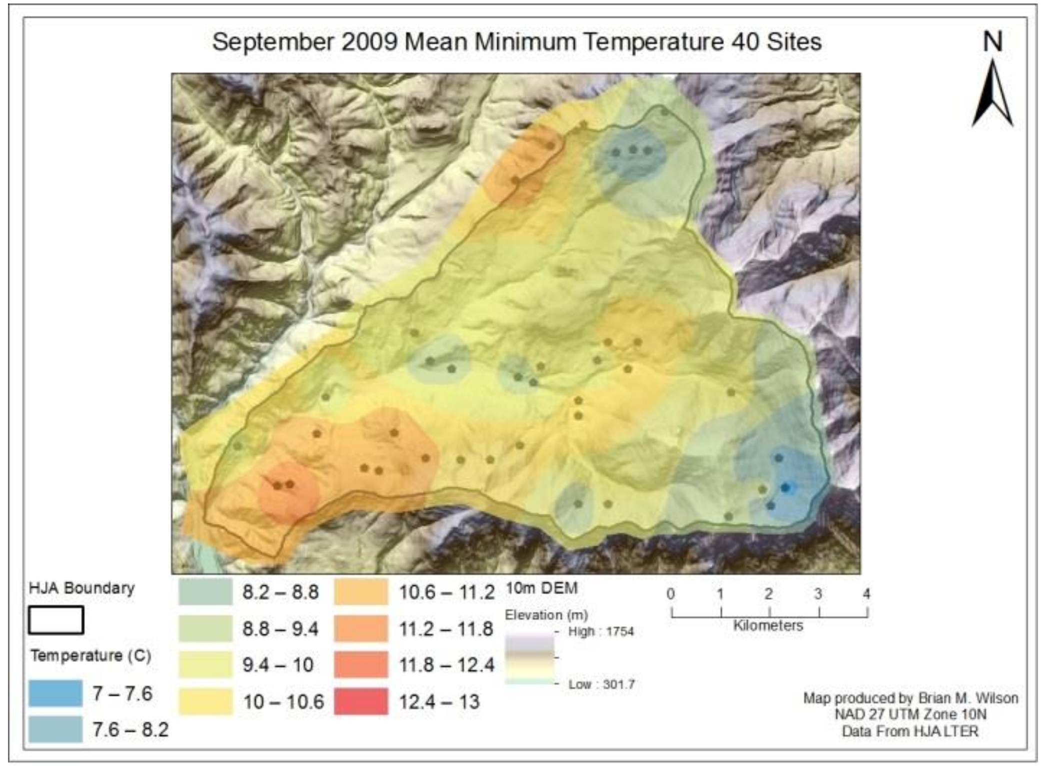
Mean Monthly Maximum Temperature 3 Consecutive Years September 2009 to September 2011 using 40 BIRD Sites.

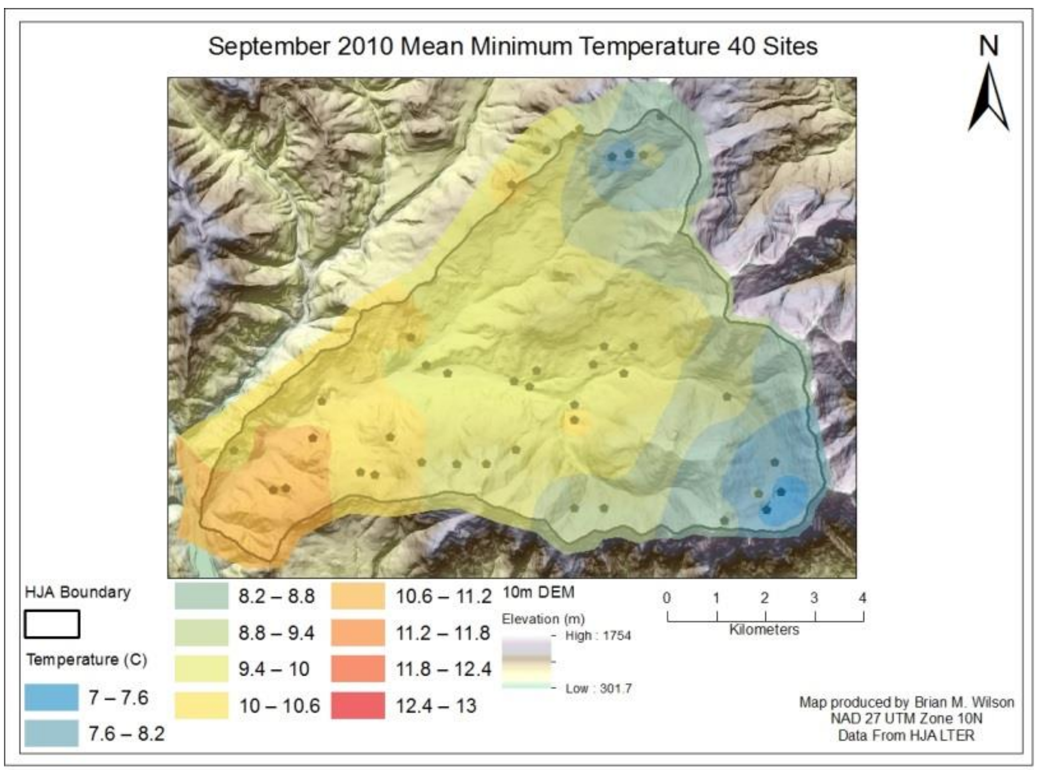


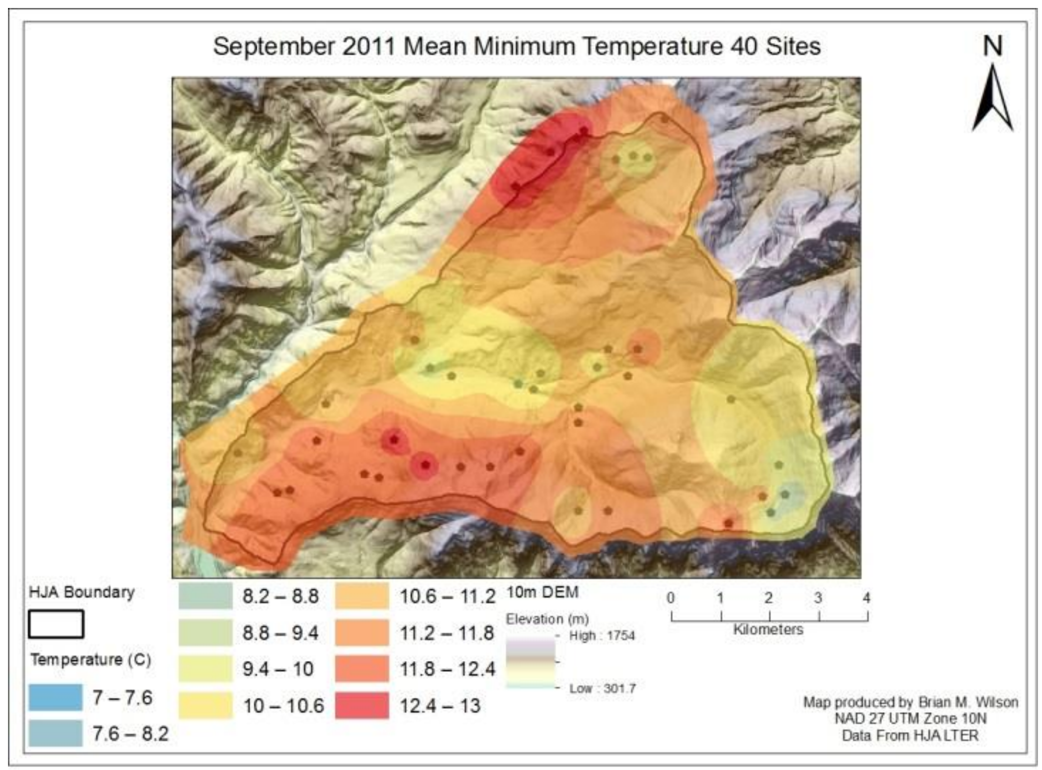




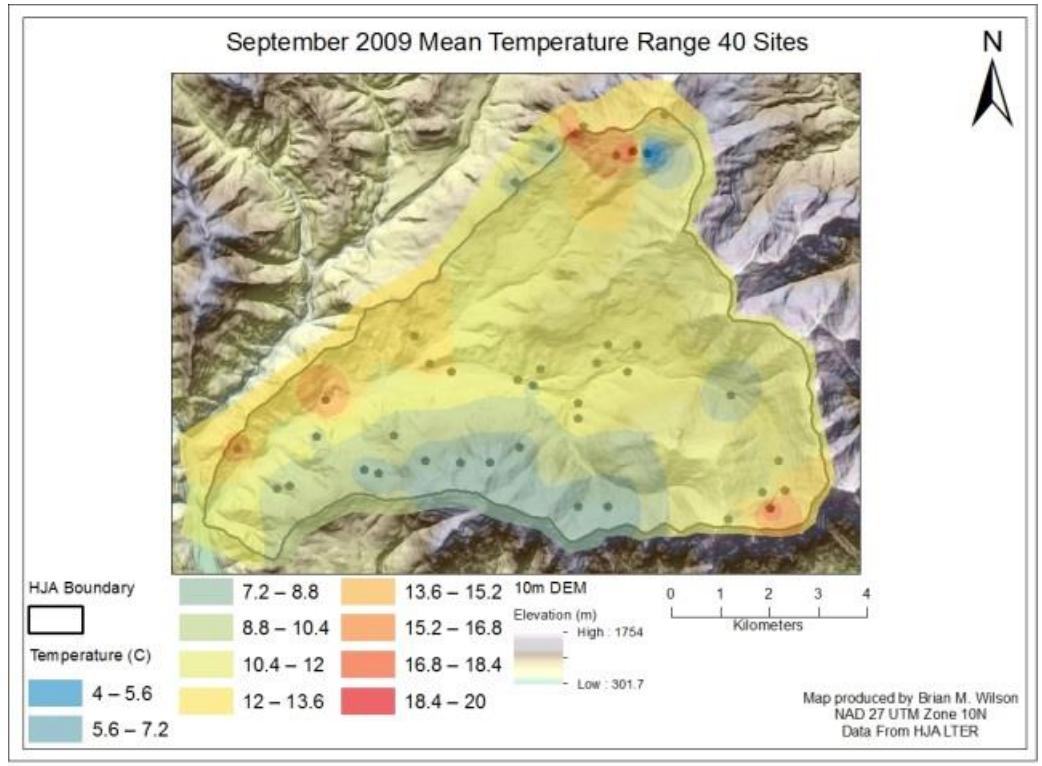
Mean Monthly Minimum Temperature 3 Consecutive Years September 2009 to September 2011 using 40 BIRD Sites.

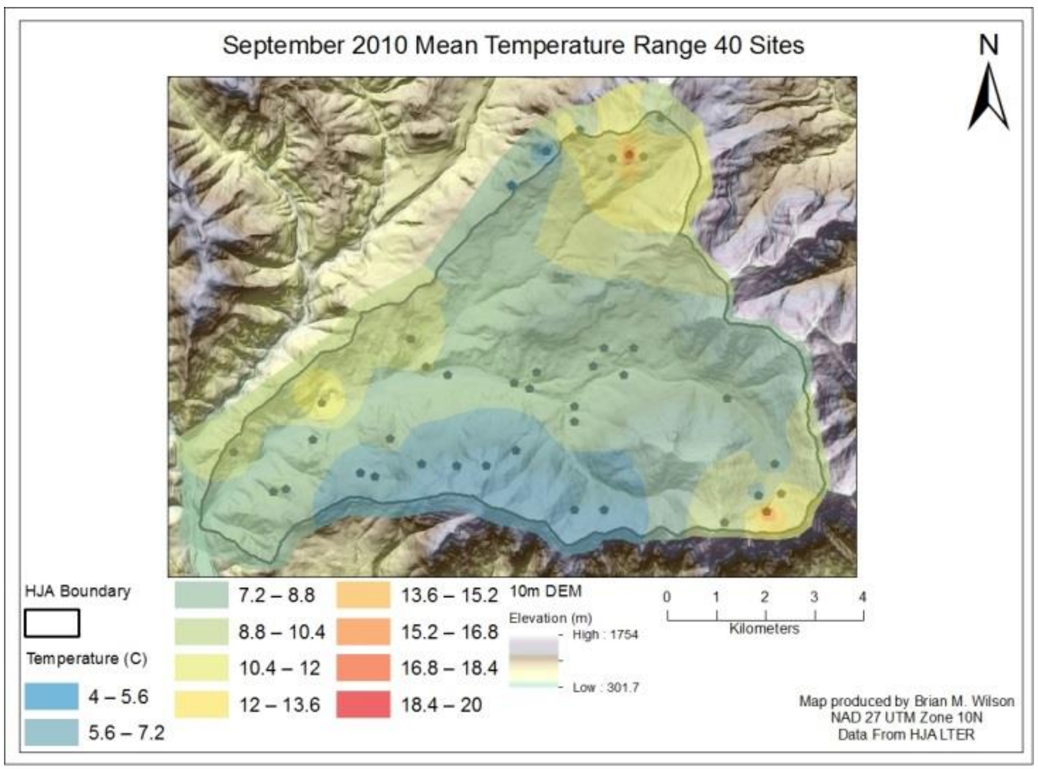


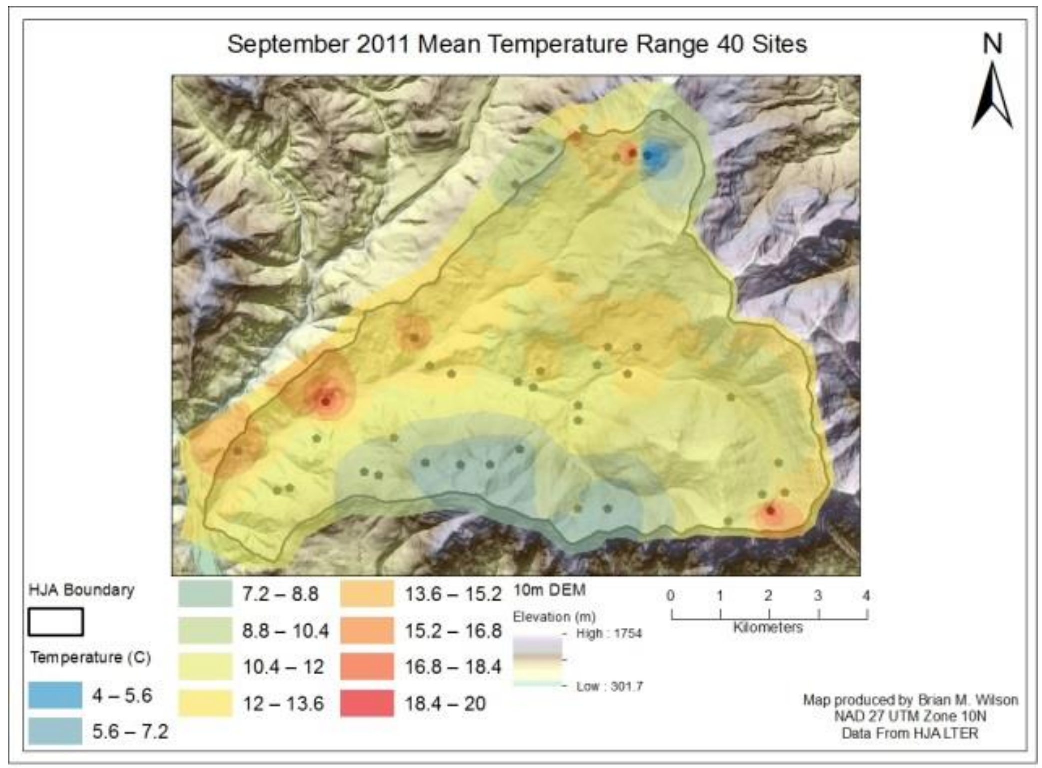




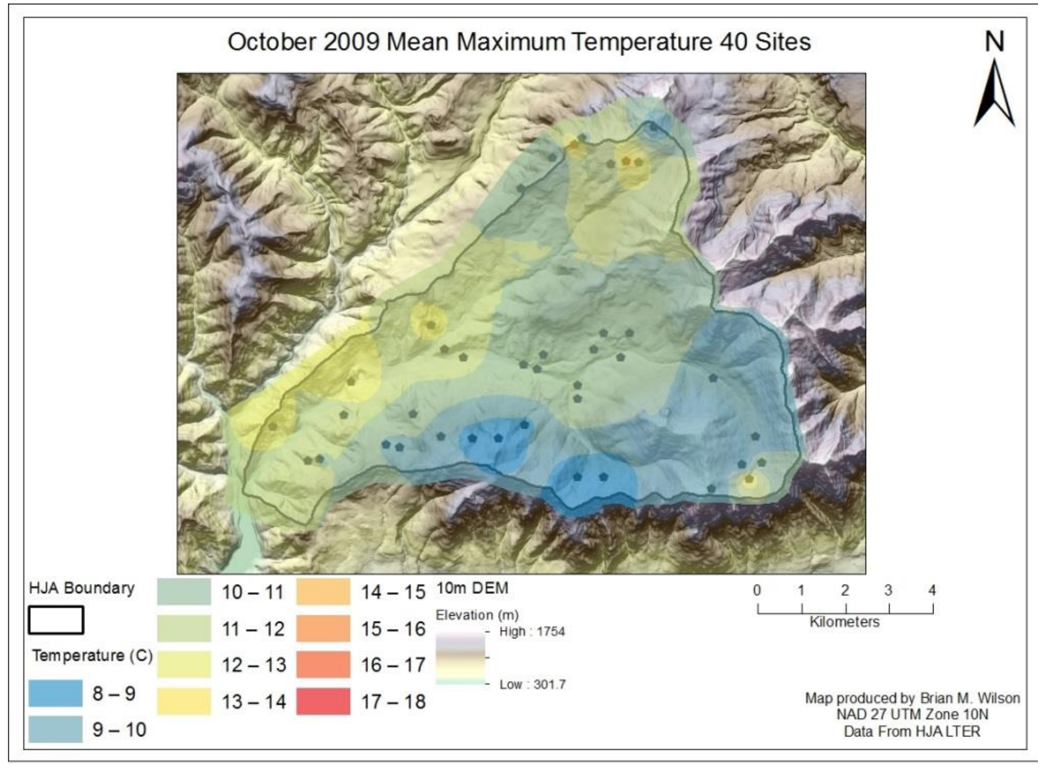
Mean Monthly Temperature Range 3 Consecutive Years September 2009 to September 2011 using 40 BIRD Sites.

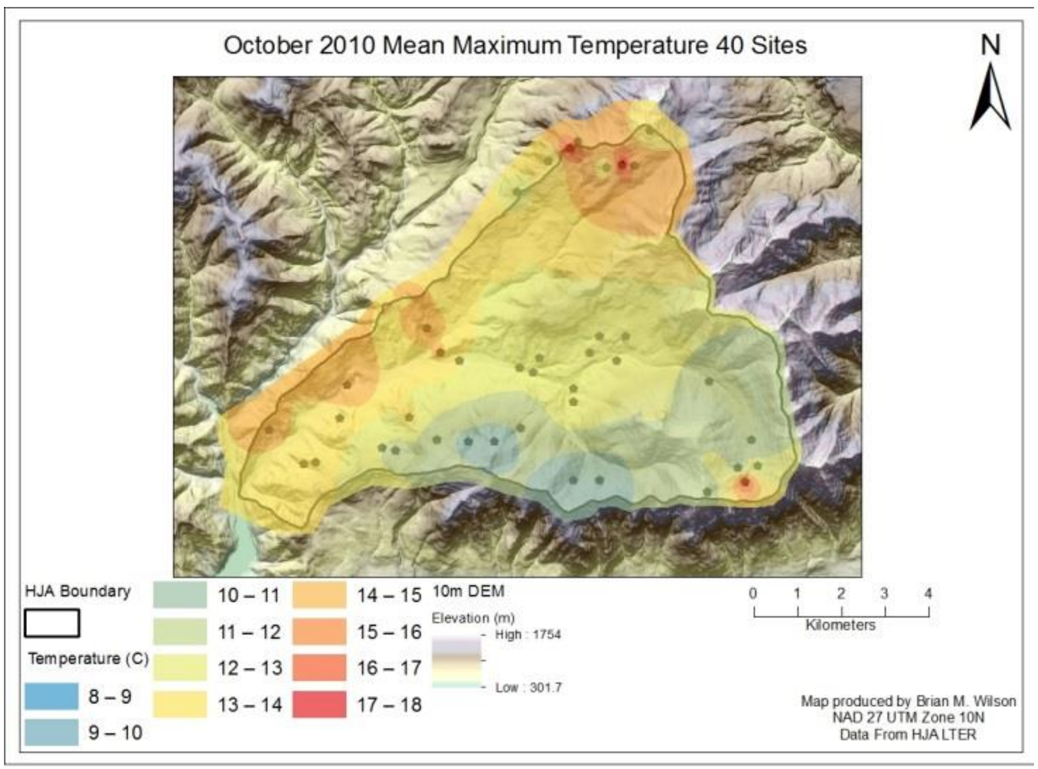


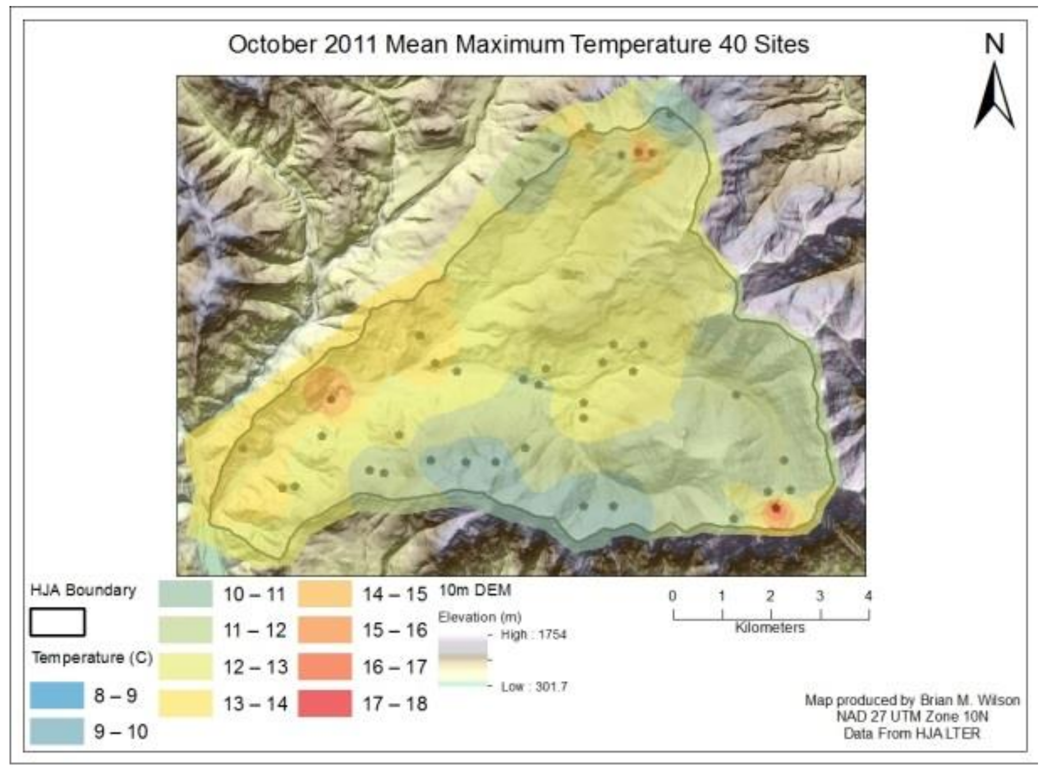




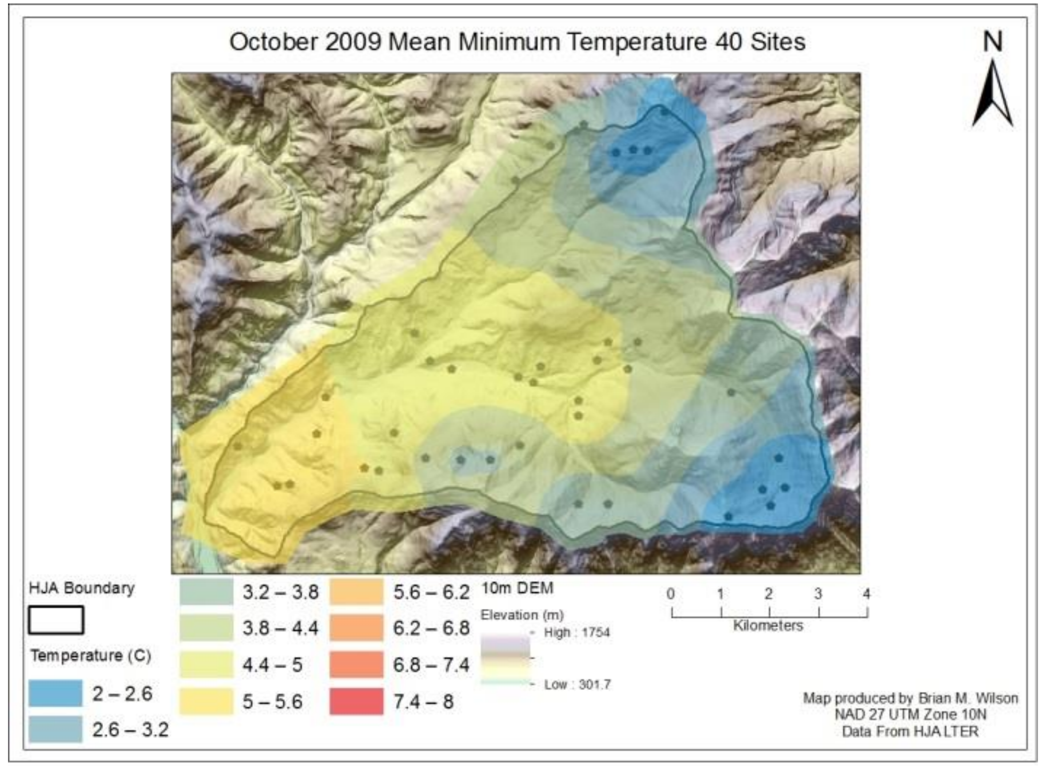
Mean Monthly Maximum Temperature 3 Consecutive Years October 2009 to October 2011 using 40 BIRD Sites.

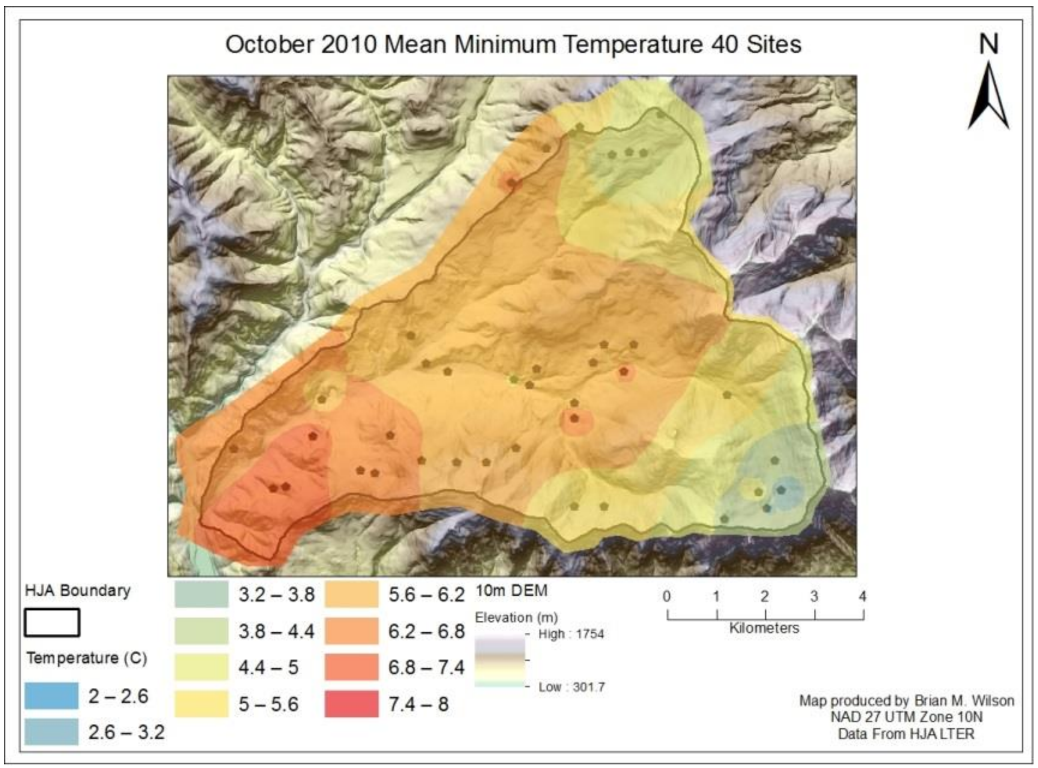


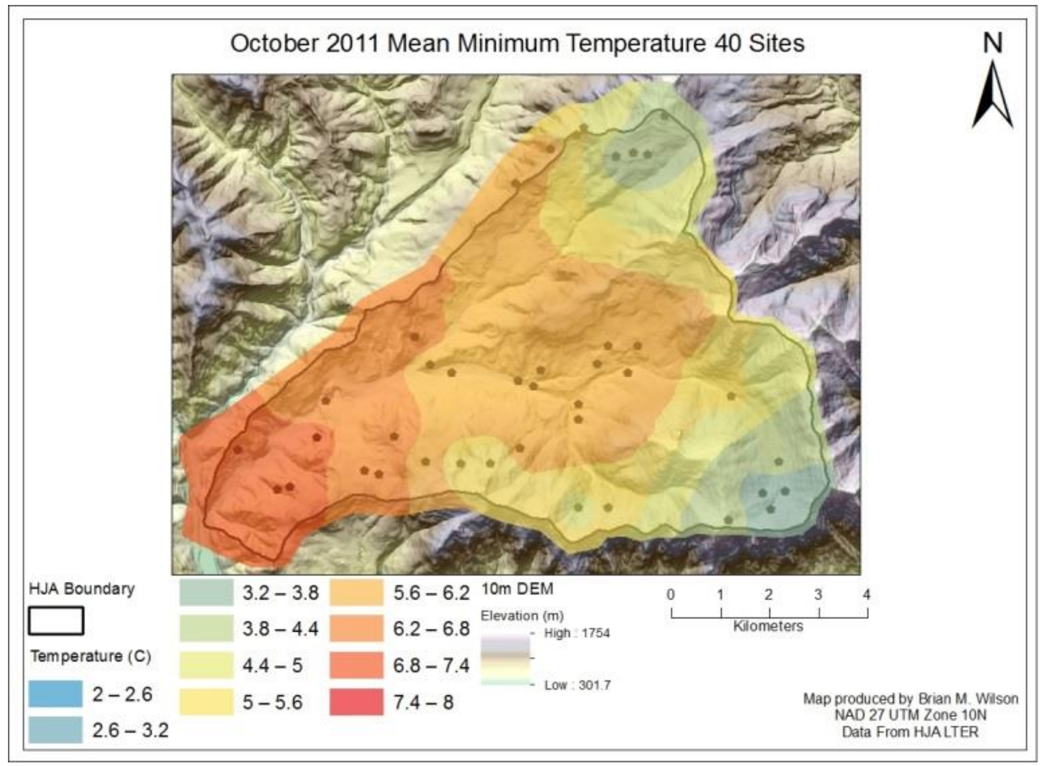




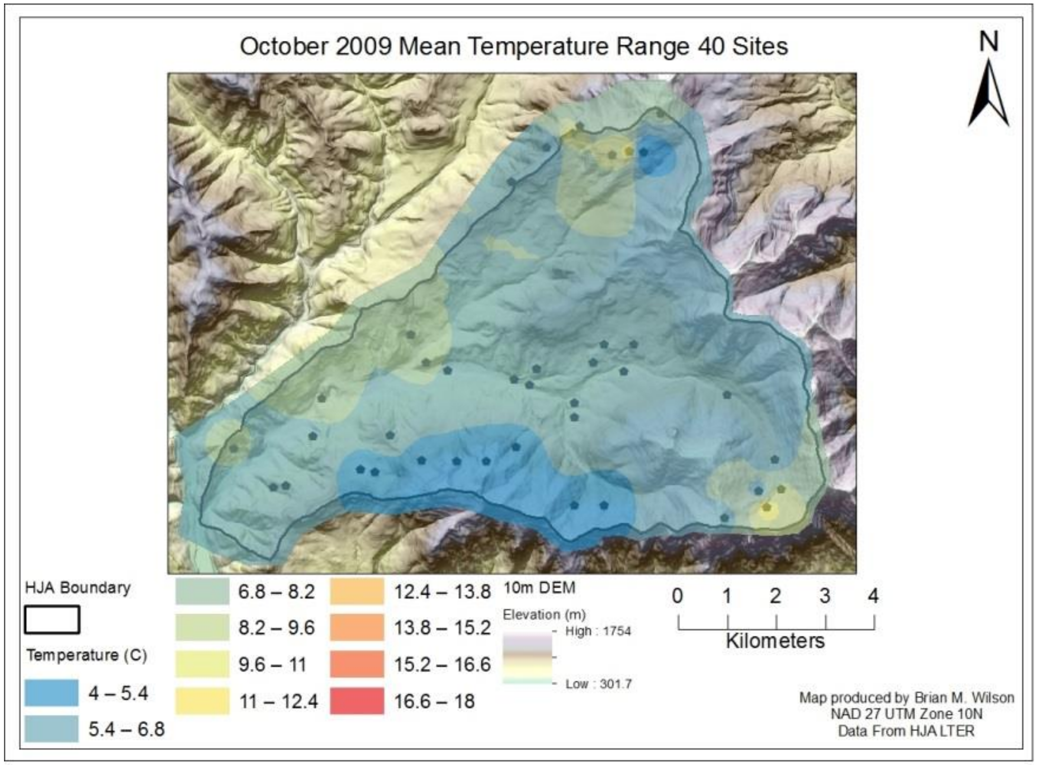
Mean Monthly Minimum Temperature 3 Consecutive Years October 2009 to October 2011 using 40 BIRD Sites.

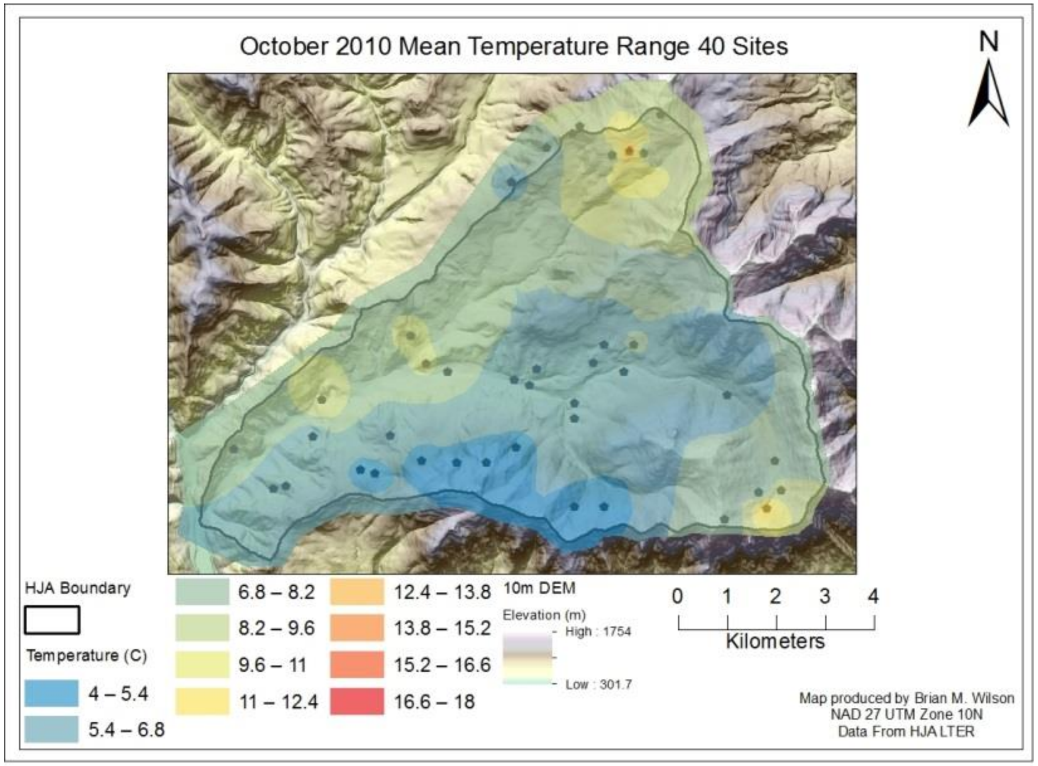


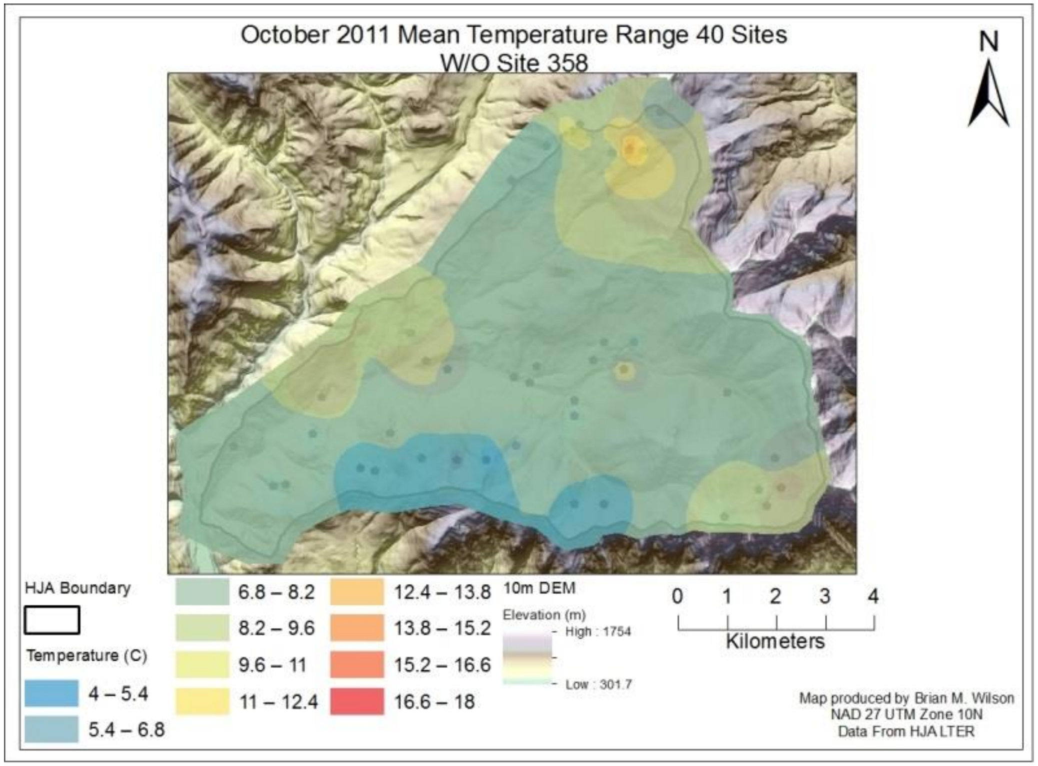




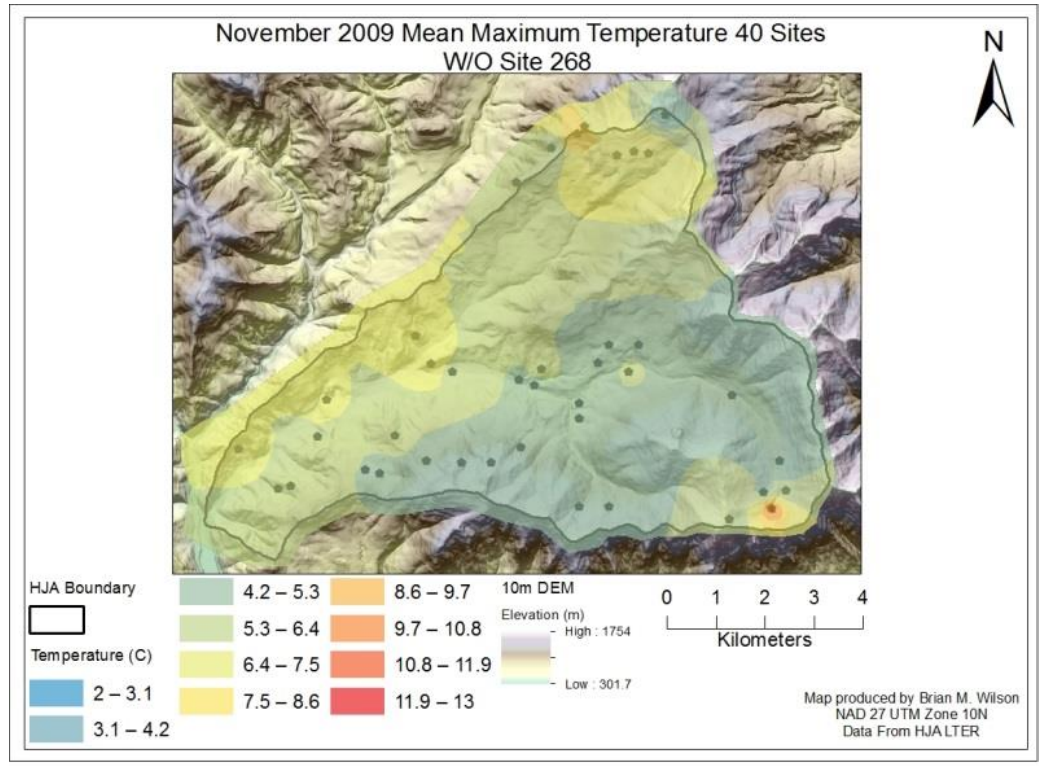
Mean Monthly Temperature Range 3 consecutive Years October 2009 to October 2011 using 40 BIRD Sites.

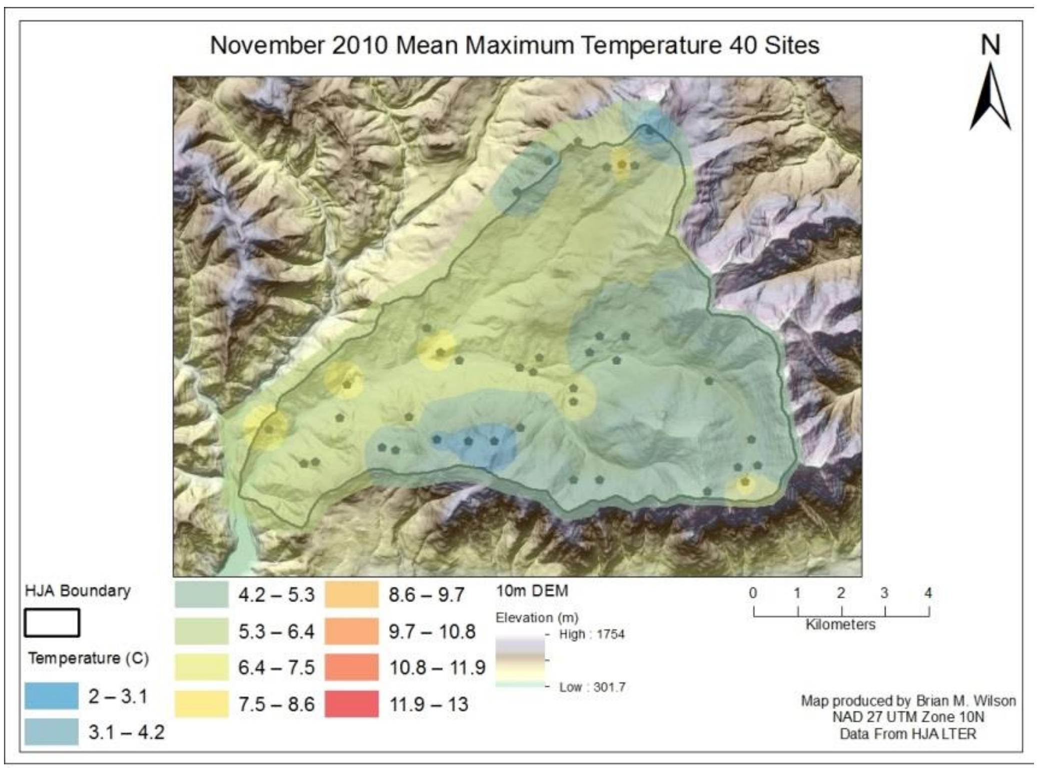


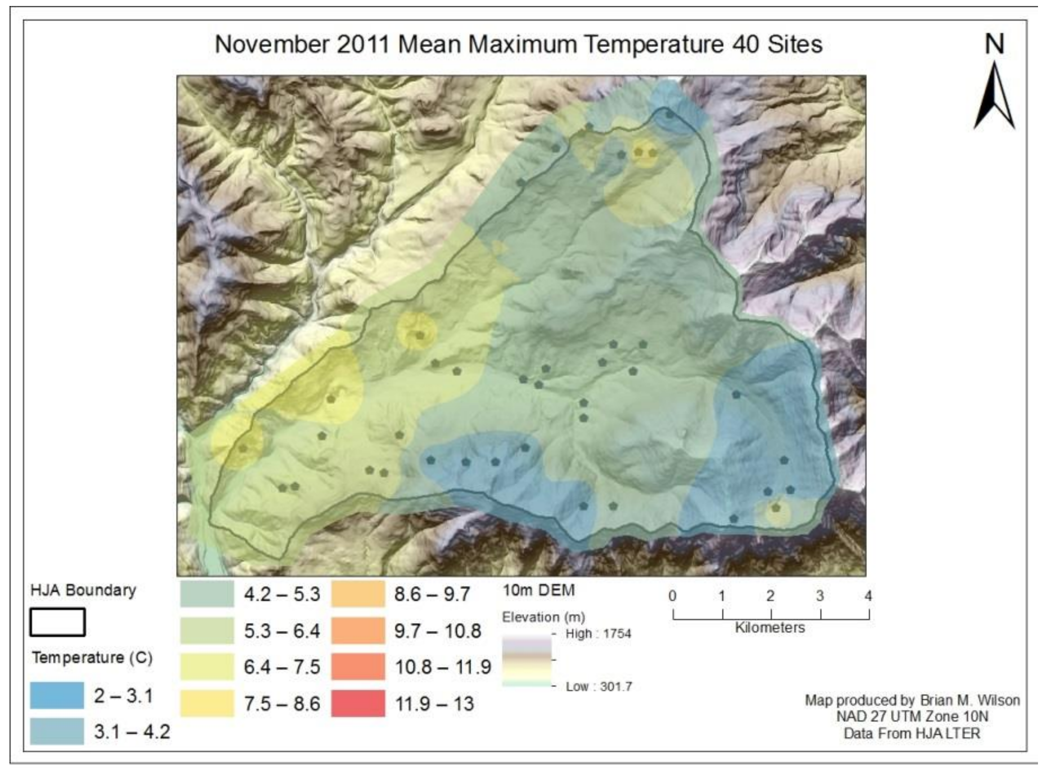




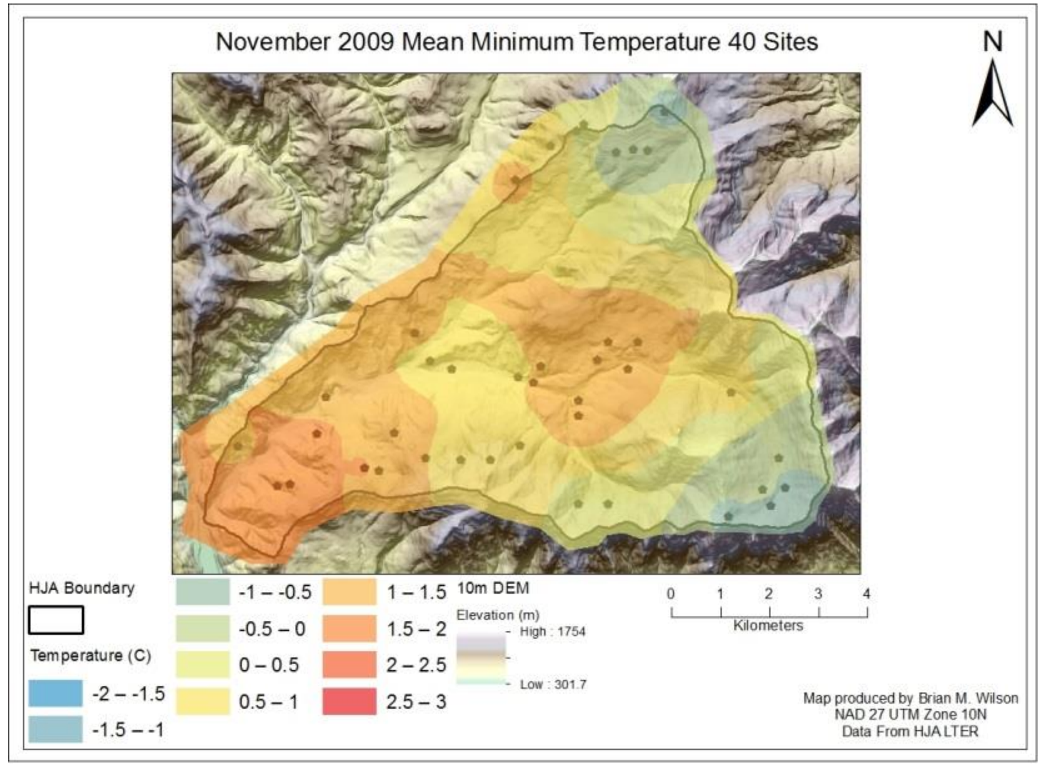
Mean Monthly Maximum Temperature 3 Consecutive Years November 2009 to November 2011 using 40 BIRD Sites.

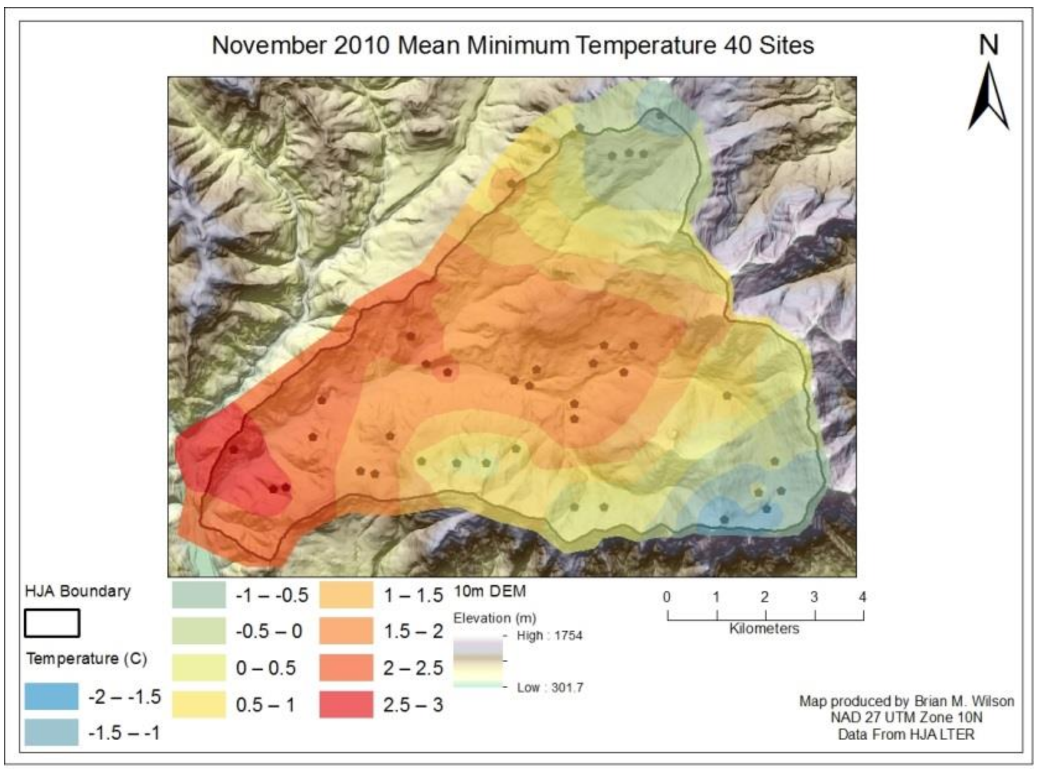


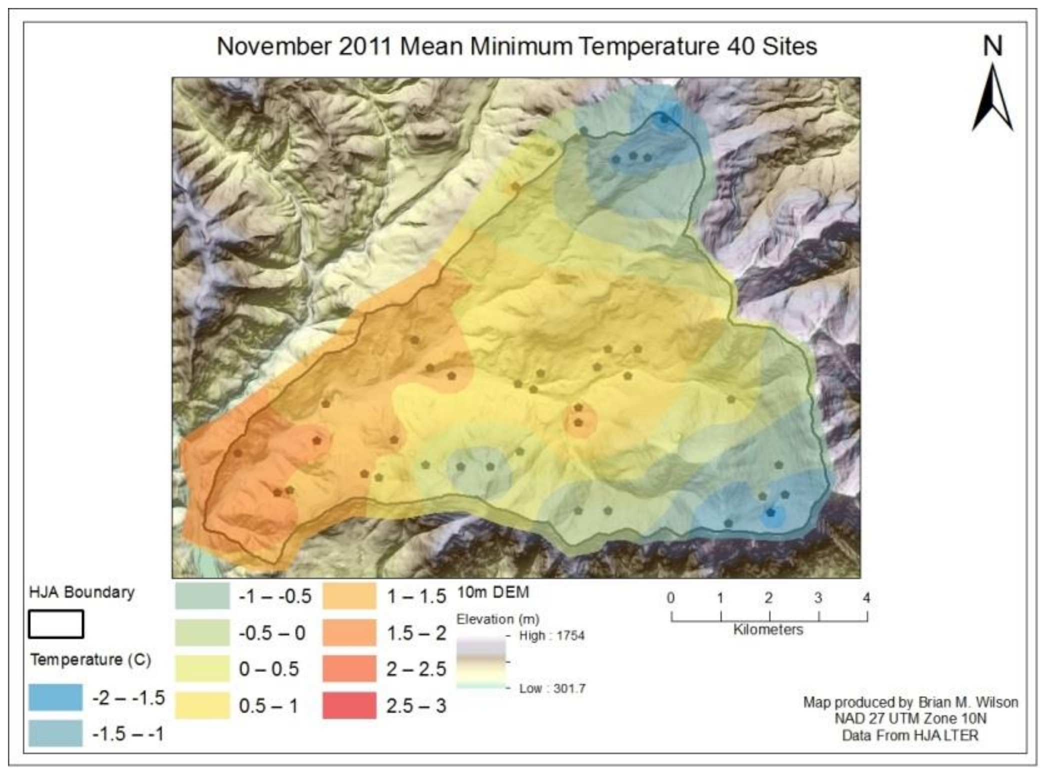




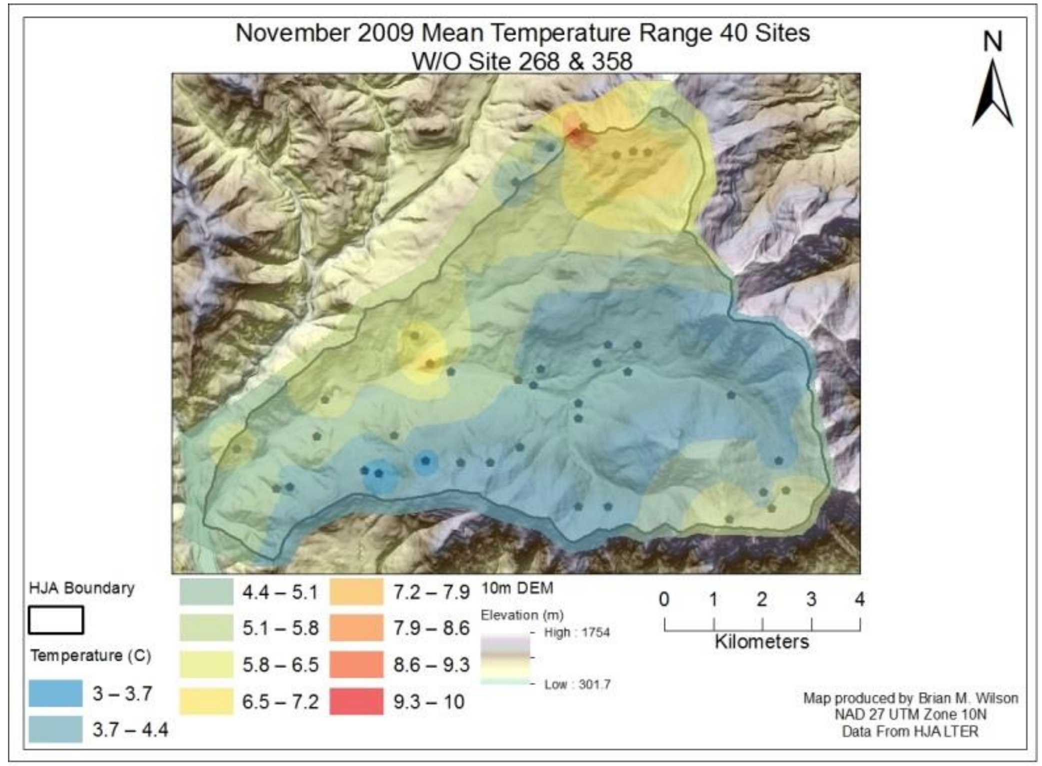
Mean Monthly Minimum Temperature 3 Consecutive Years November 2009 to November 2011 using 40 BIRD Sites.

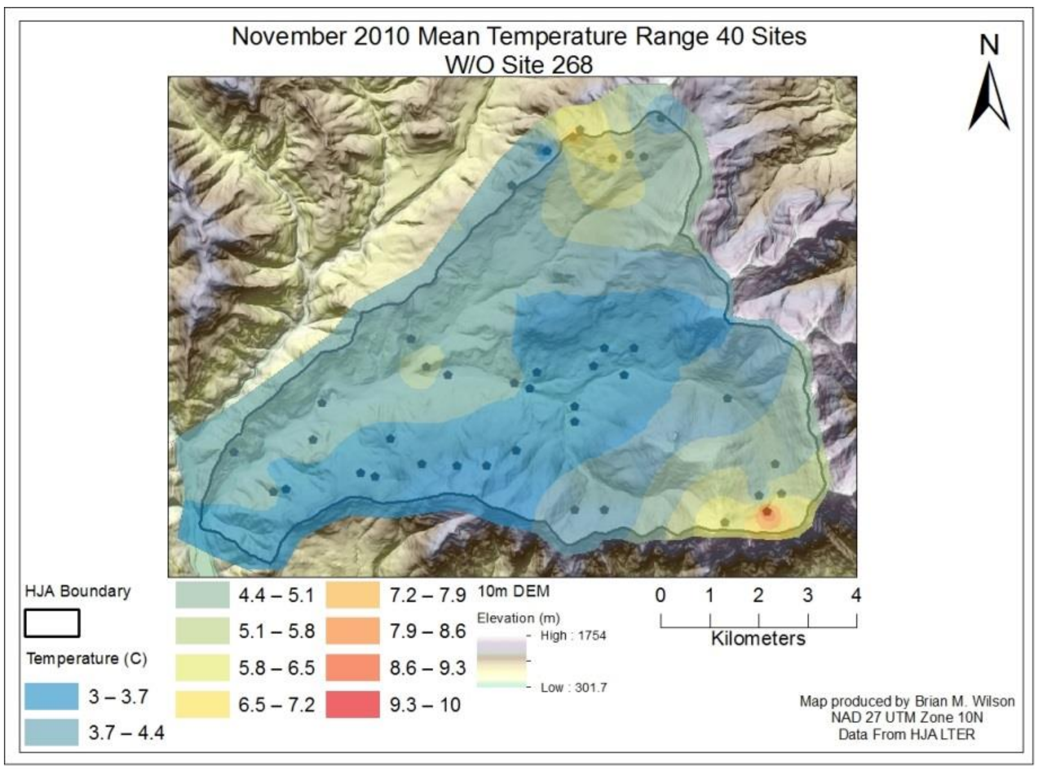


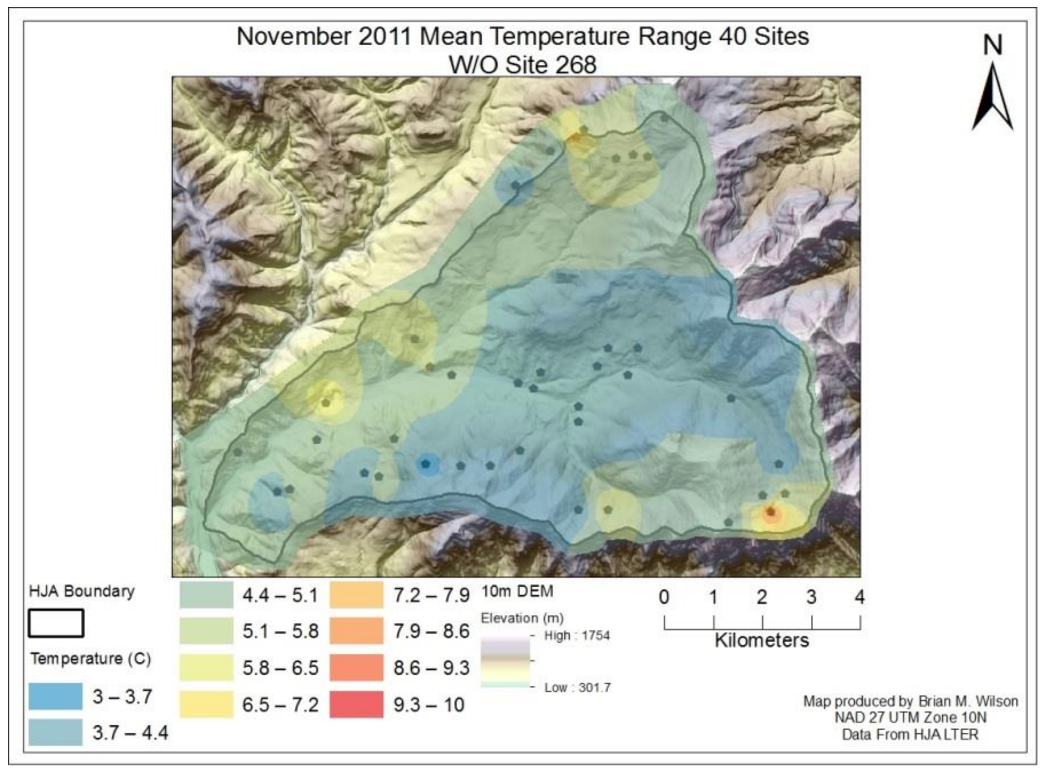




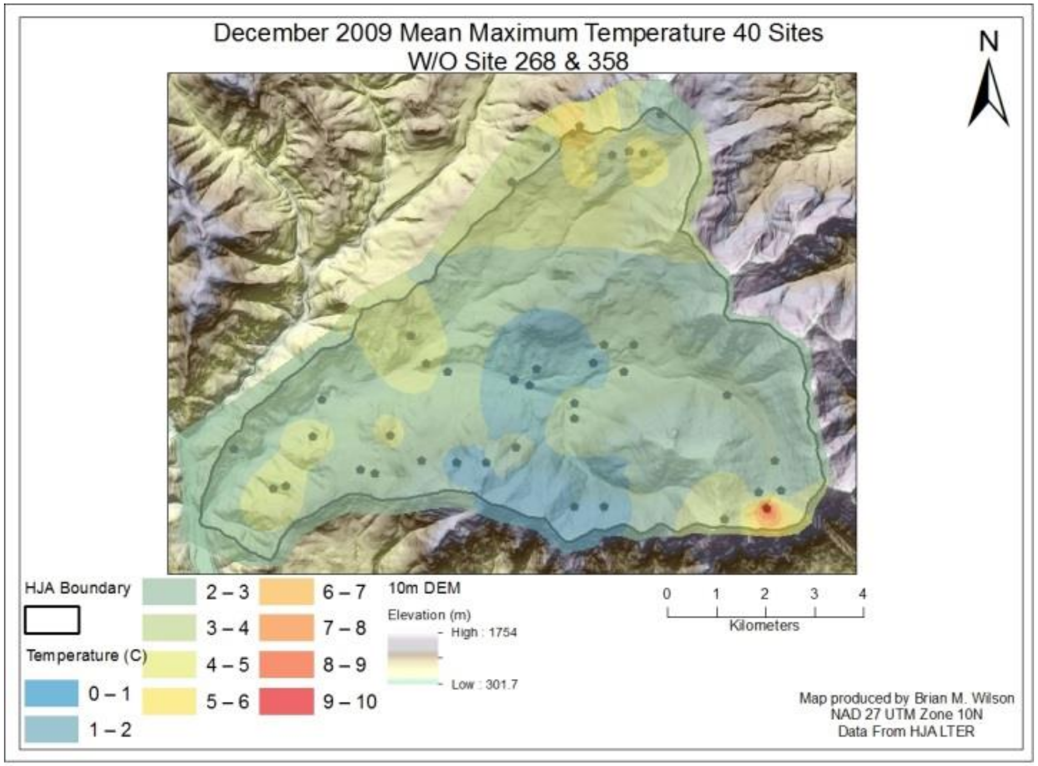
Mean Monthly Temperature Range 3 Consecutive Years November 2009 to November 2011 using 40 BIRD Sites.

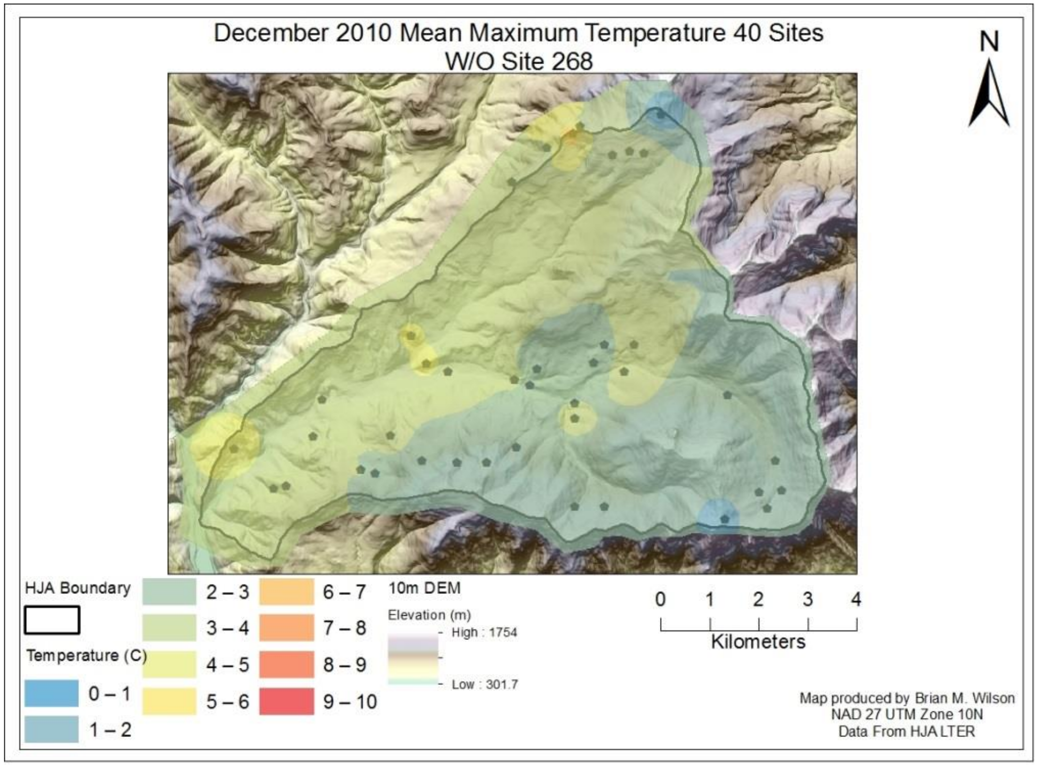


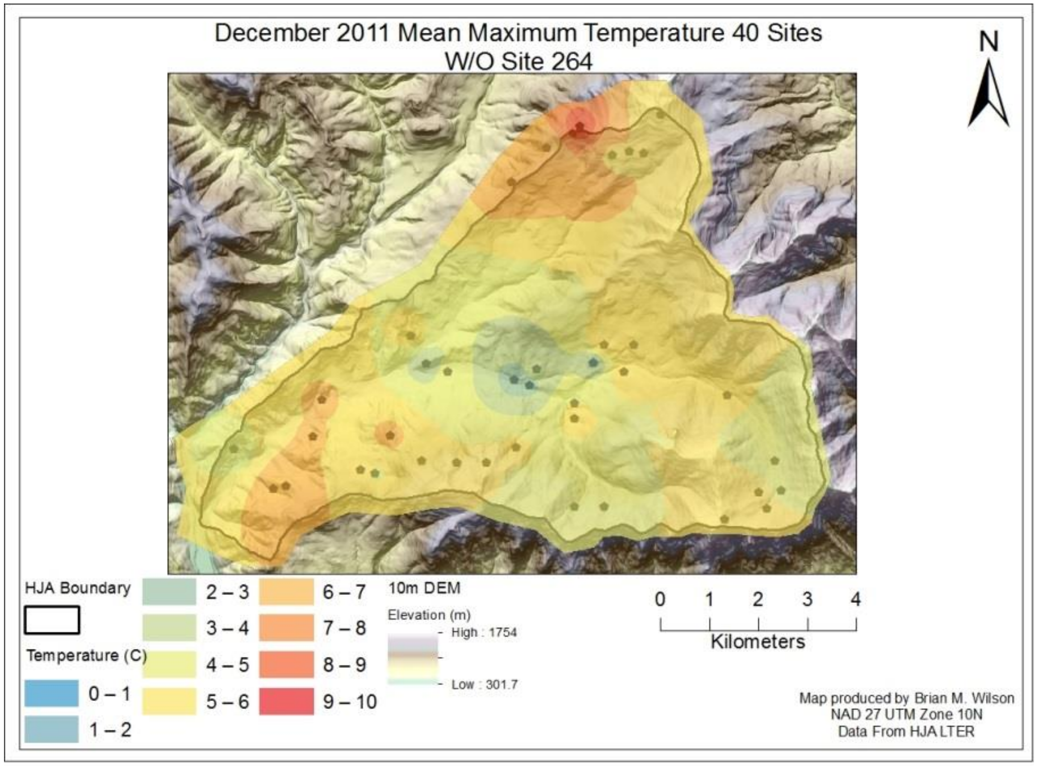




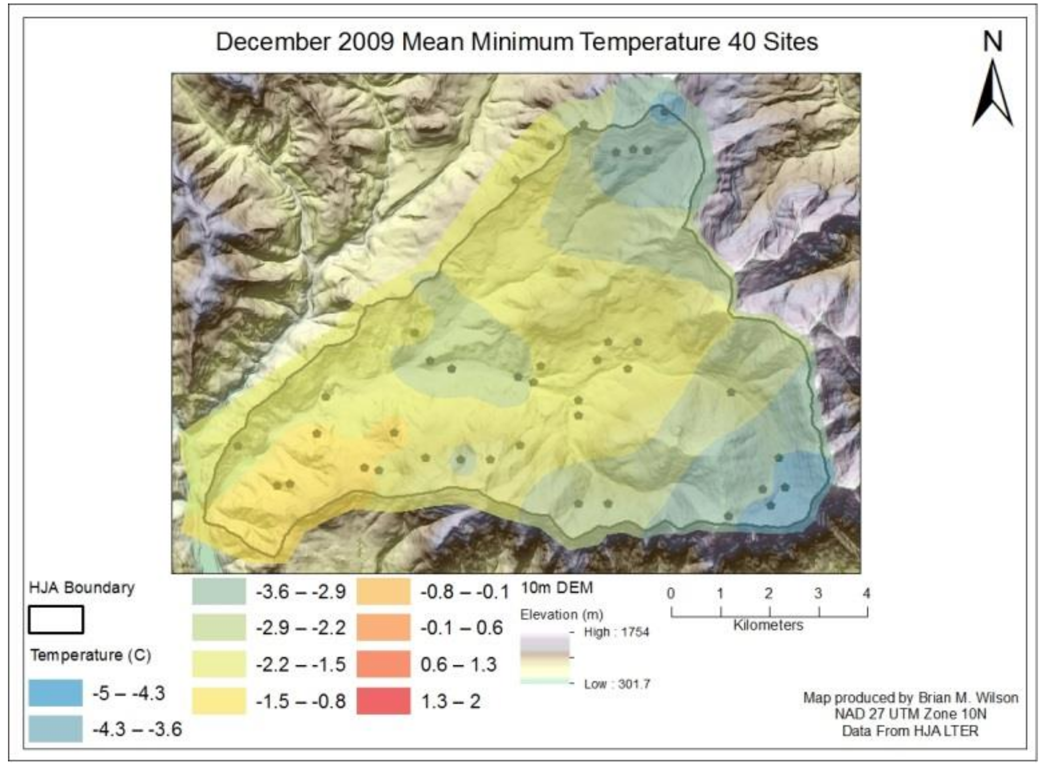
Mean Monthly Maximum Temperature 3 Consecutive Years December 2009 to December 2011 using 40 BIRD Sites.

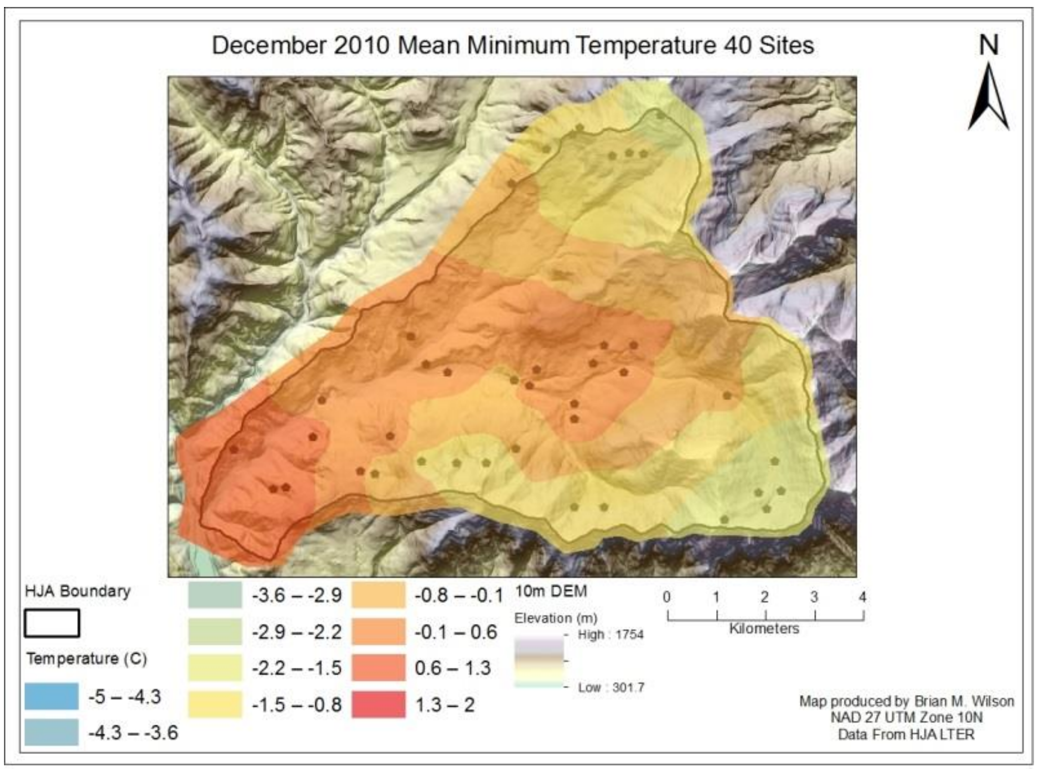


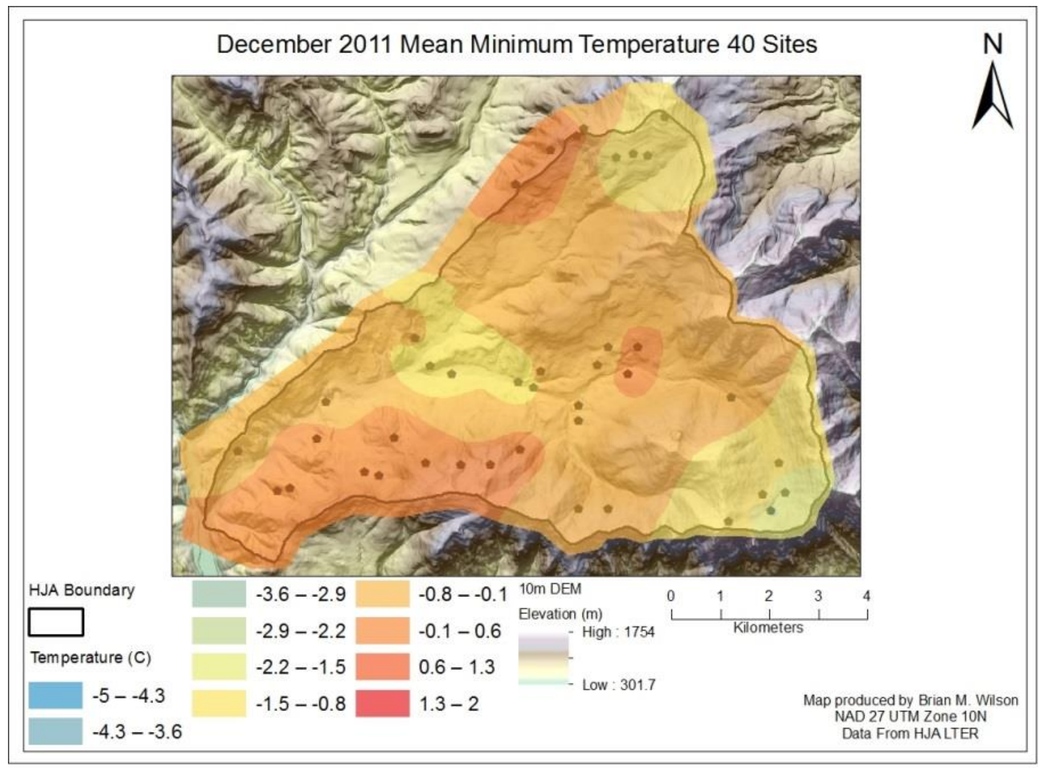




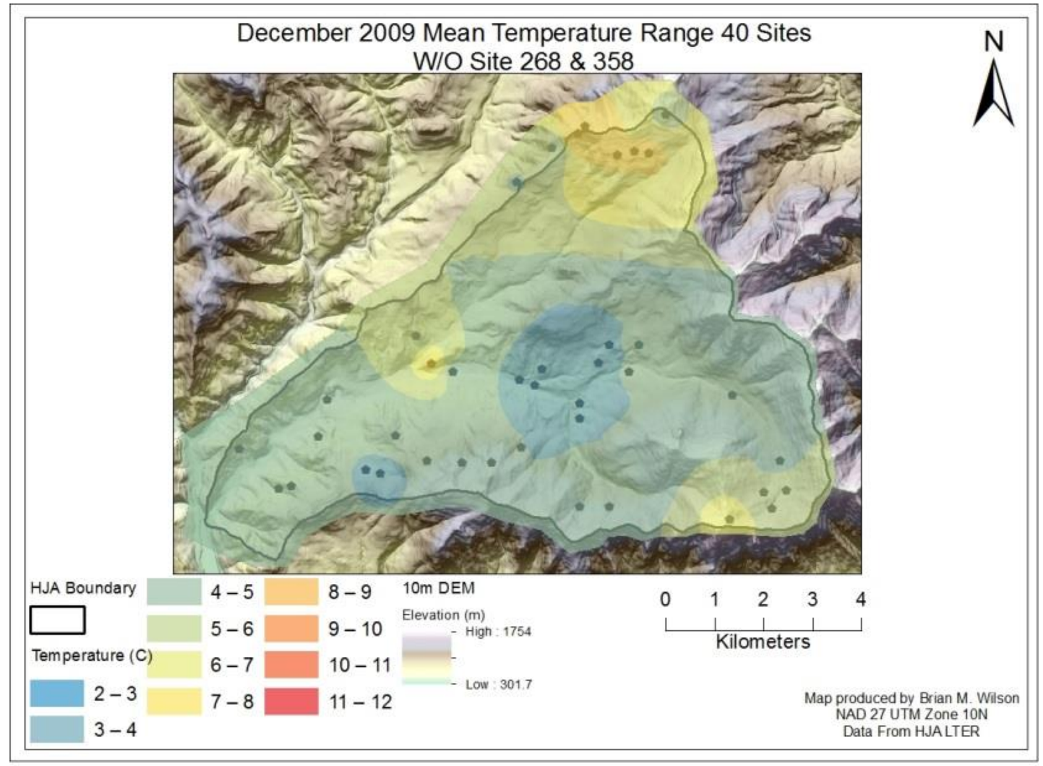
Mean Monthly Minimum Temperature 3 Consecutive Years December 2009 to December 2011 using 40 BIRD Sites.

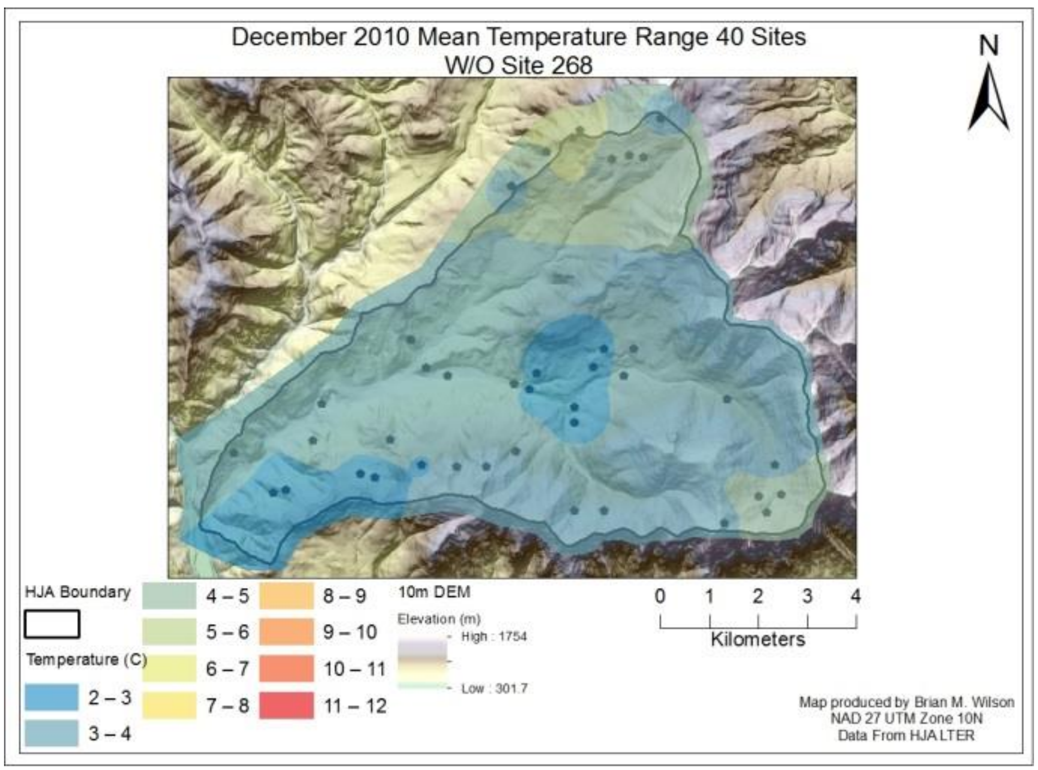


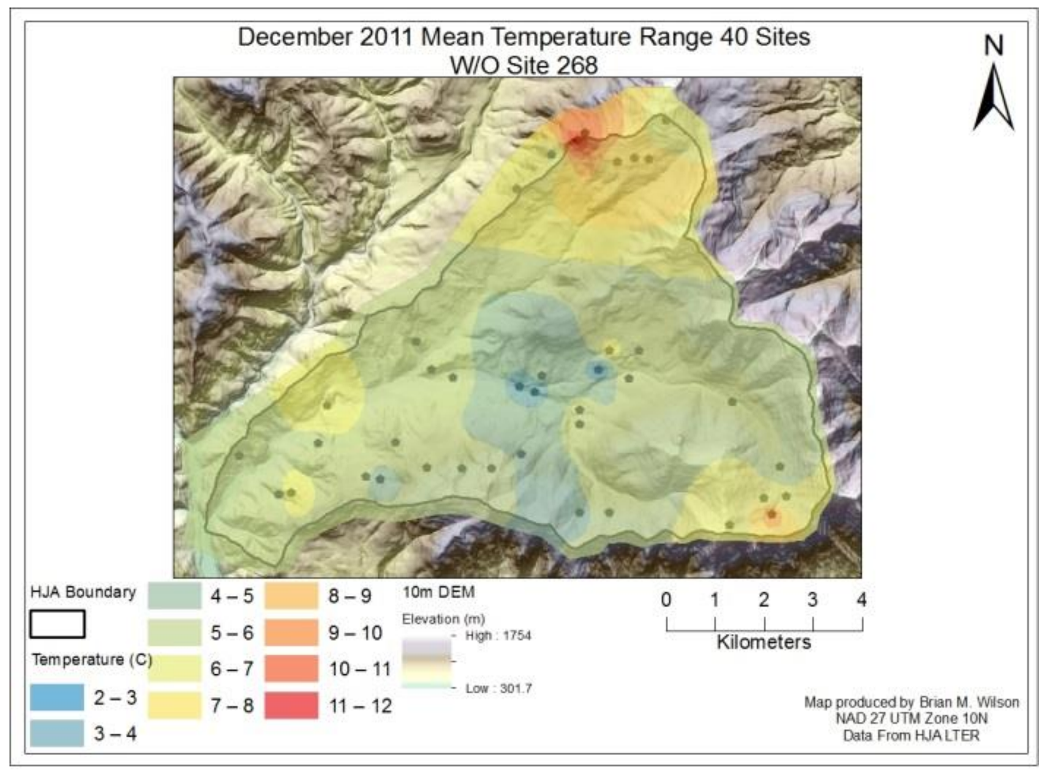




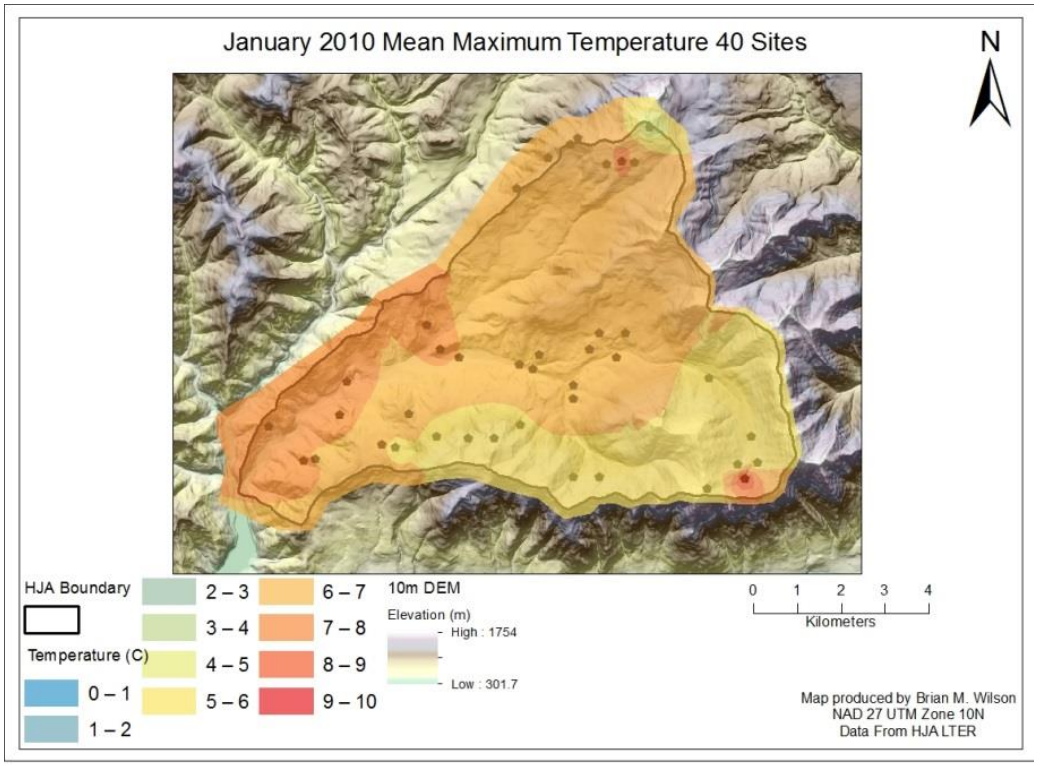
Mean Monthly Temperature Range 3 Consecutive Years December 2009 to December 2011 using 40 BIRD Sites.

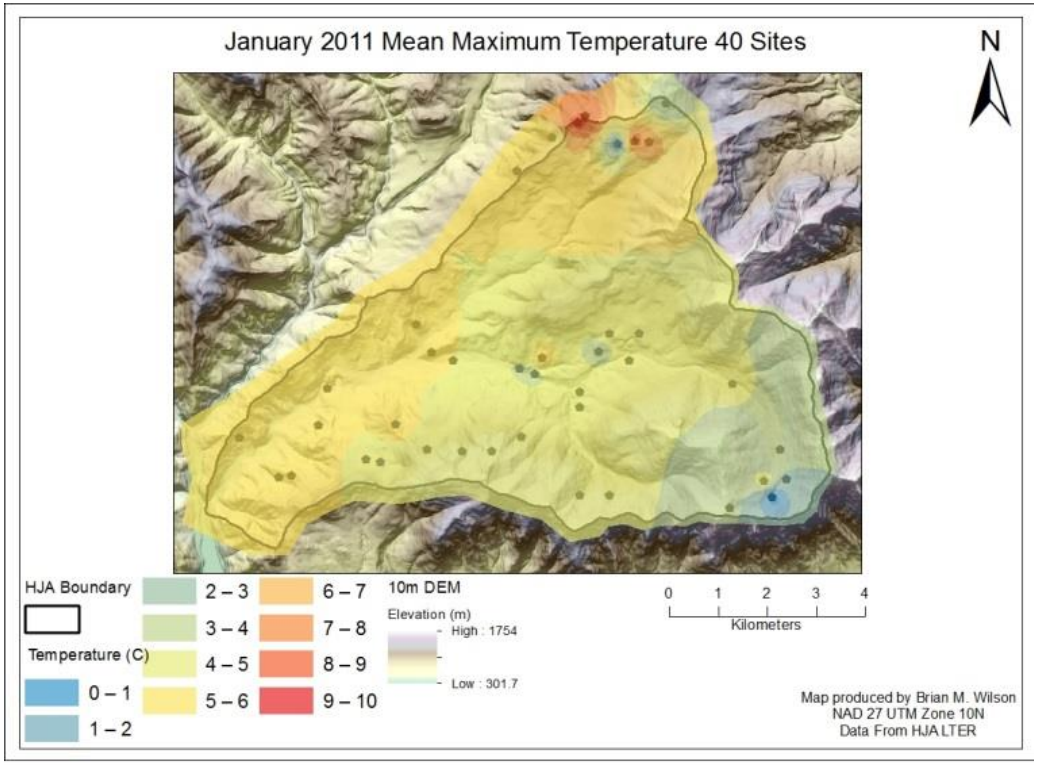


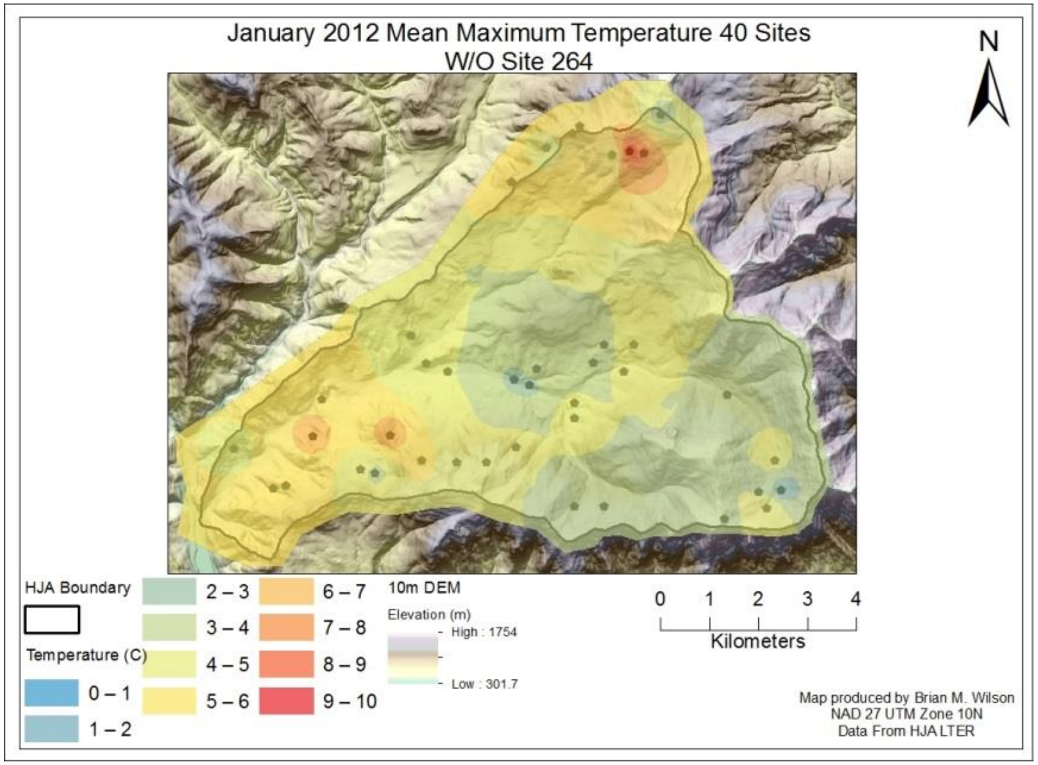




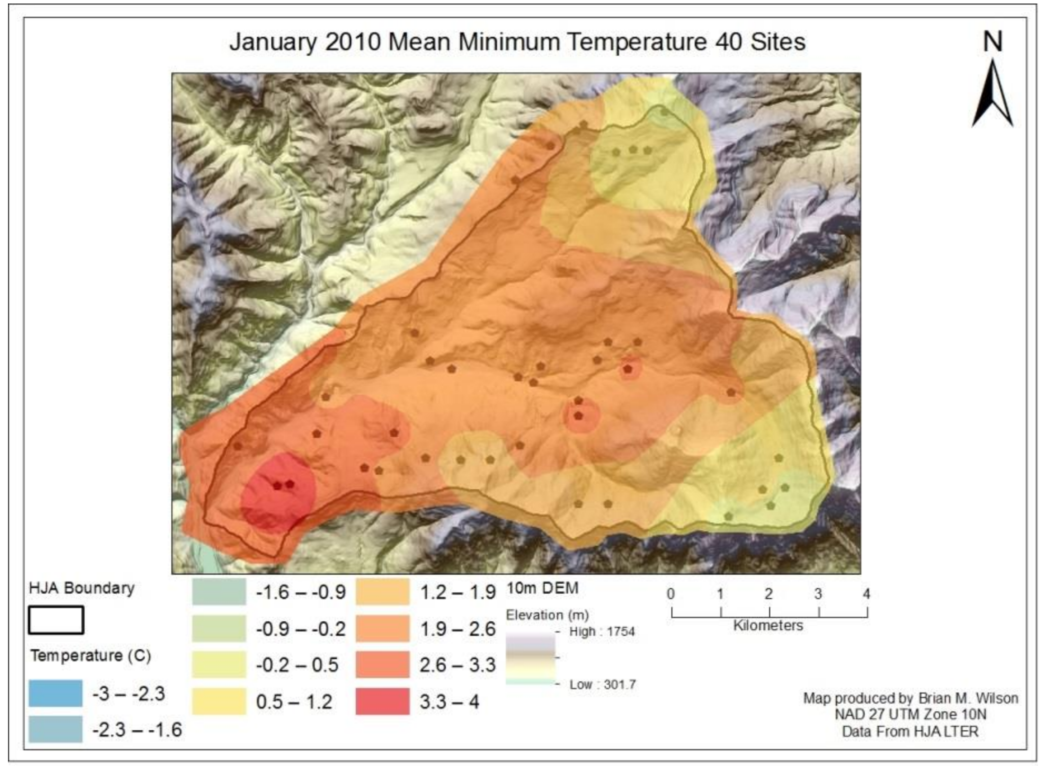
Mean Monthly Maximum Temperature 3 Consecutive Years January 2010 to January 2012 using 40 BIRD Sites.

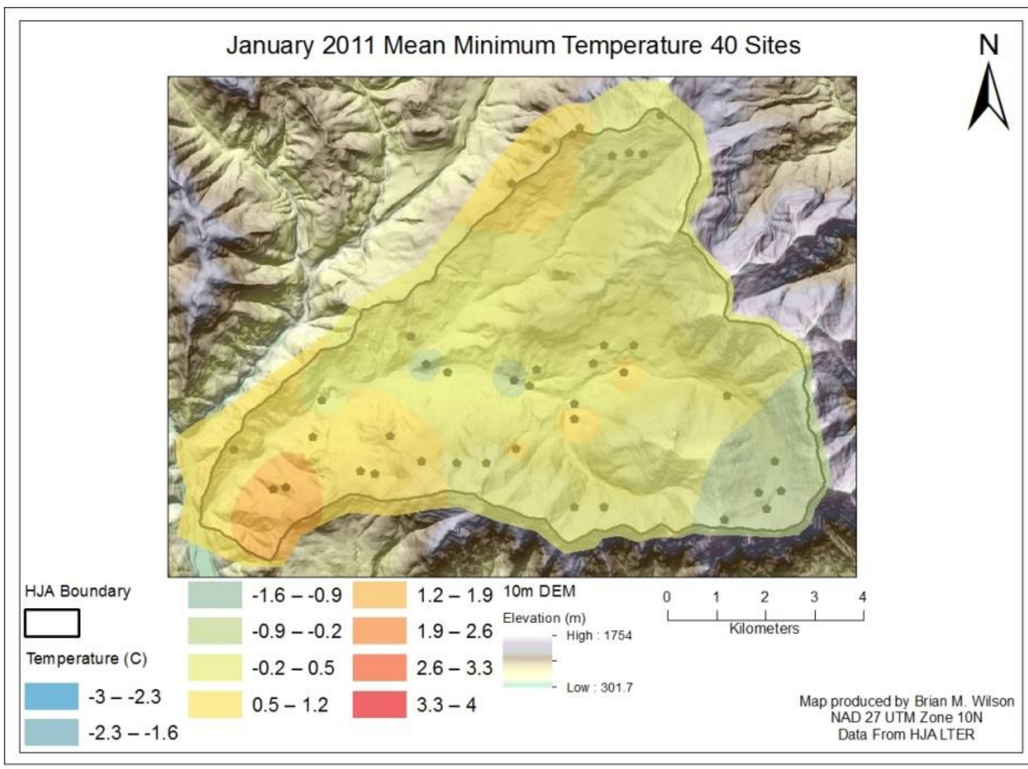


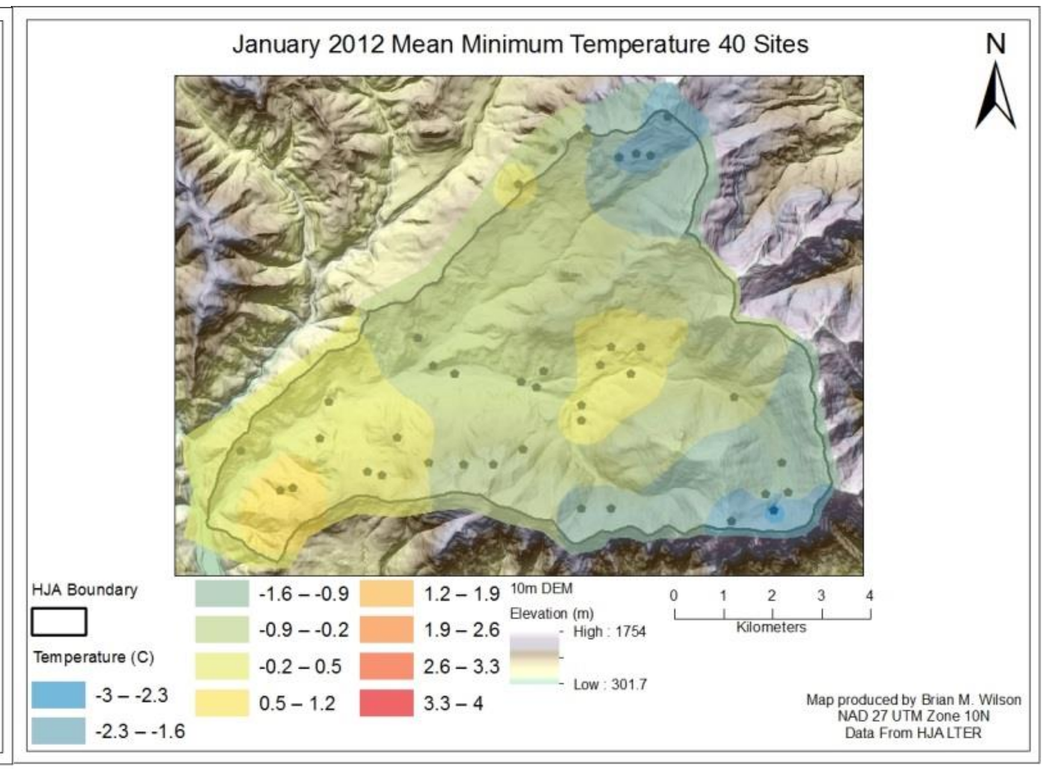




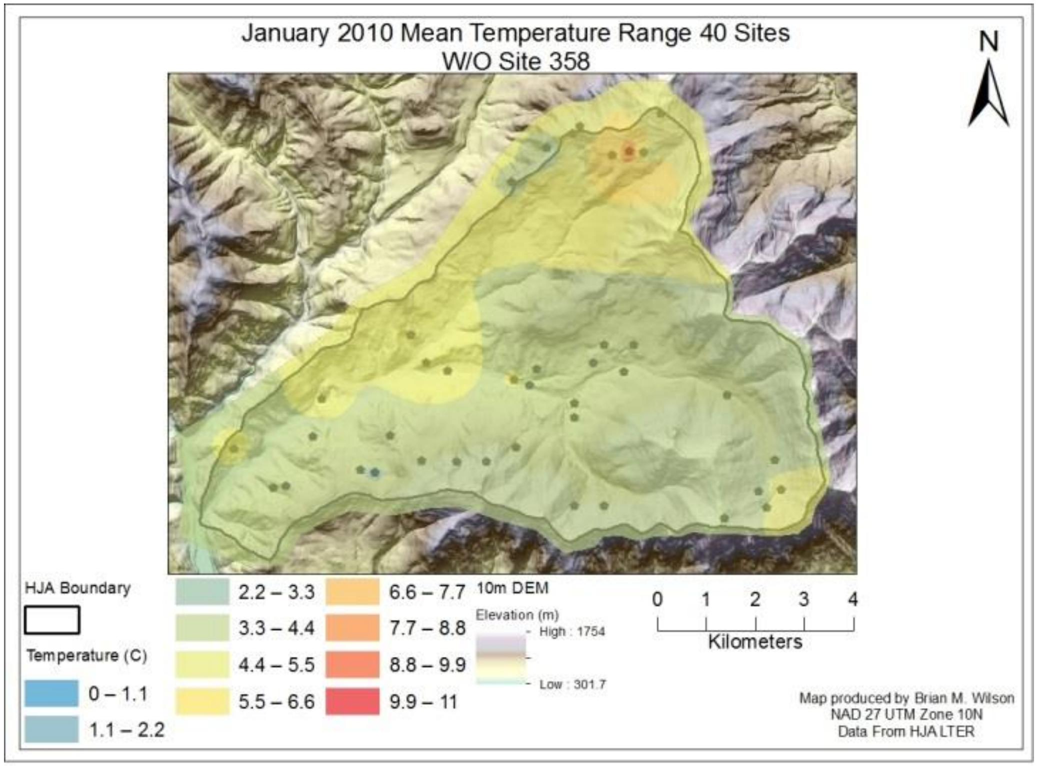
Mean Monthly Minimum Temperature 3 Consecutive Years January 2010 to January 2012 using 40 BIRD Sites.

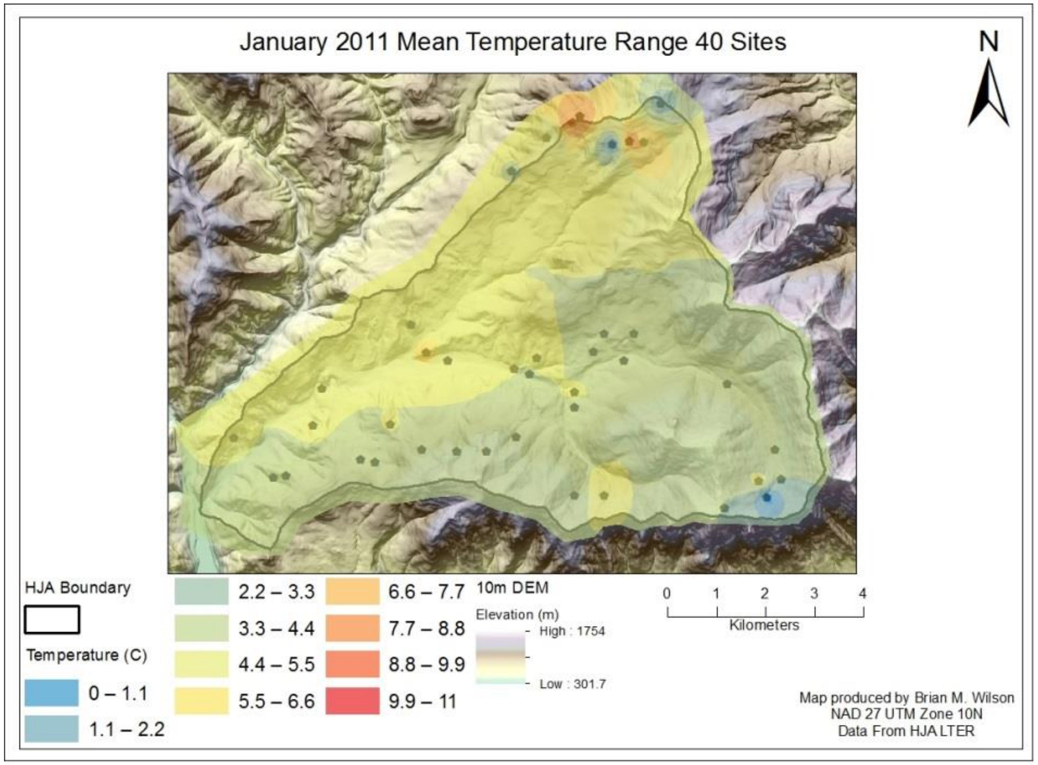


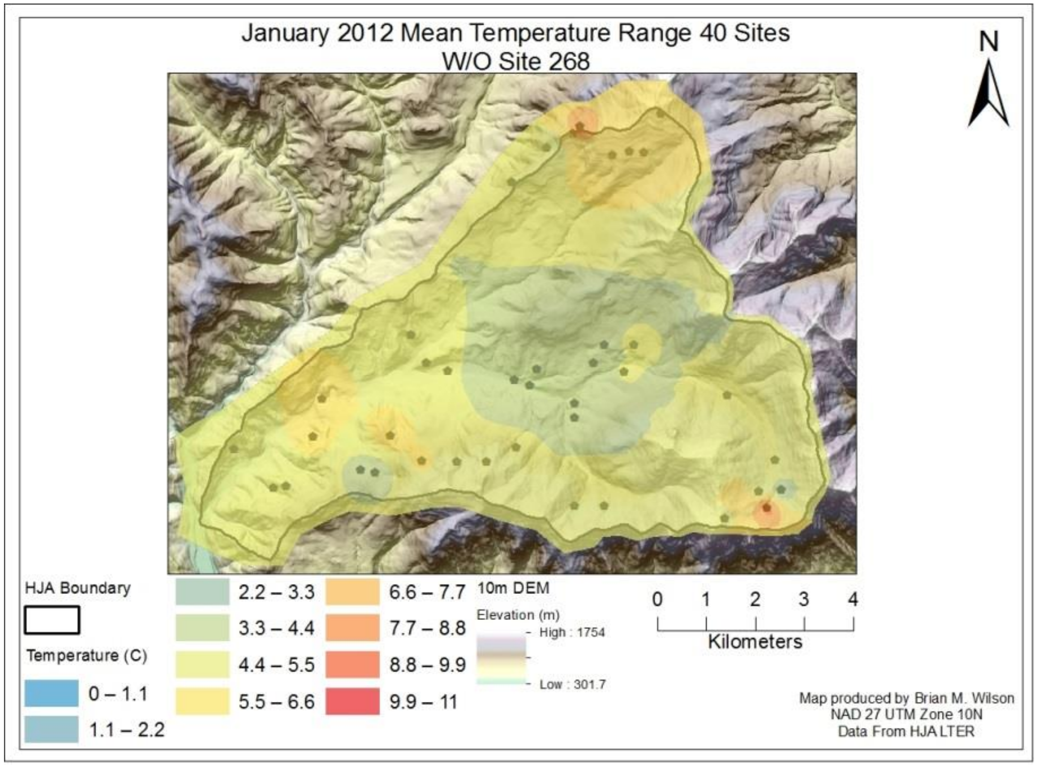




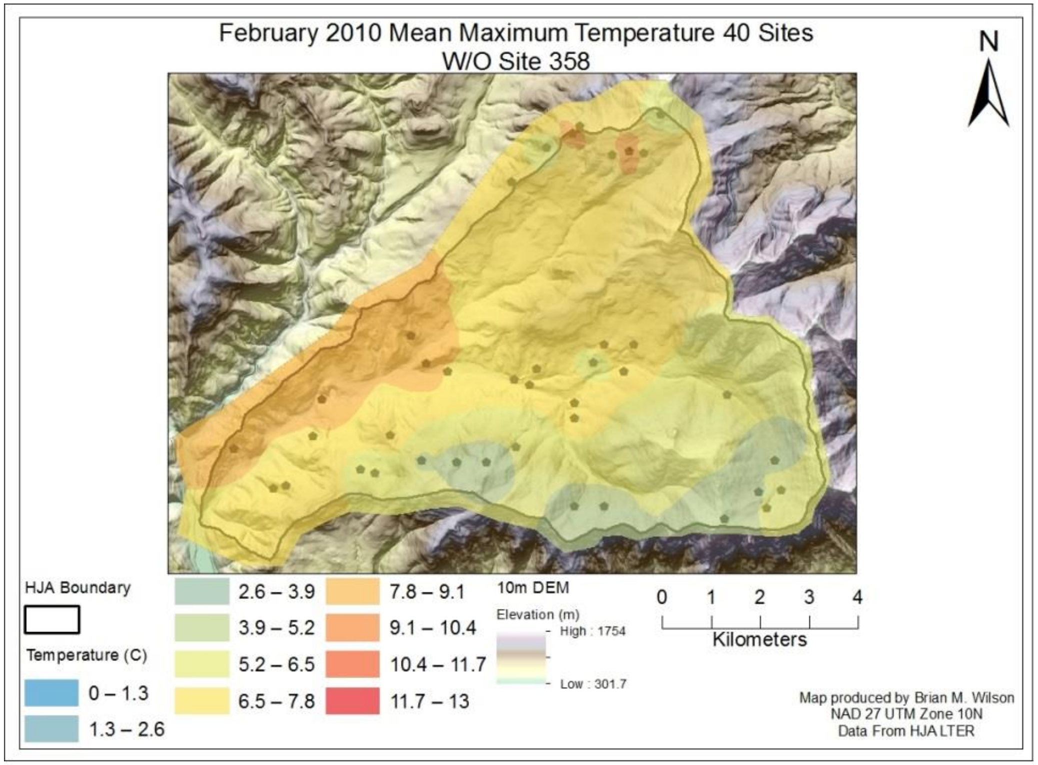
Mean Monthly Temperature Range 3 Consecutive Years January 2010 to January 2012 using 40 BIRD Sites.

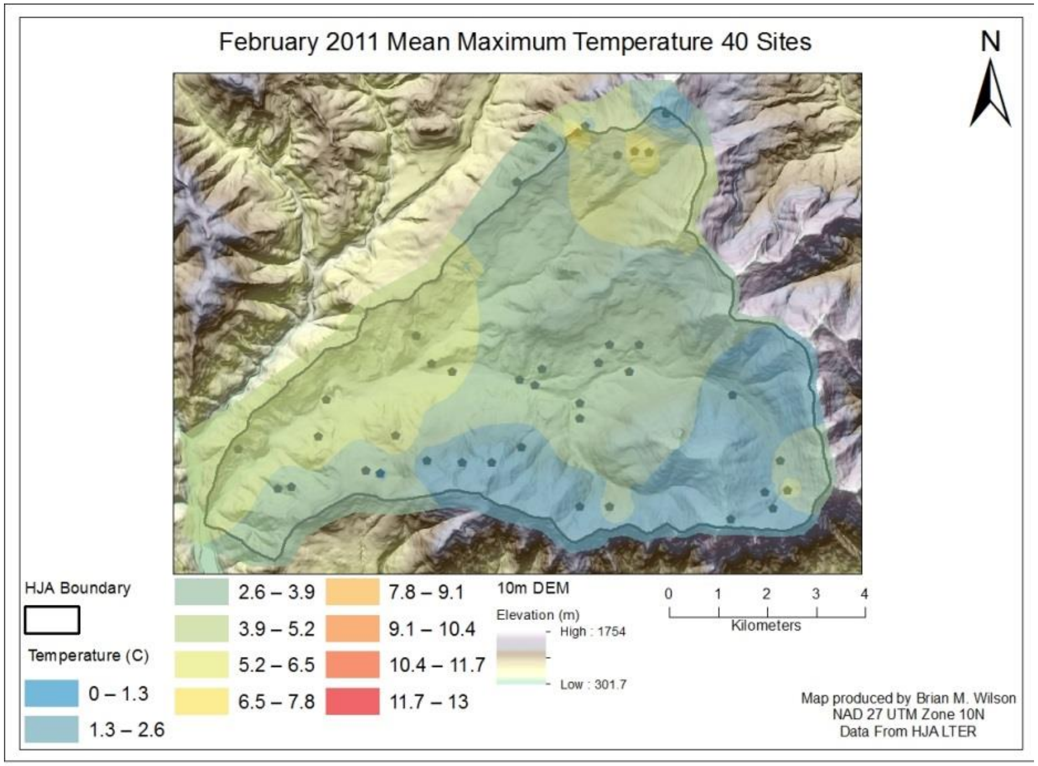


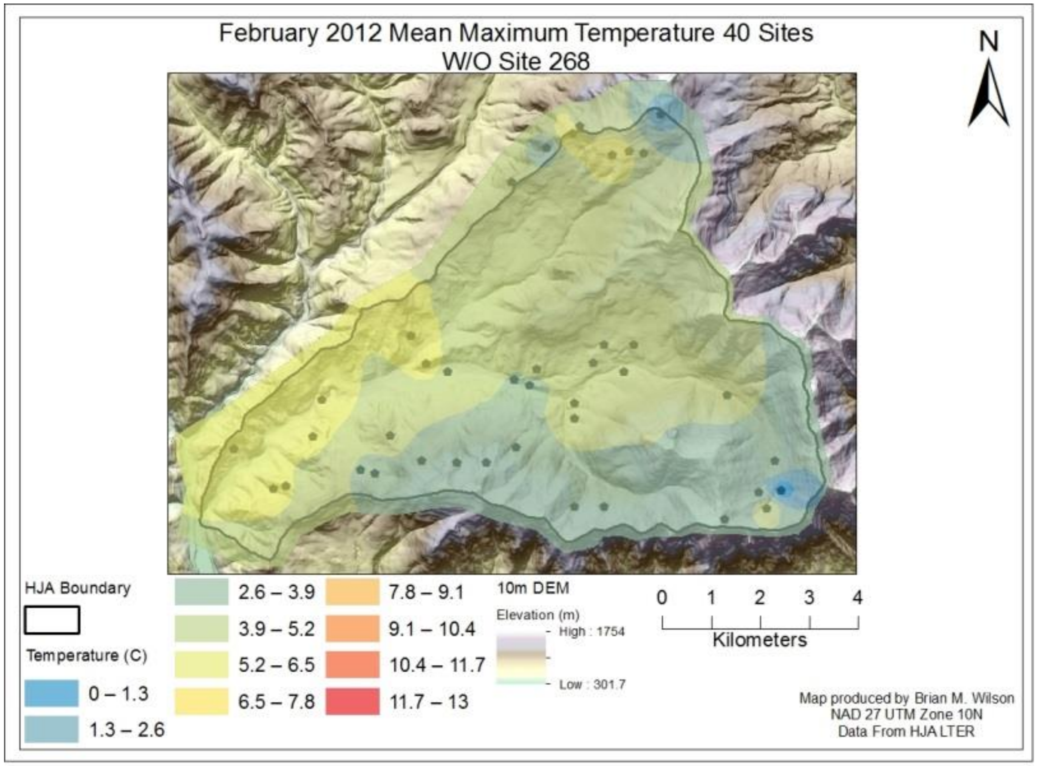




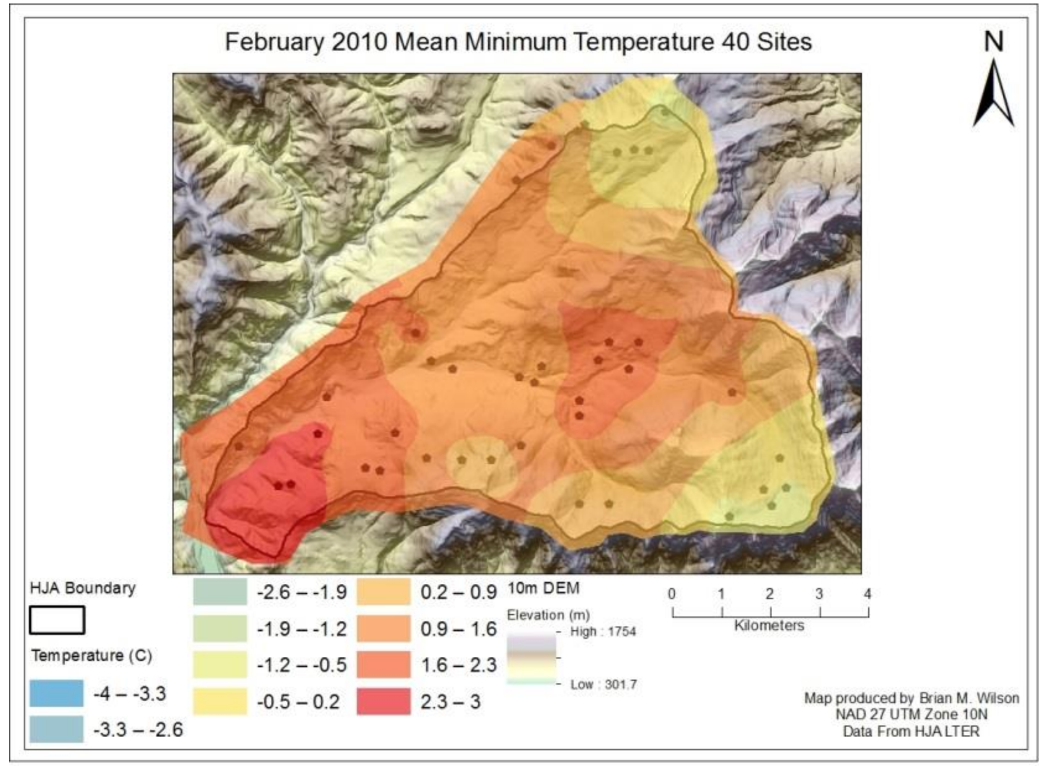
Mean Monthly Maximum Temperature 3 Consecutive Years February 2010 to February 2012 using 40 BIRD Sites.

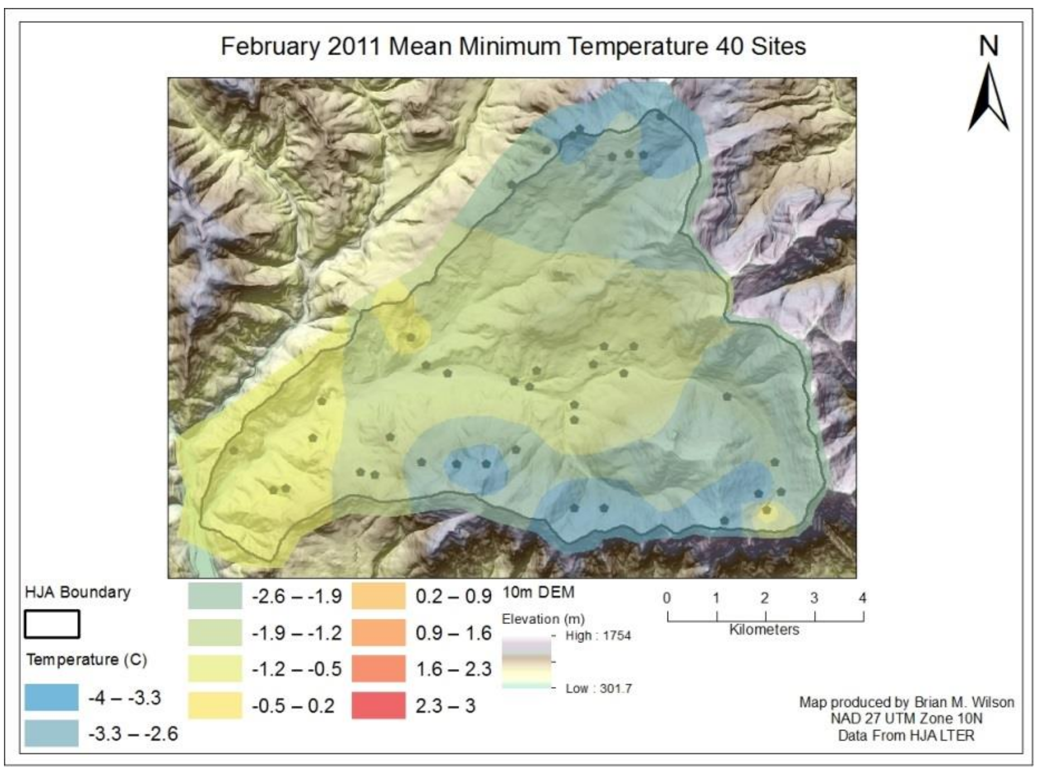


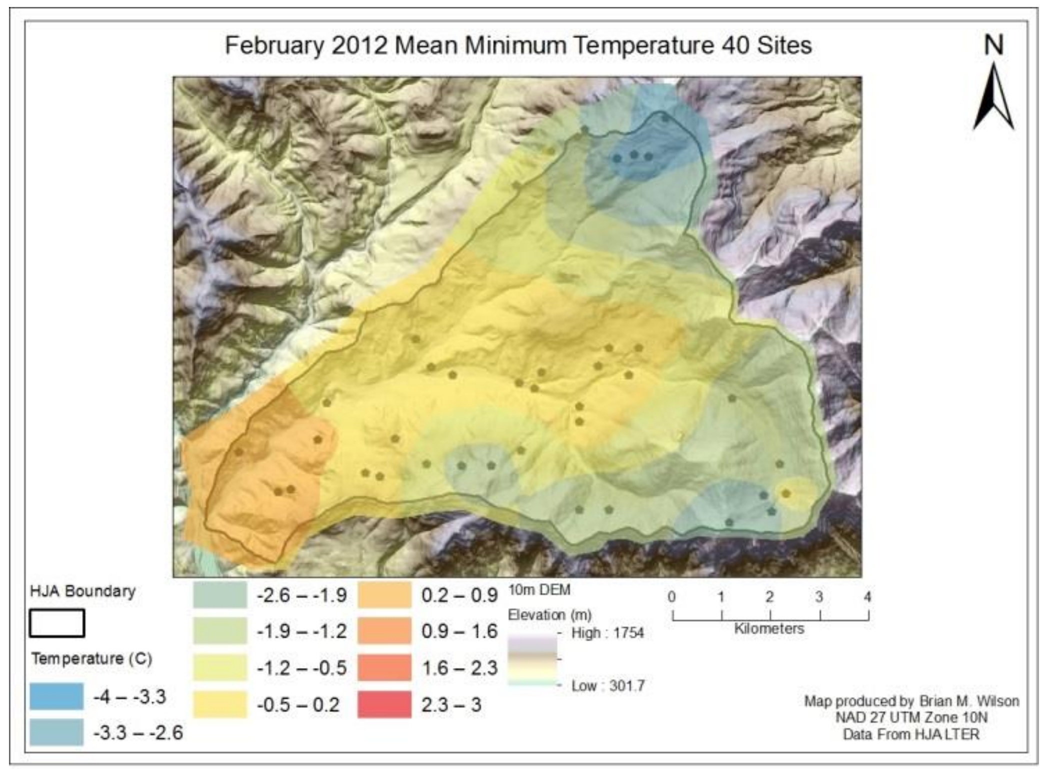




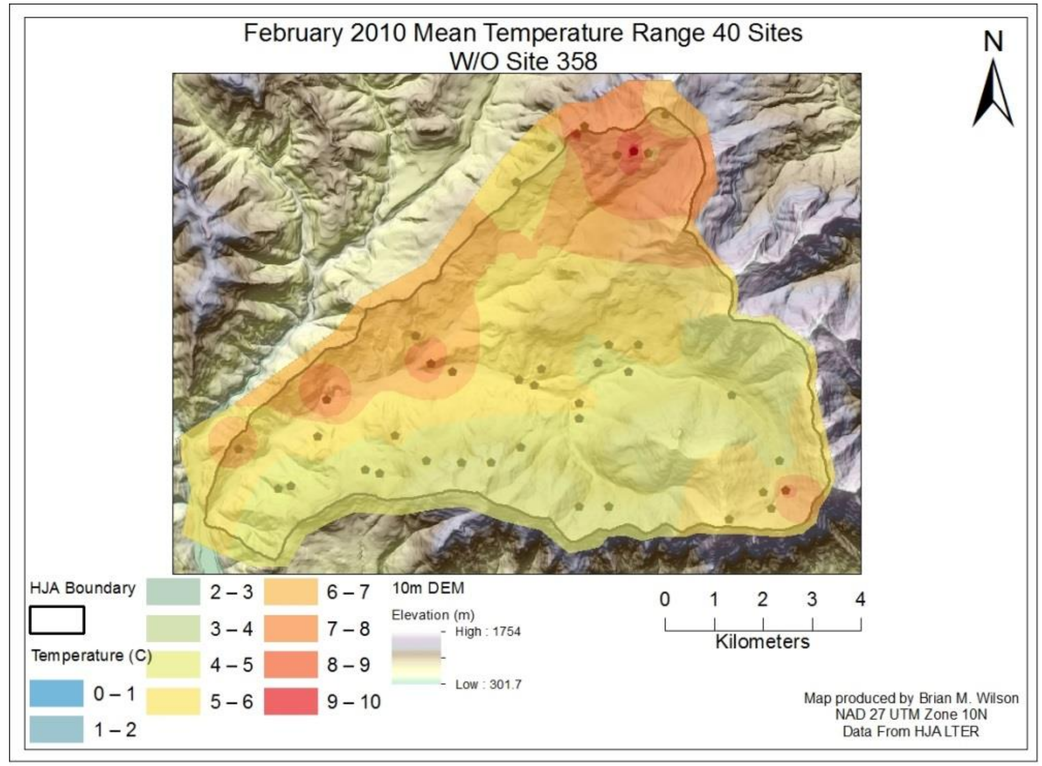
Mean Monthly Minimum Temperature 3 Consecutive Years February 2010 to February 2012 using 40 BIRD Sites.

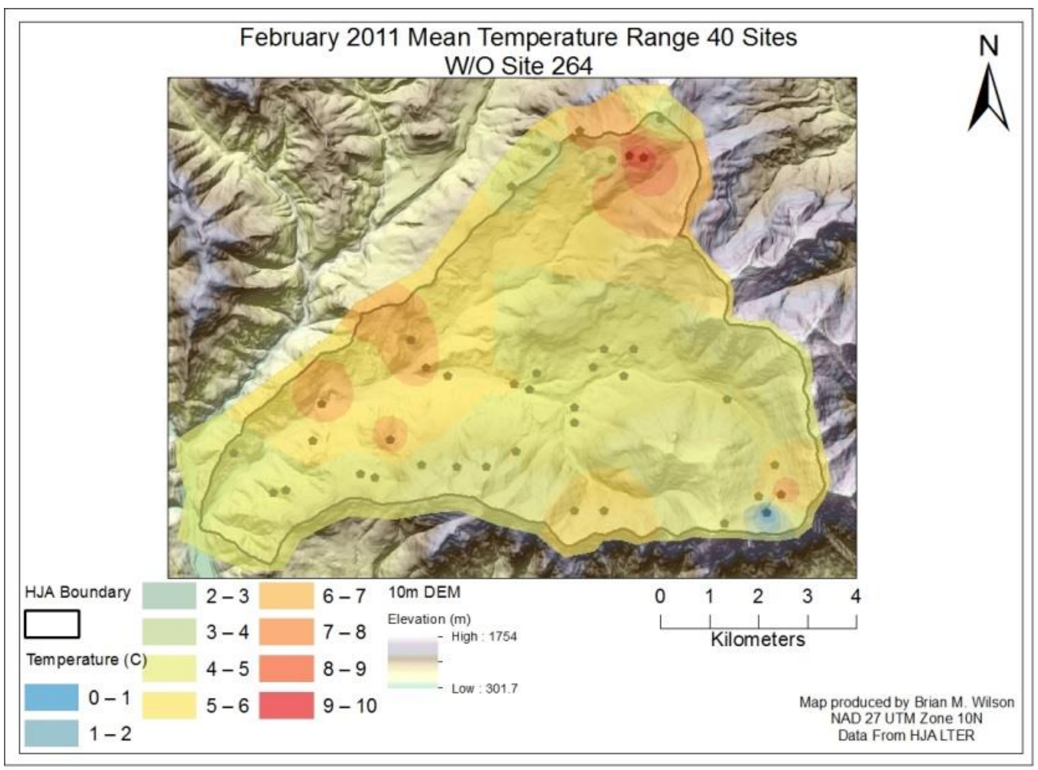


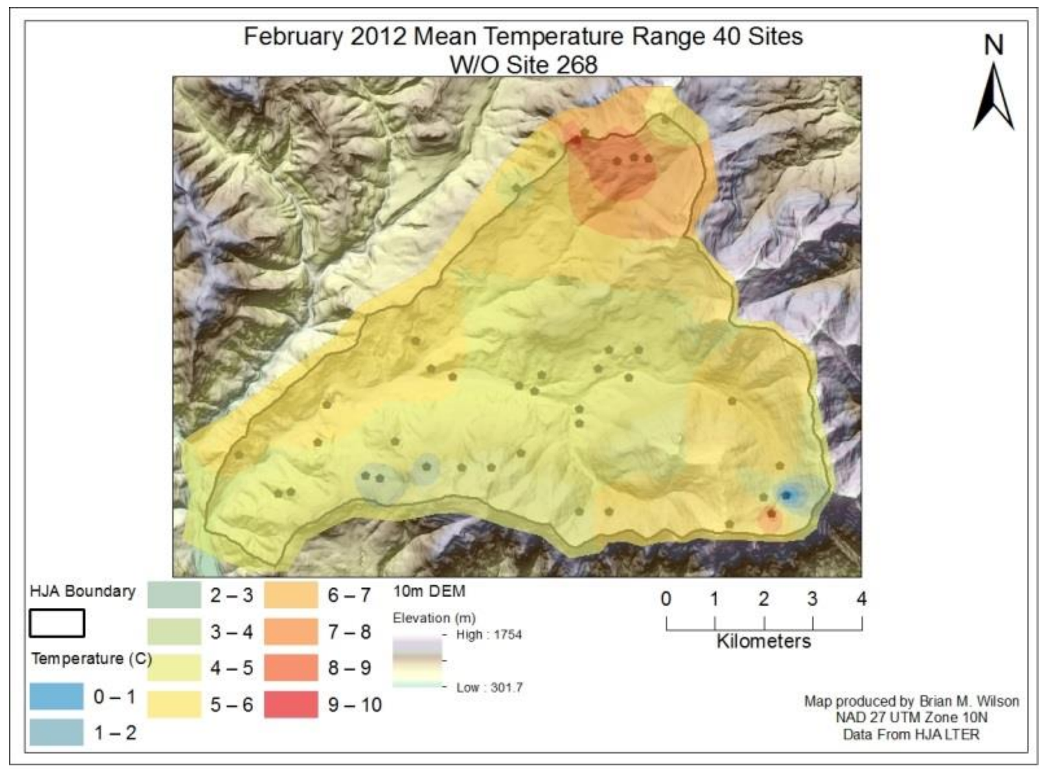




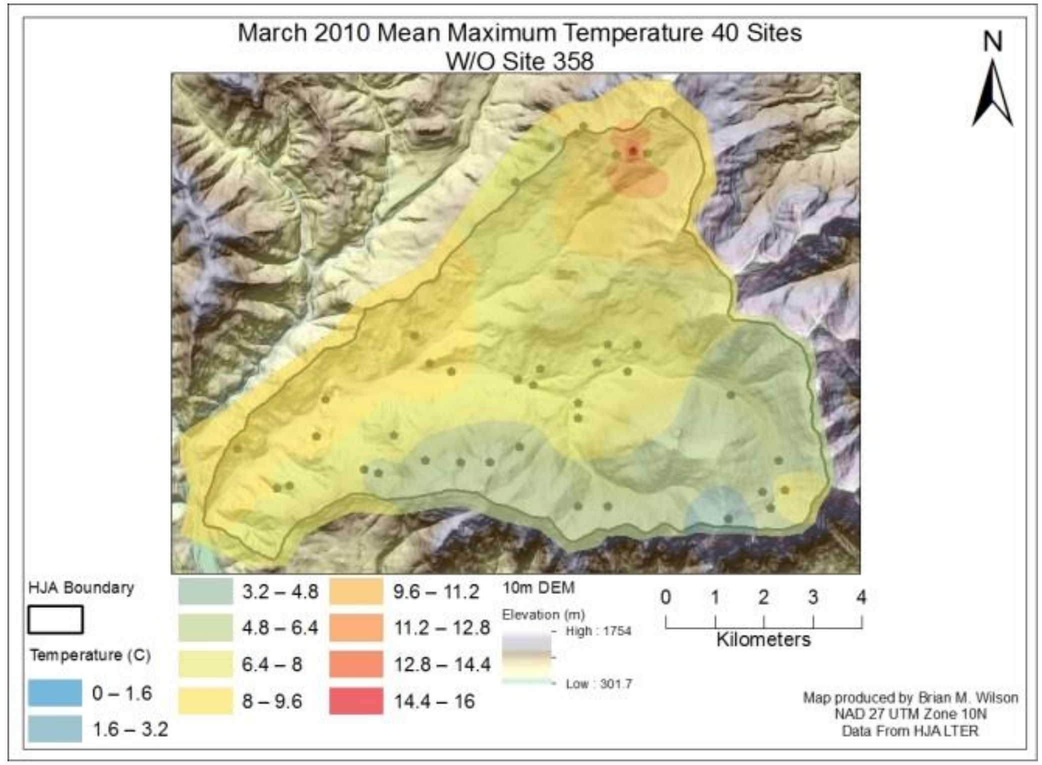
Mean Monthly Temperature Range 3 Consecutive Years February 2010 to February 2012 using 40 BIRD Sites.

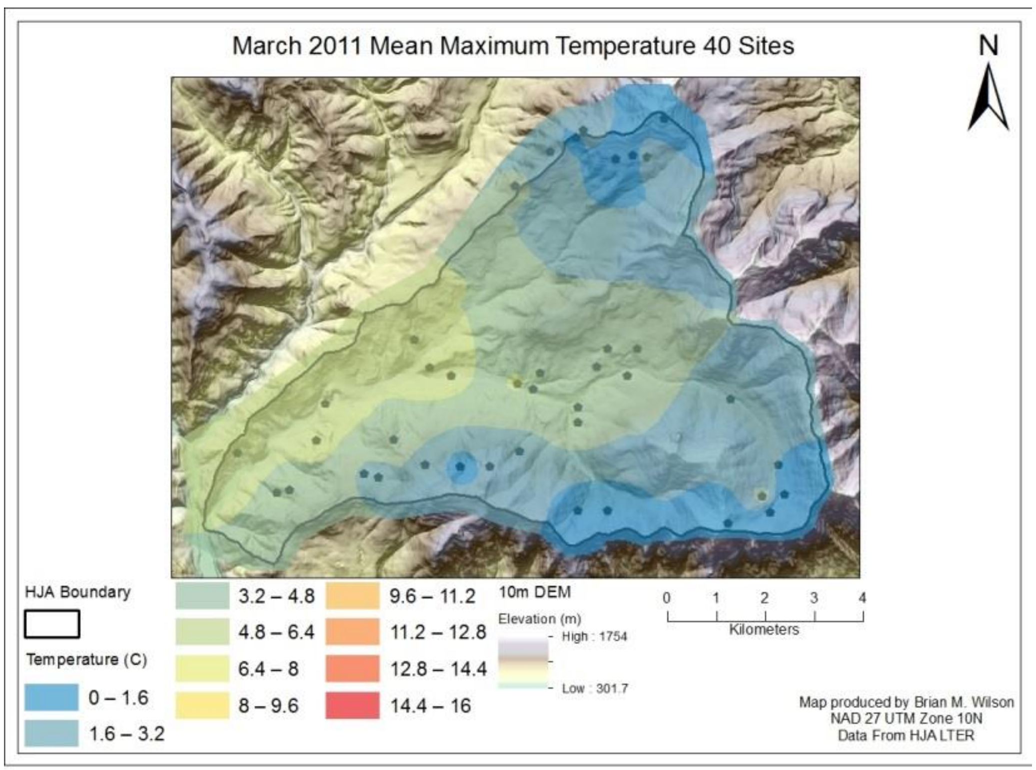


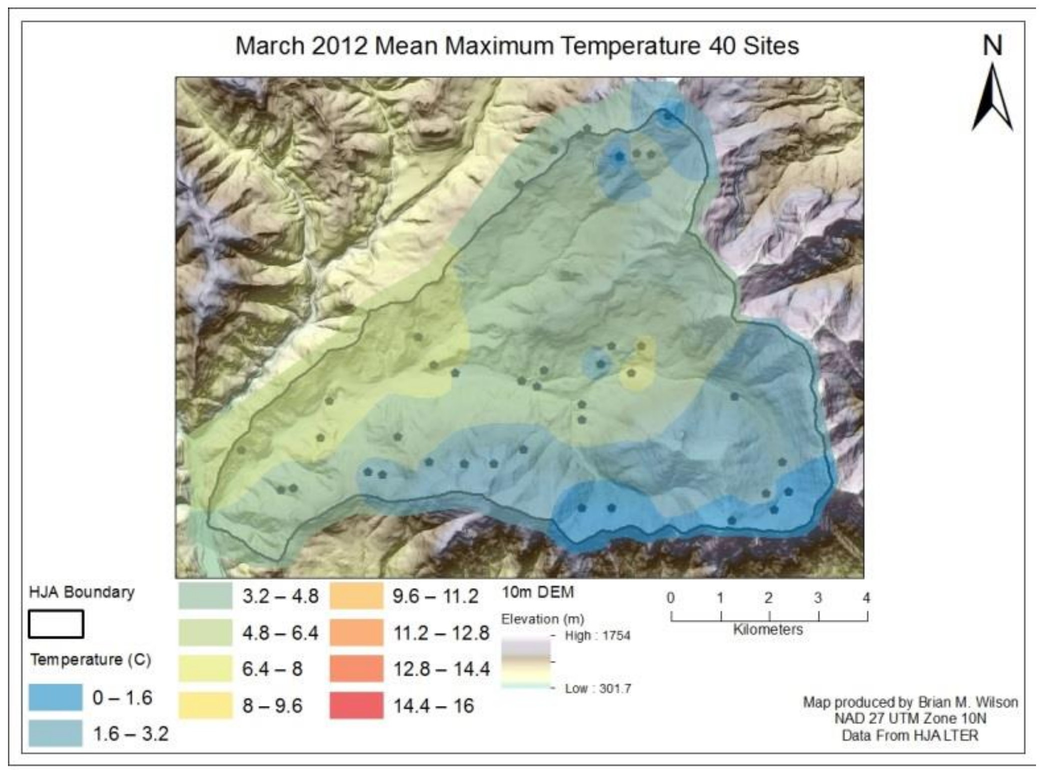




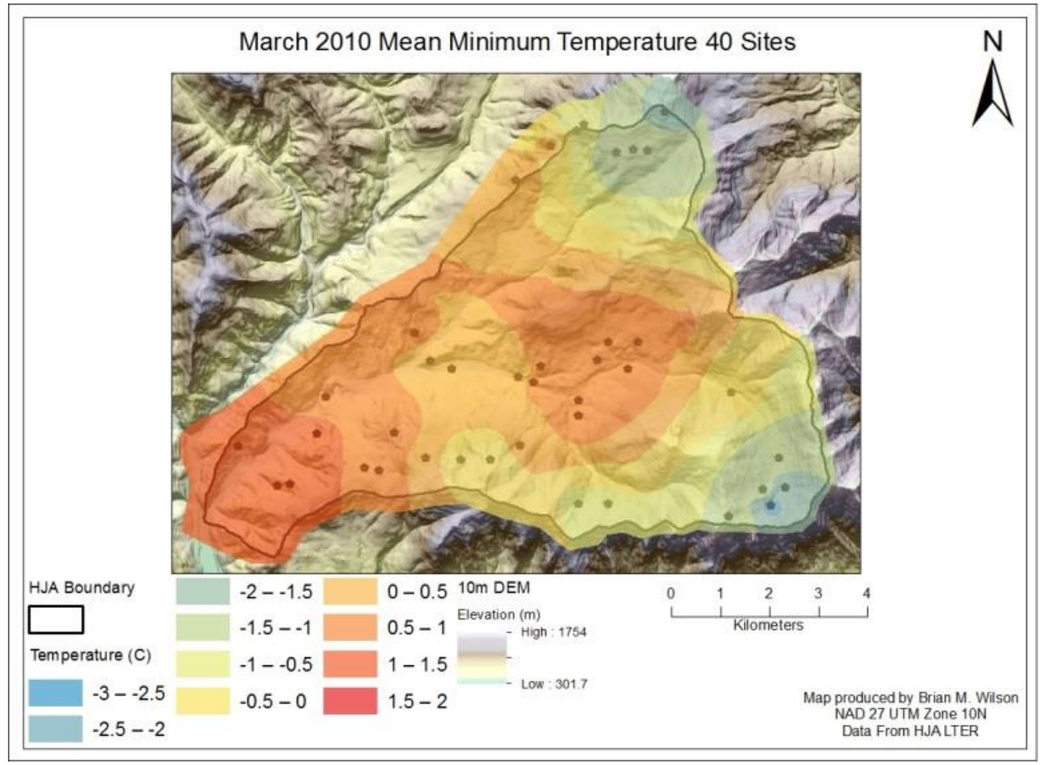
Mean Monthly Maximum Temperature 3 Consecutive Years March 2010 to March 2012 using 40 BIRD Sites.

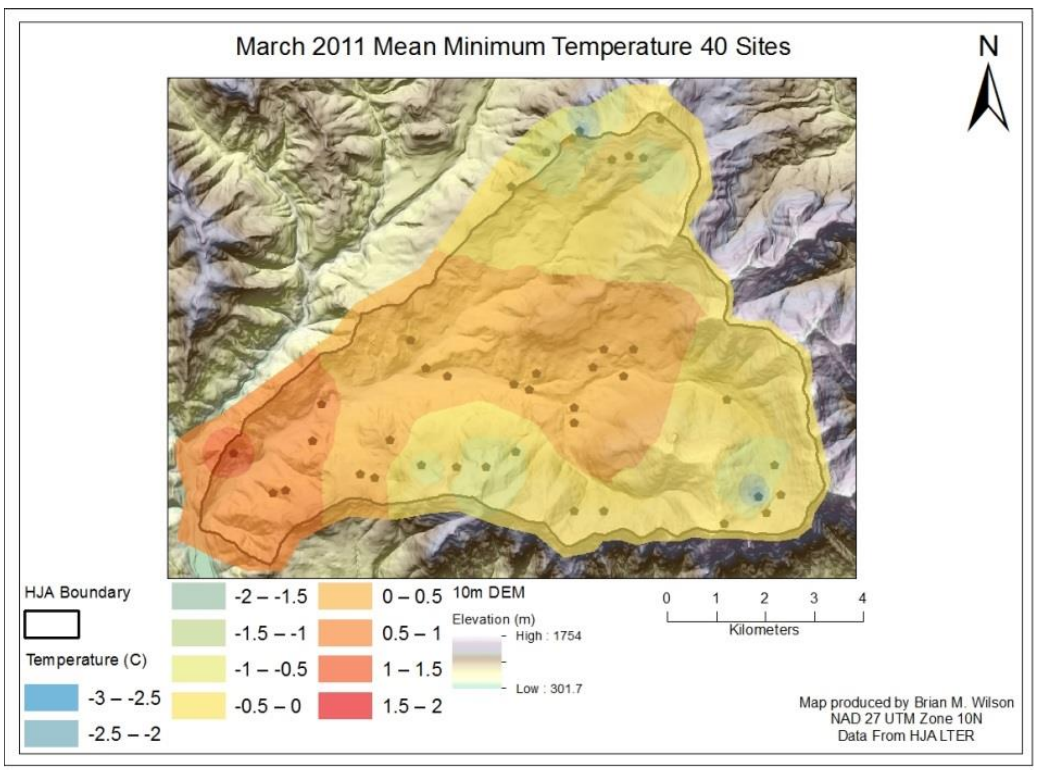


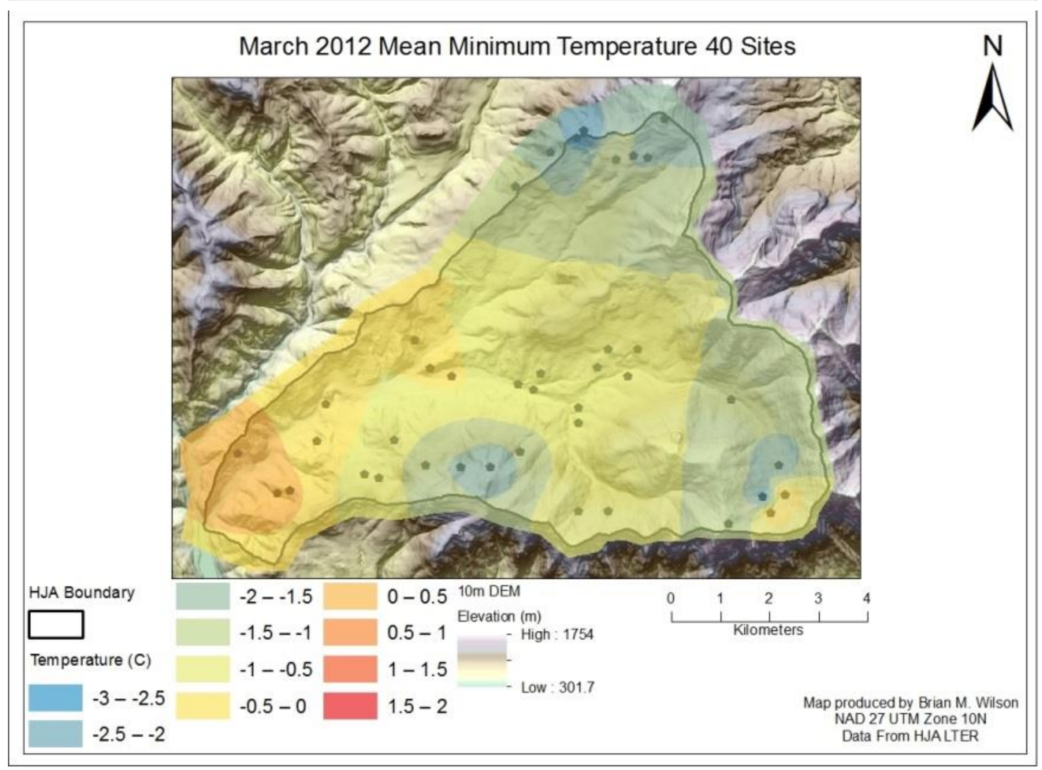




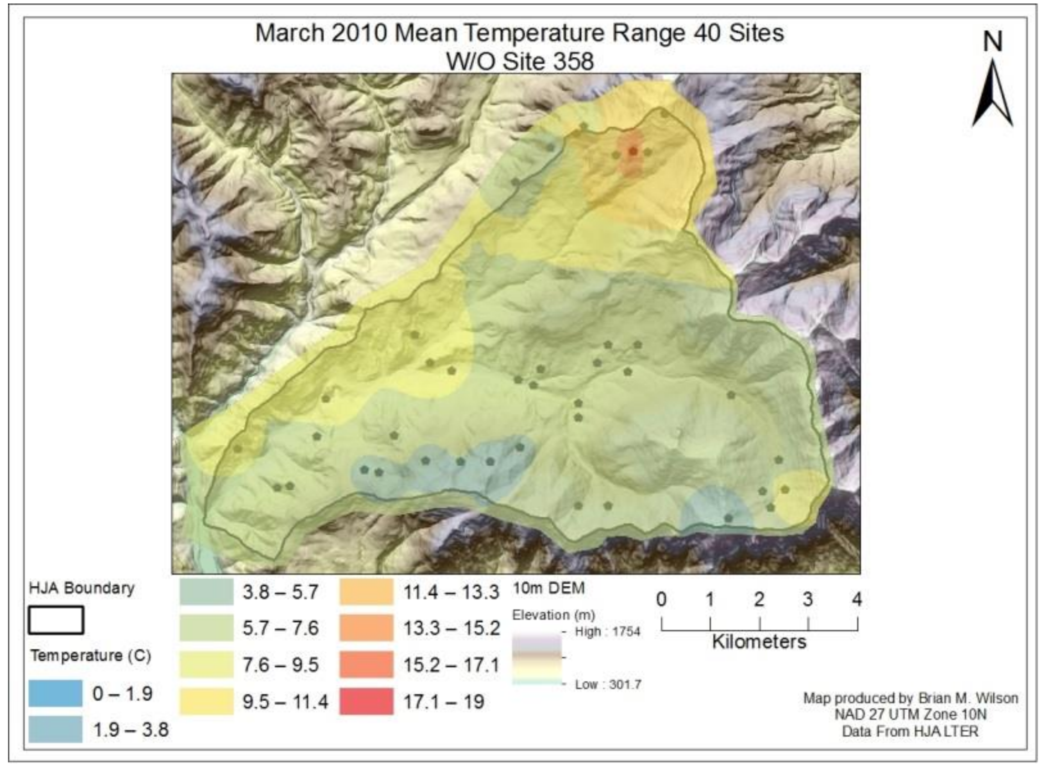
Mean Monthly Minimum Temperature 3 Consecutive Years March 2010 to March 2012 using 40 BIRD Sites.

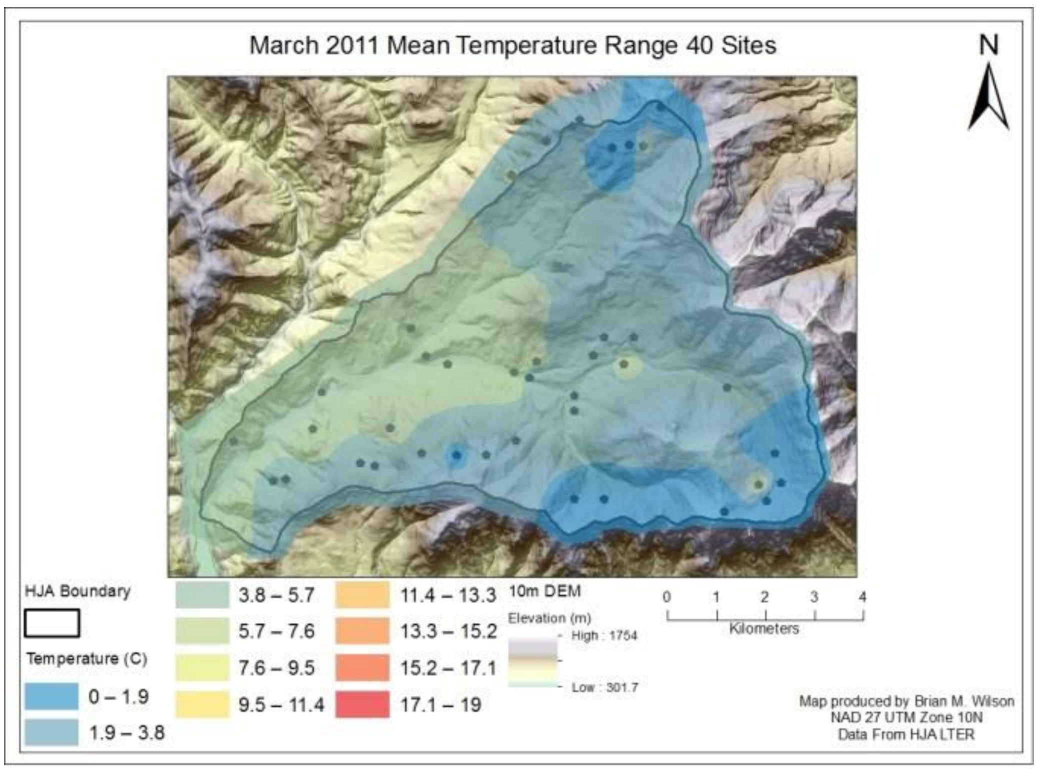


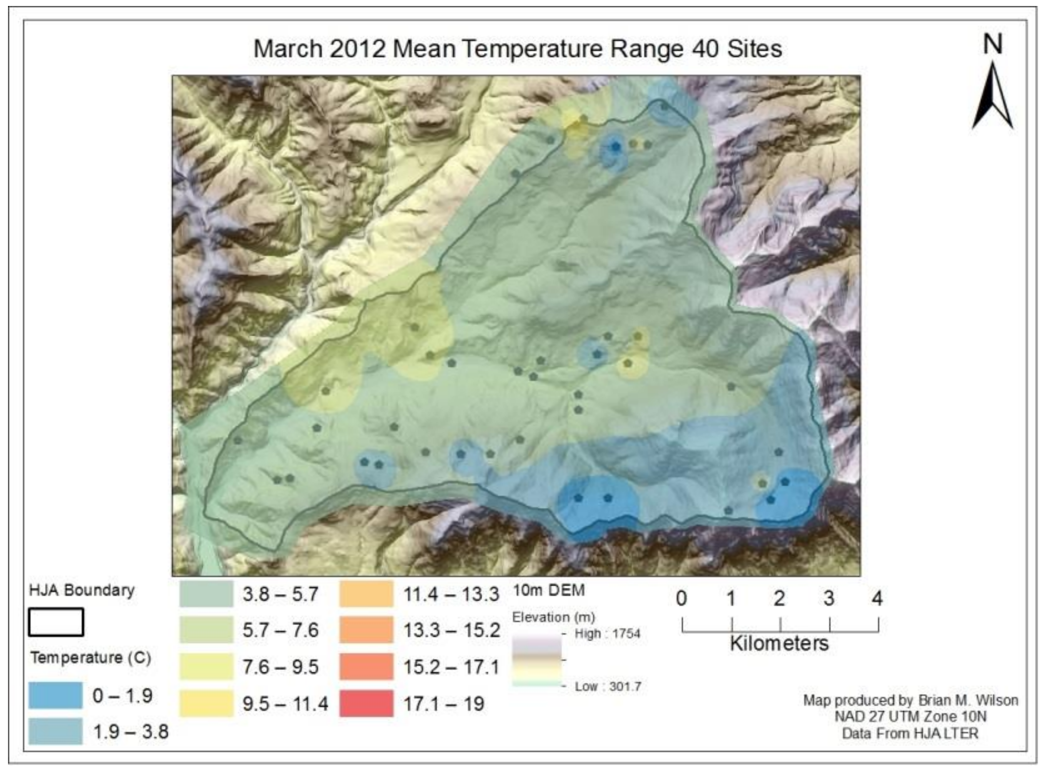




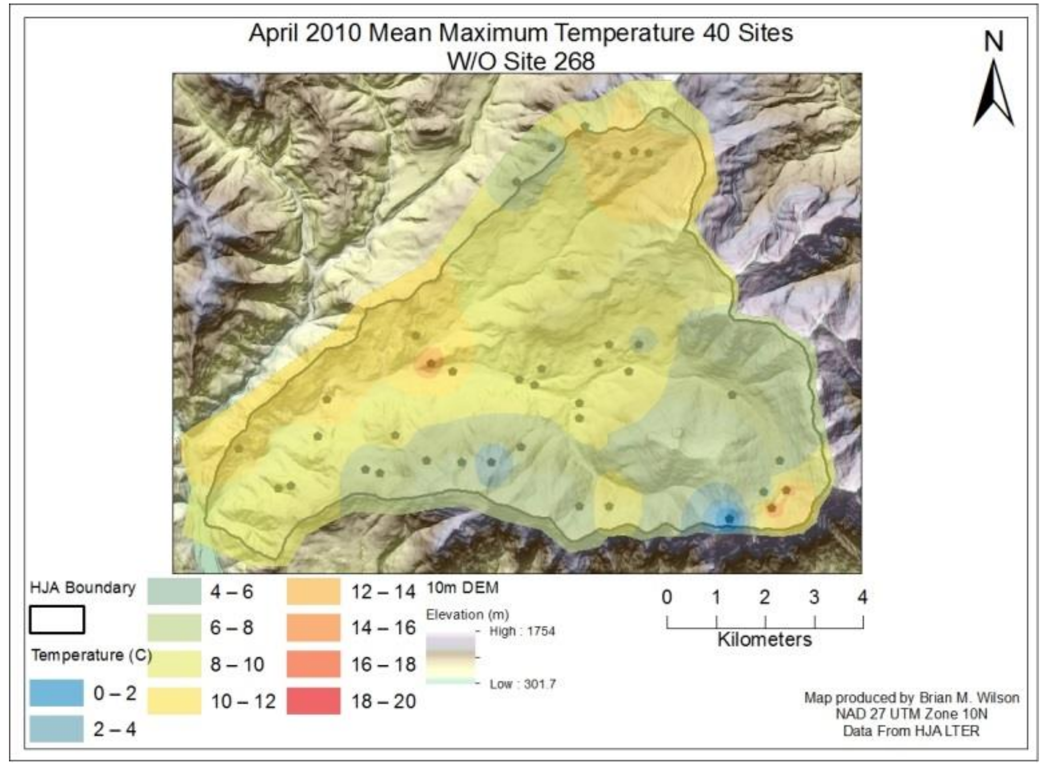
Mean Monthly Temperature Range 3 Consecutive Years March 2010 to March 2012 using 40 BIRD Sites.

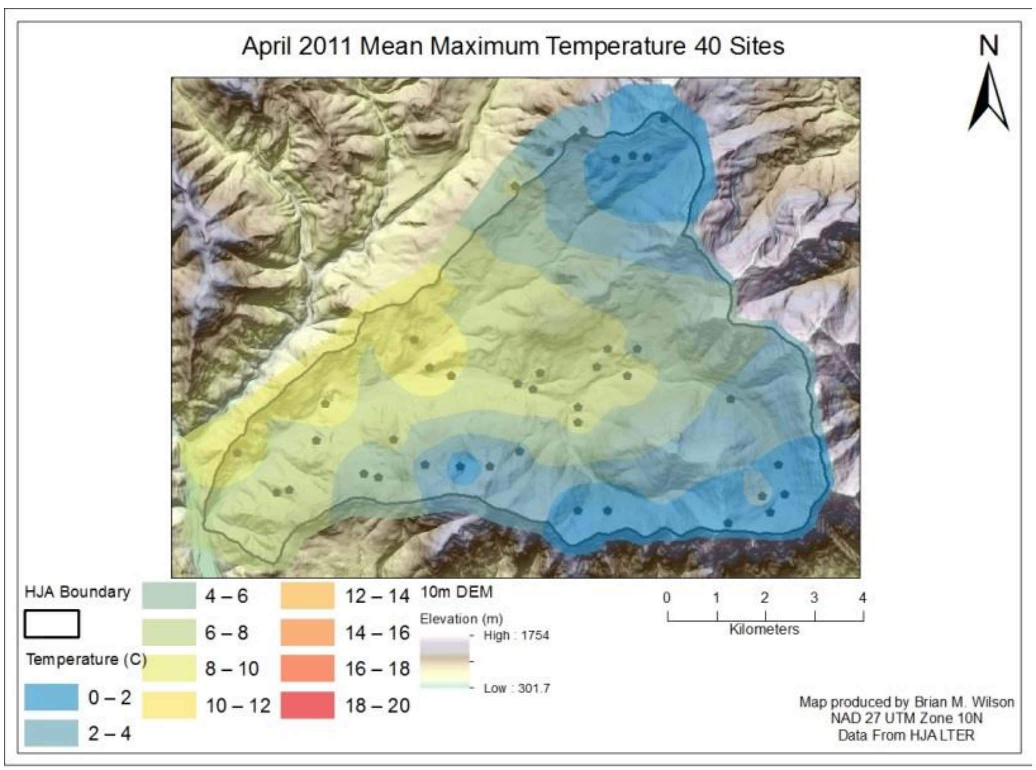


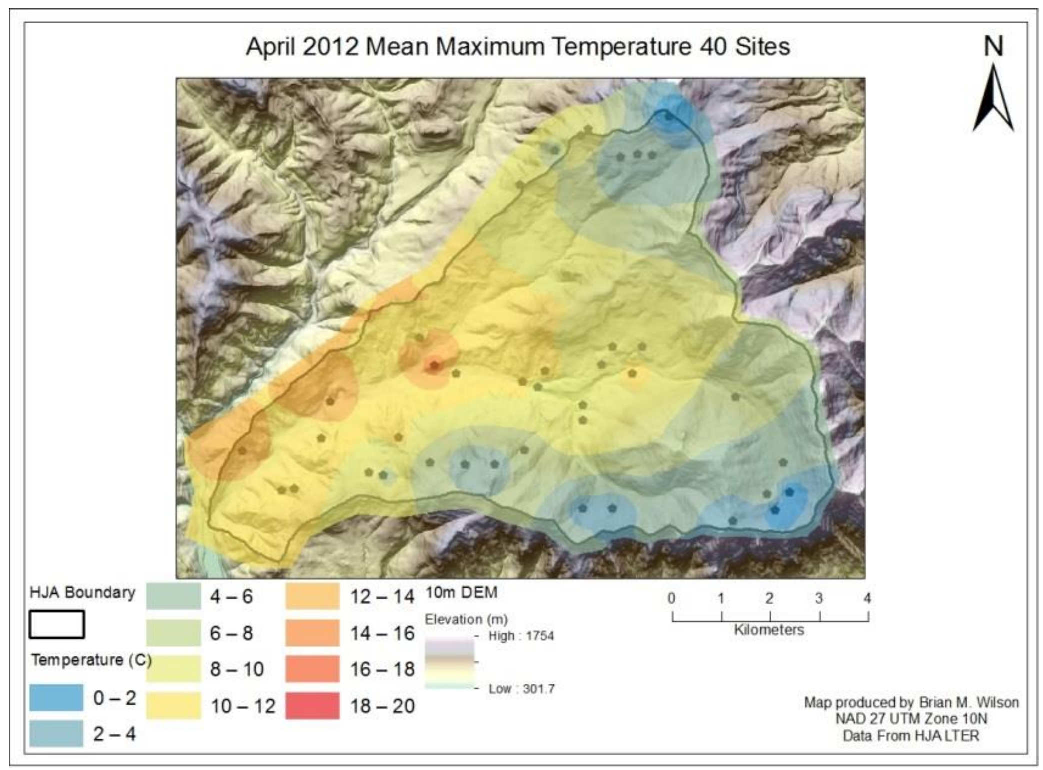




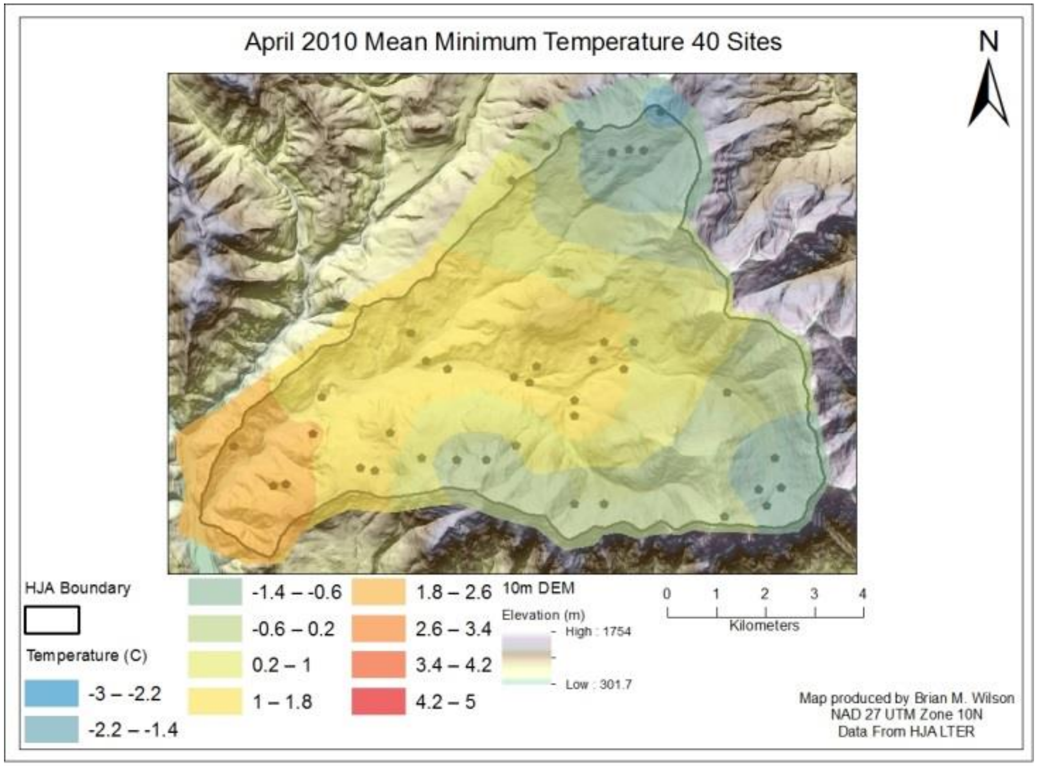
Mean Monthly Maximum Temperature 3 Consecutive Years April 2010 to April 2012 using 40 BIRD Sites.

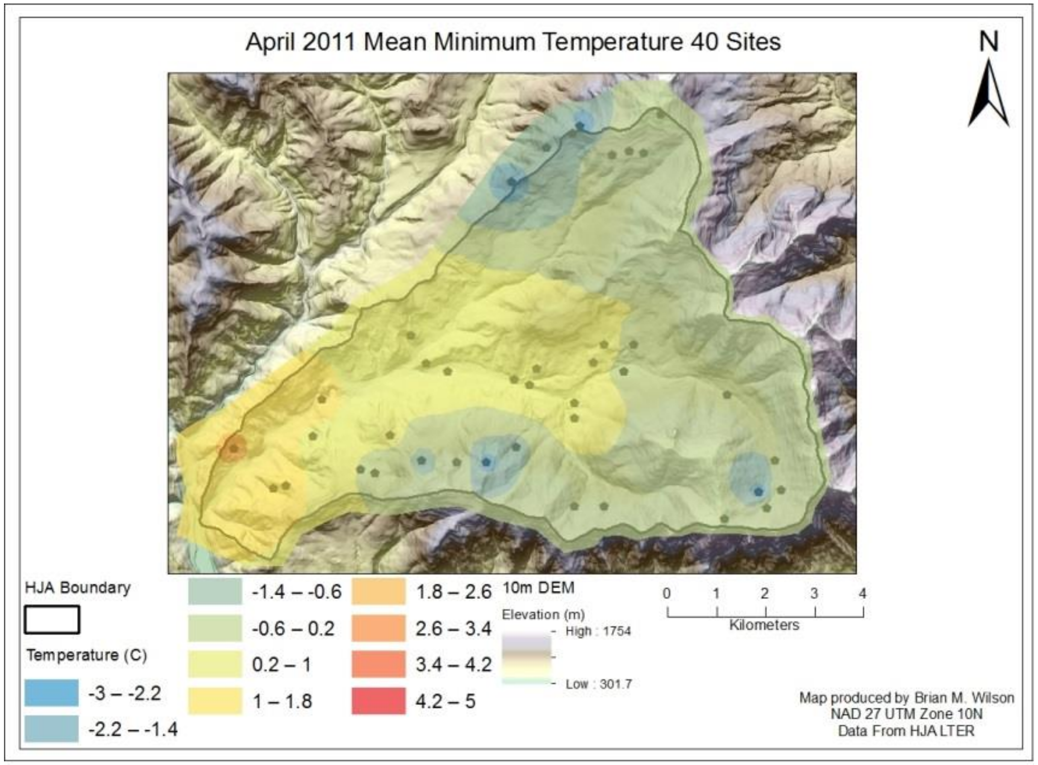


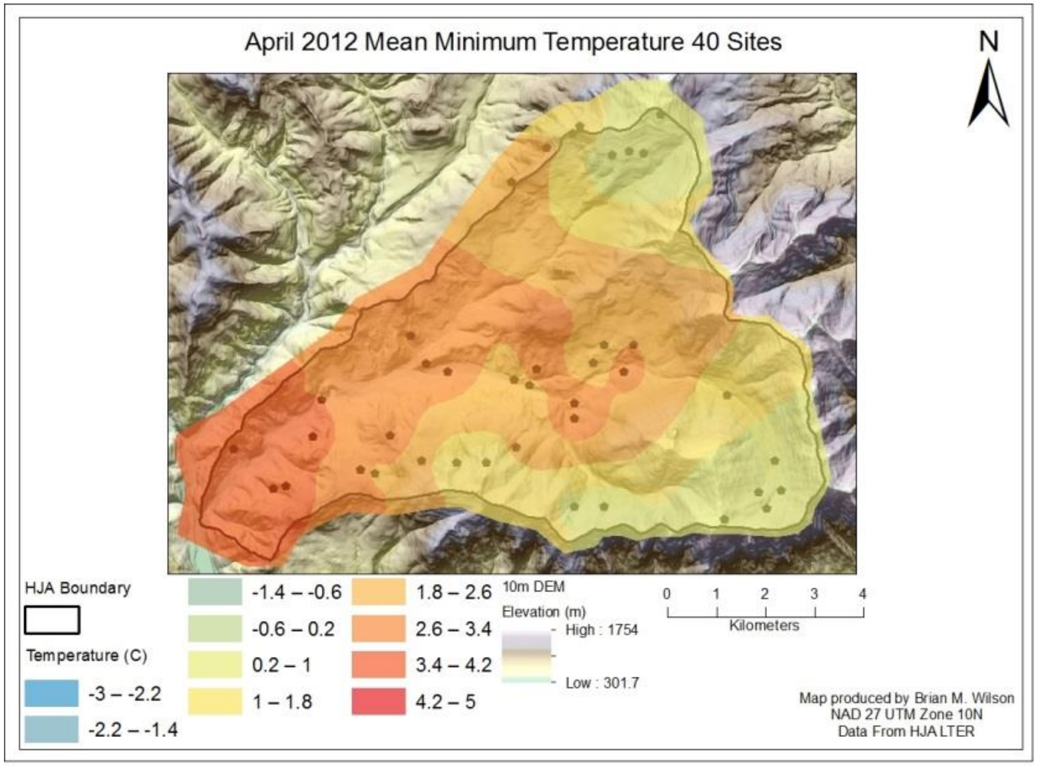




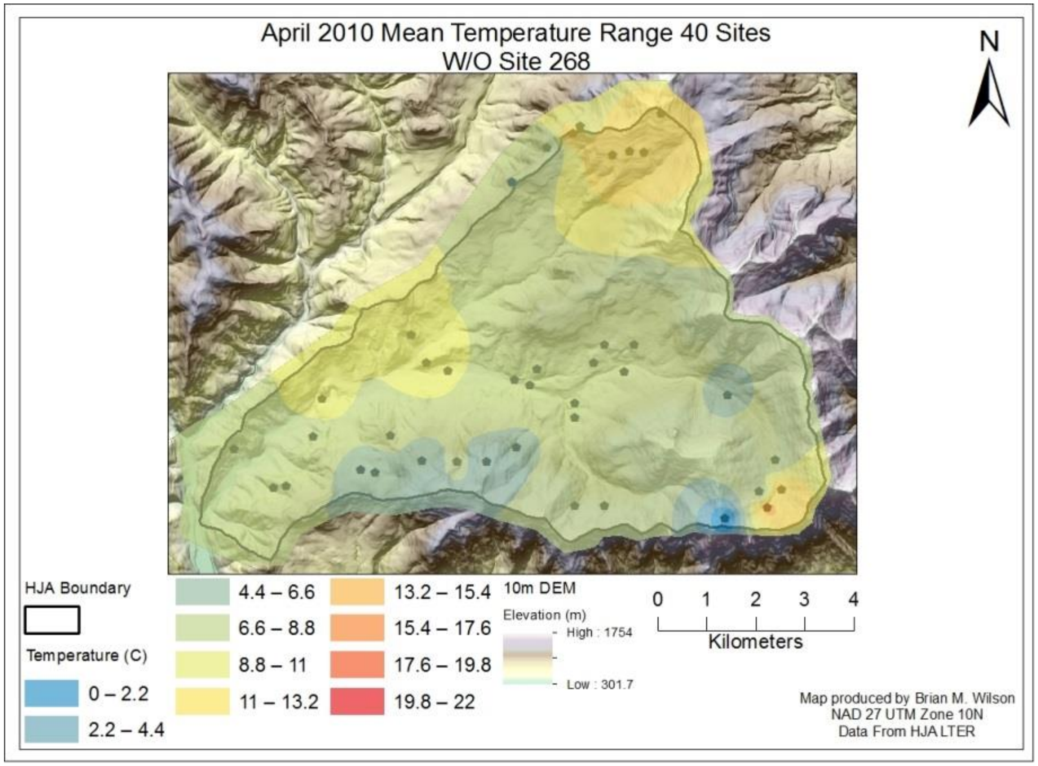
Mean Monthly Minimum Temperature 3 Consecutive Years April 2010 to April 2012 using 40 BIRD Sites.

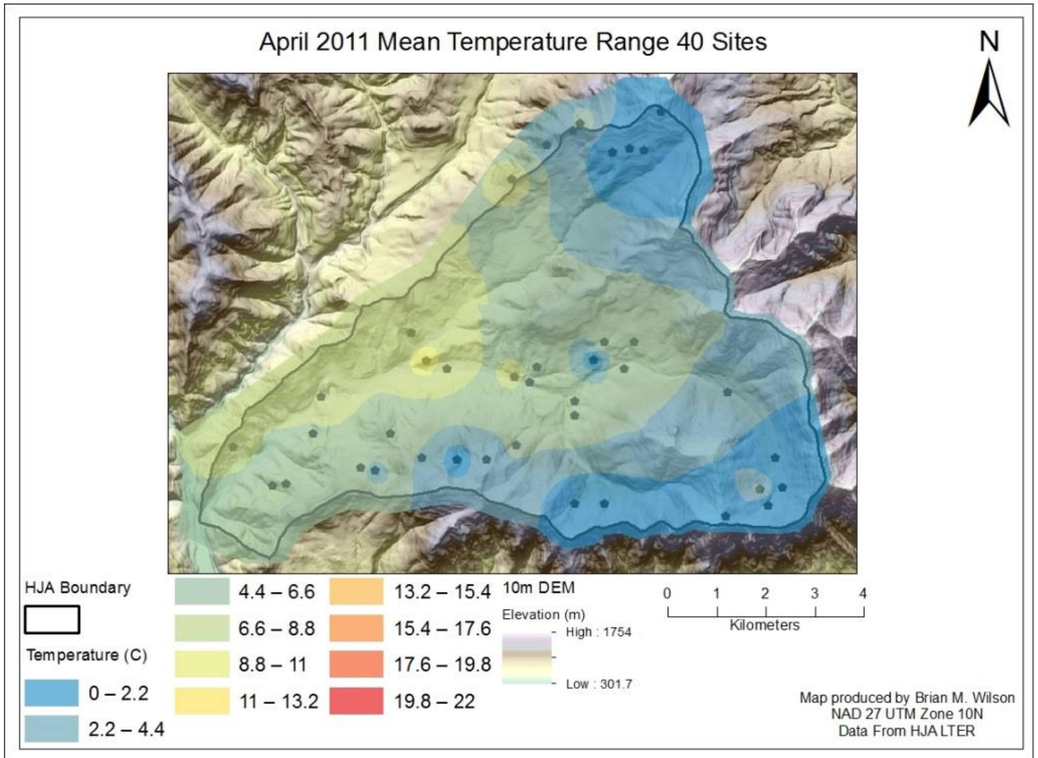


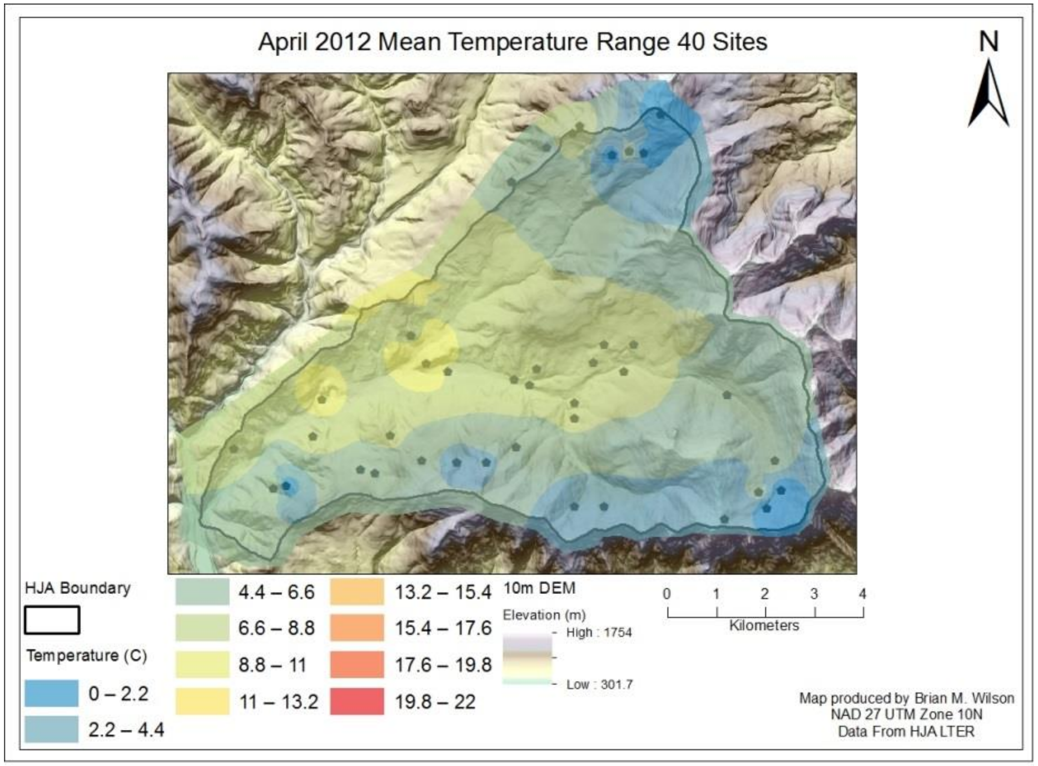




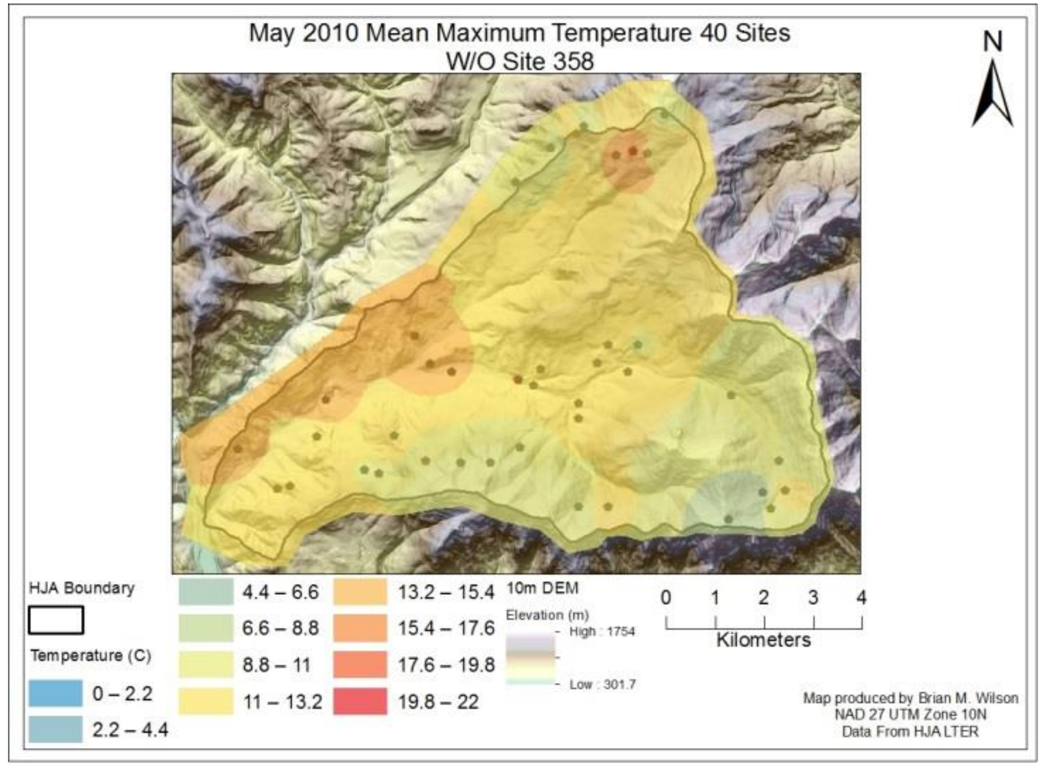
Mean Monthly Temperature Range 3 Consecutive Years April 2010 to April 2012 using 40 BIRD Sites.

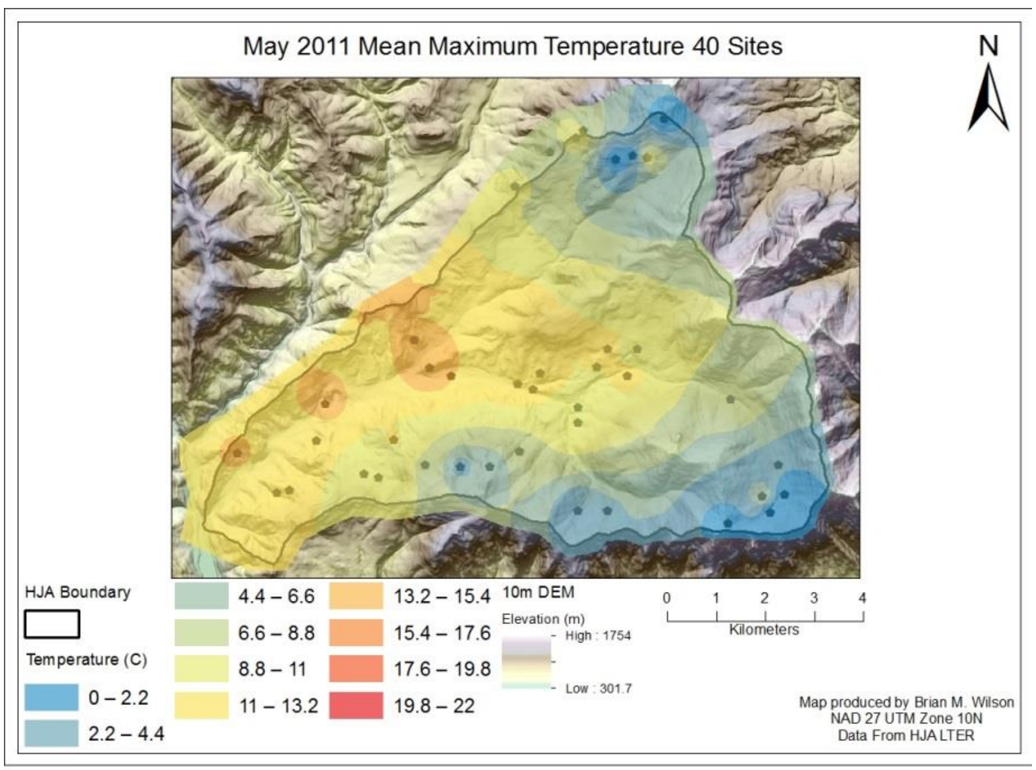


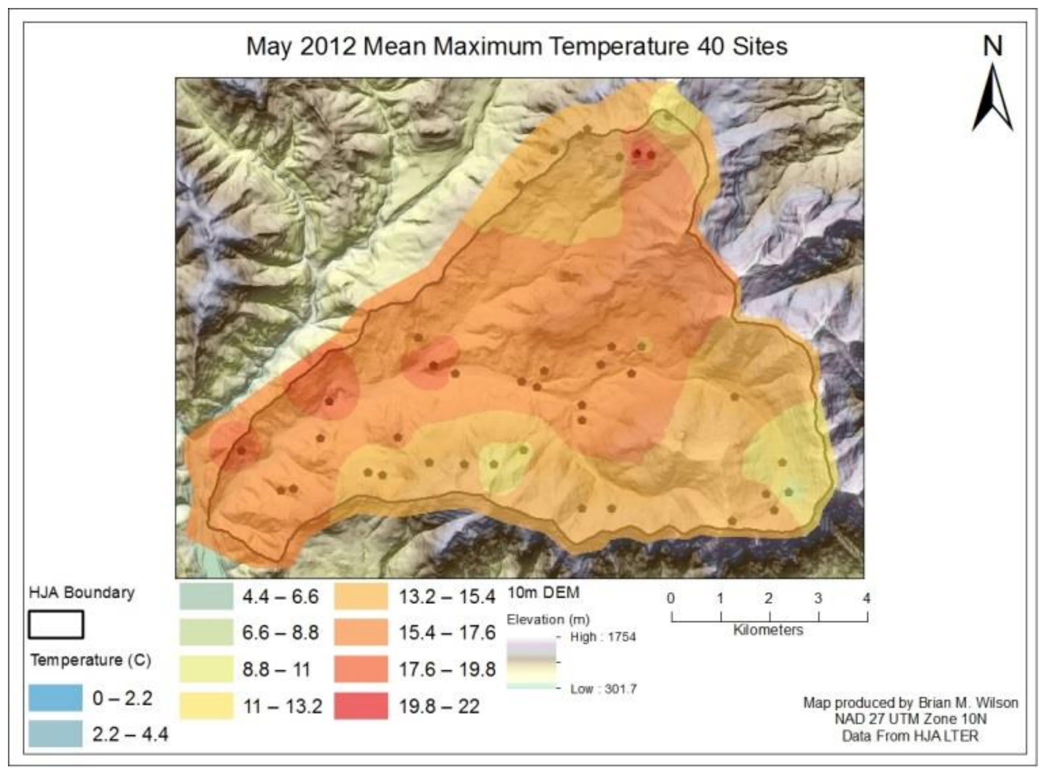




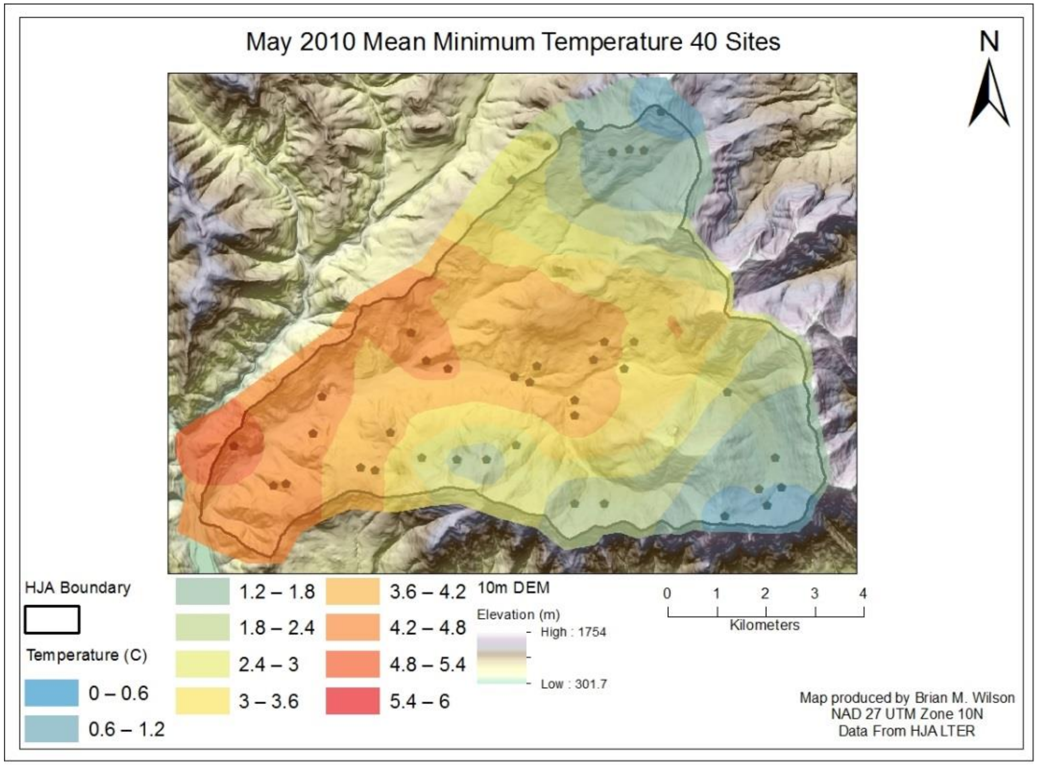
Mean Monthly Maximum Temperature 3 Consecutive Years May 2010 to May 2012 using 40 BIRD Sites.

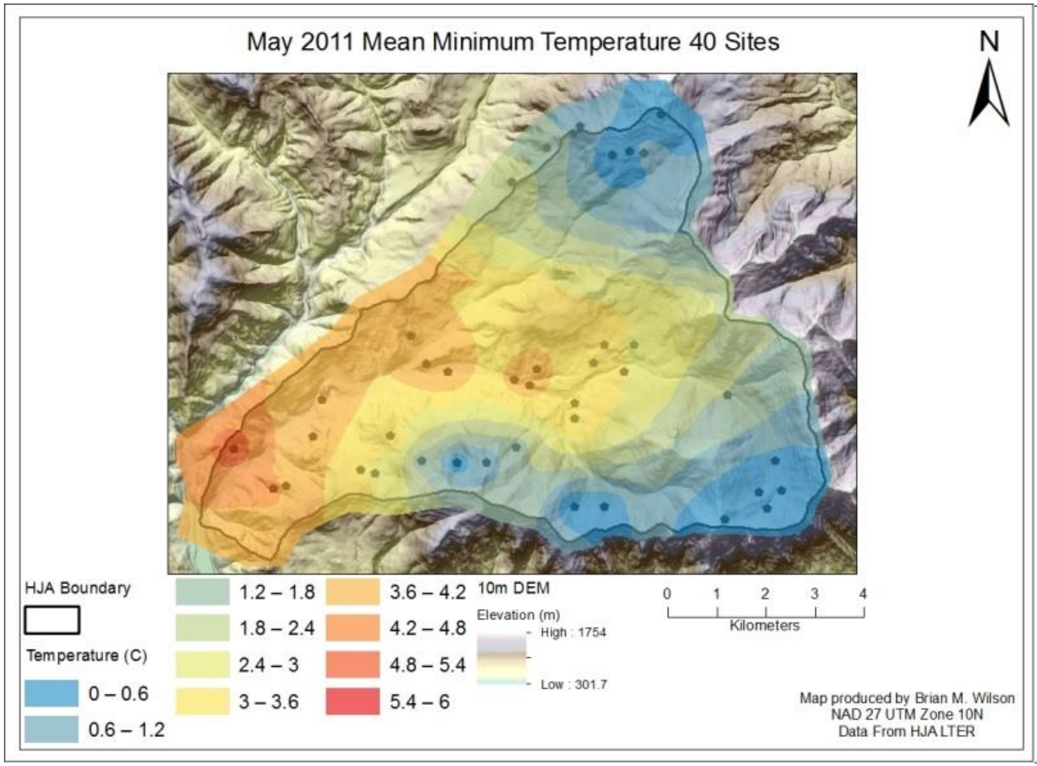


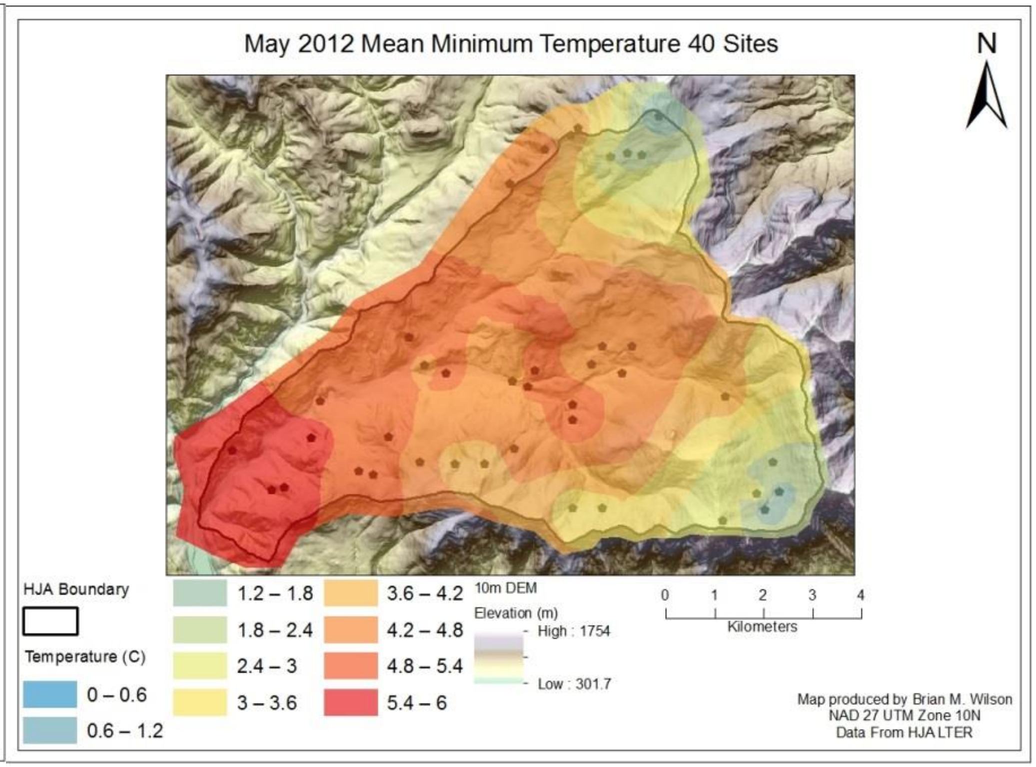




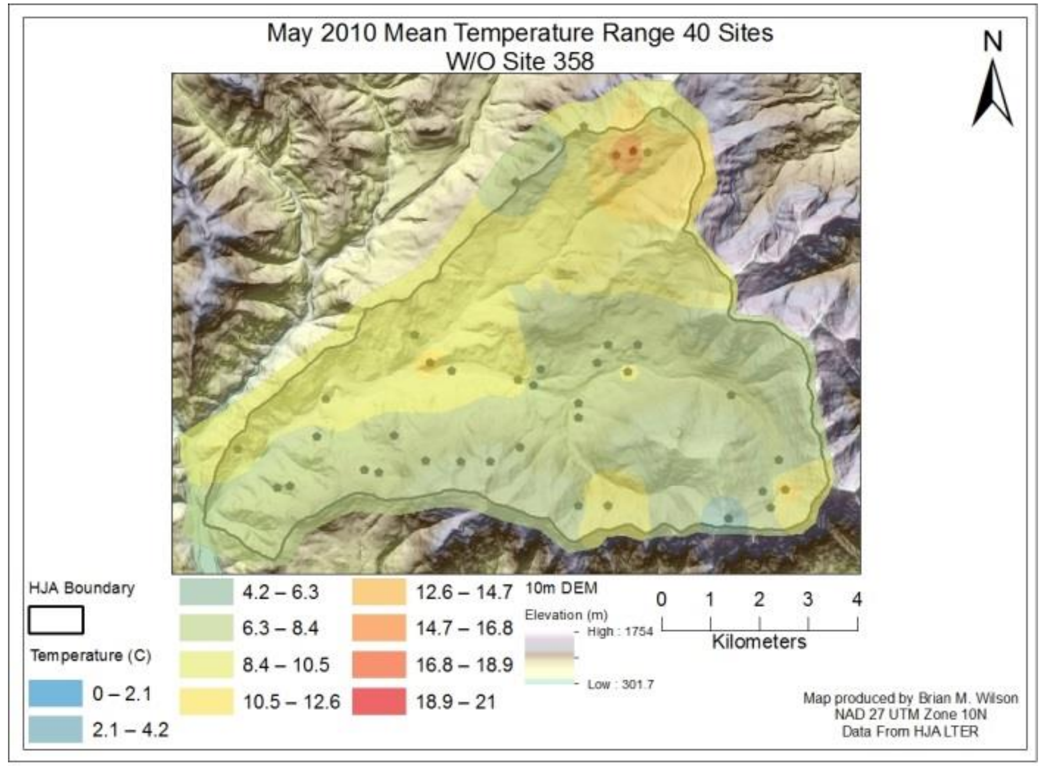
Mean Monthly Minimum Temperature 3 Consecutive Years May 2010 to May 2012 using 40 BIRD Sites.

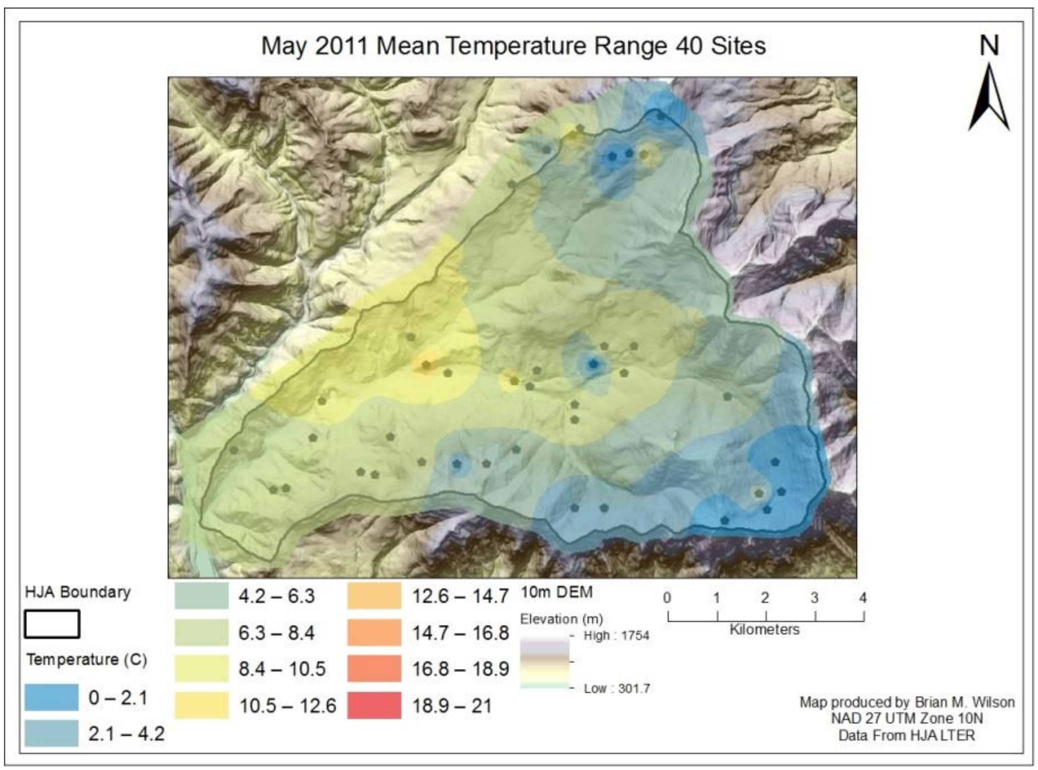


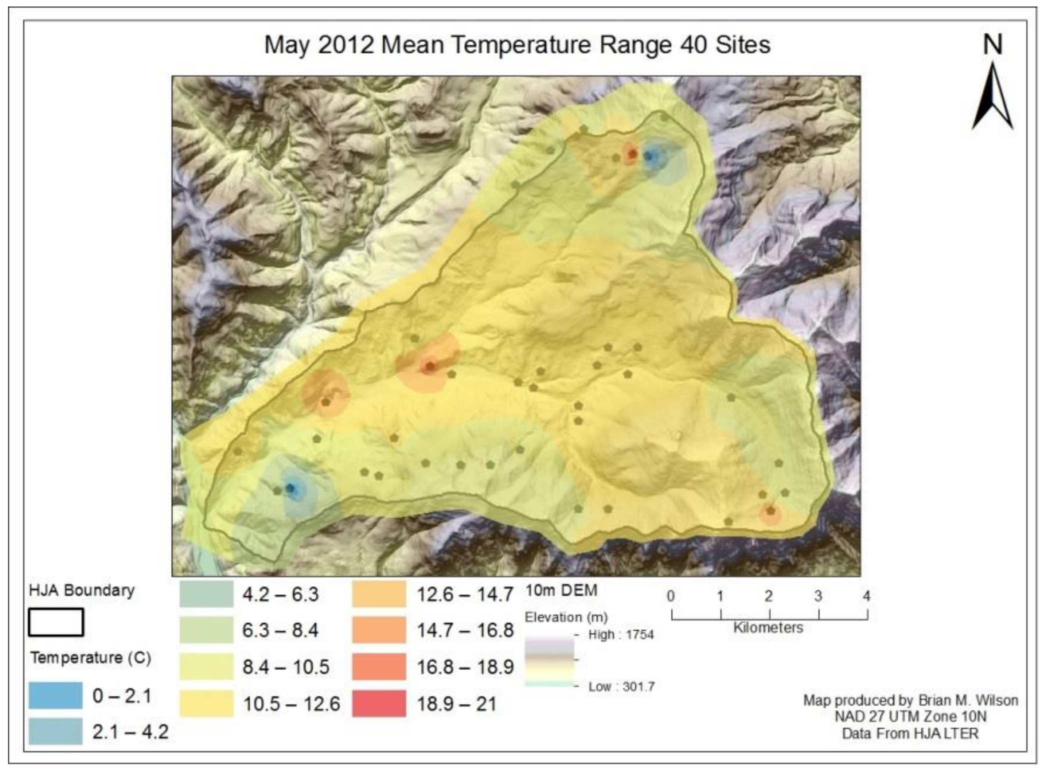




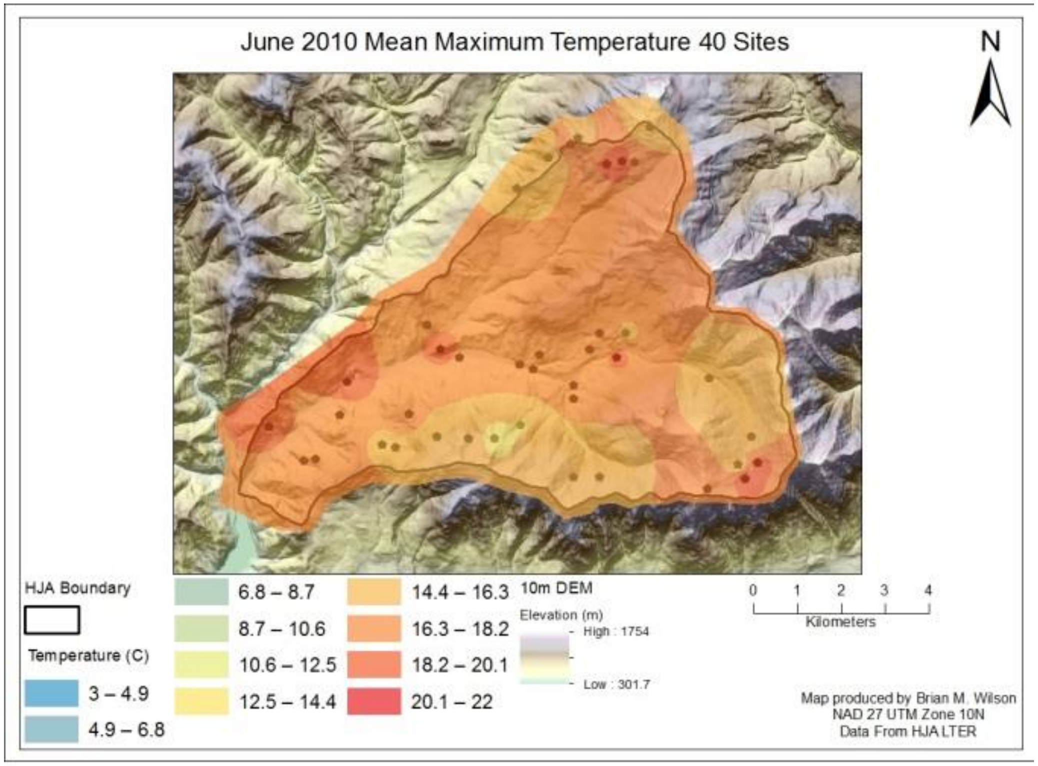
Mean Monthly Temperature Range 3 Consecutive Years May 2010 to May 2012 using 40 BIRD Sites.

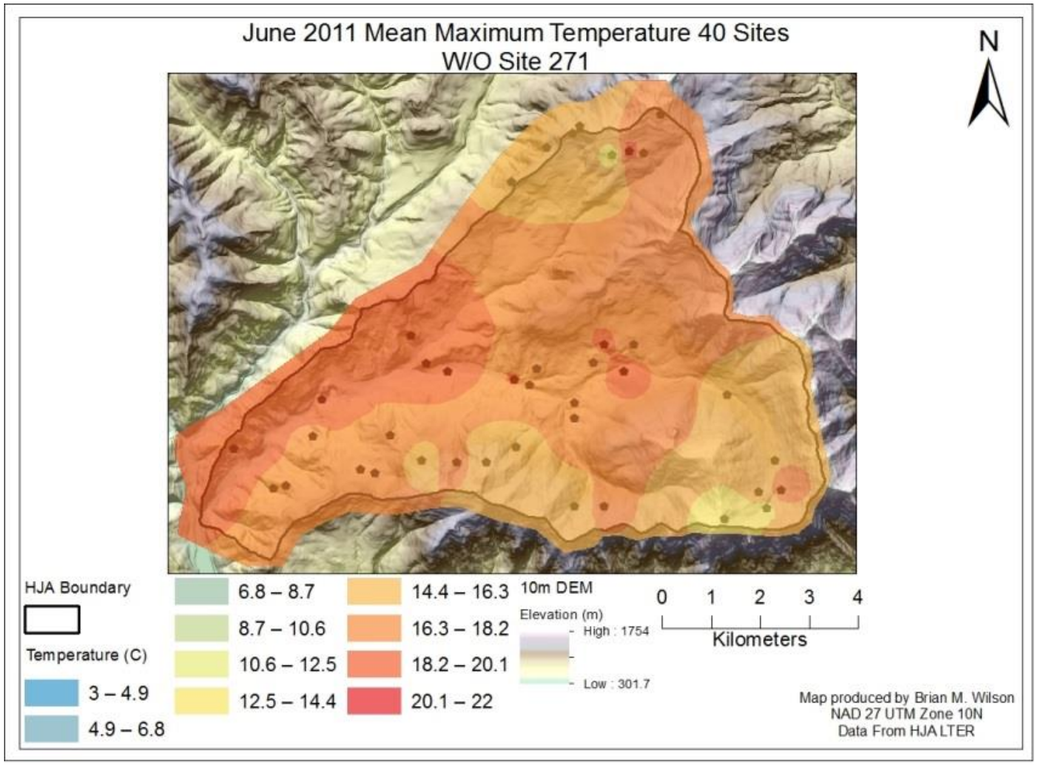


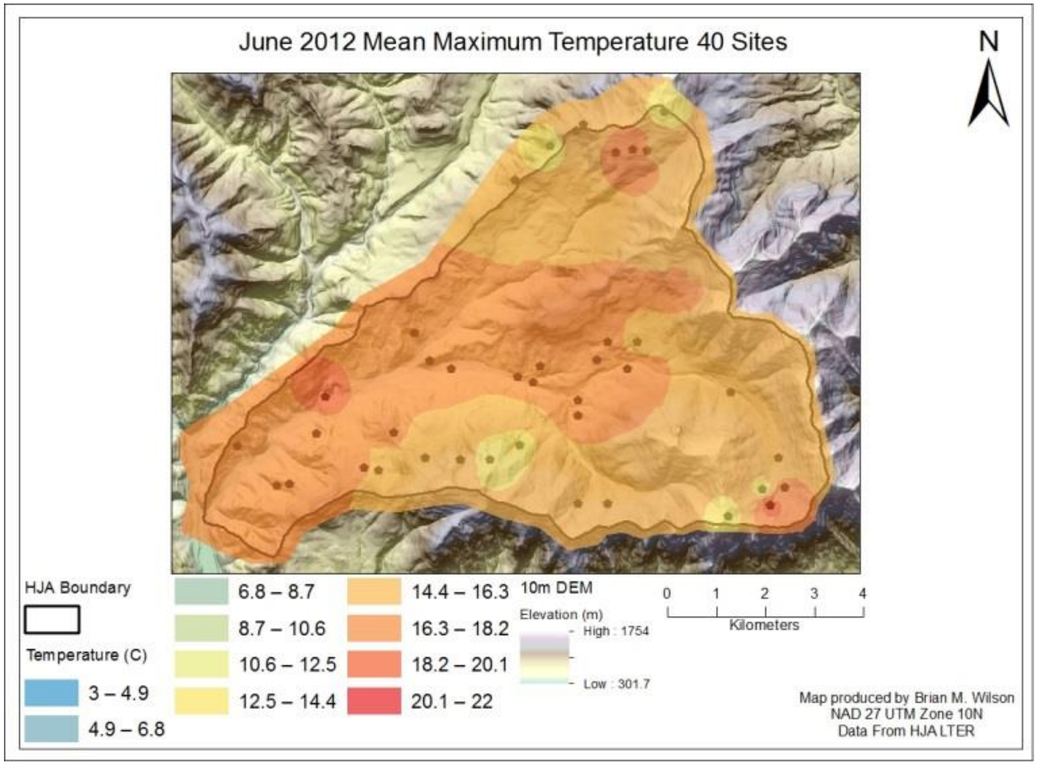




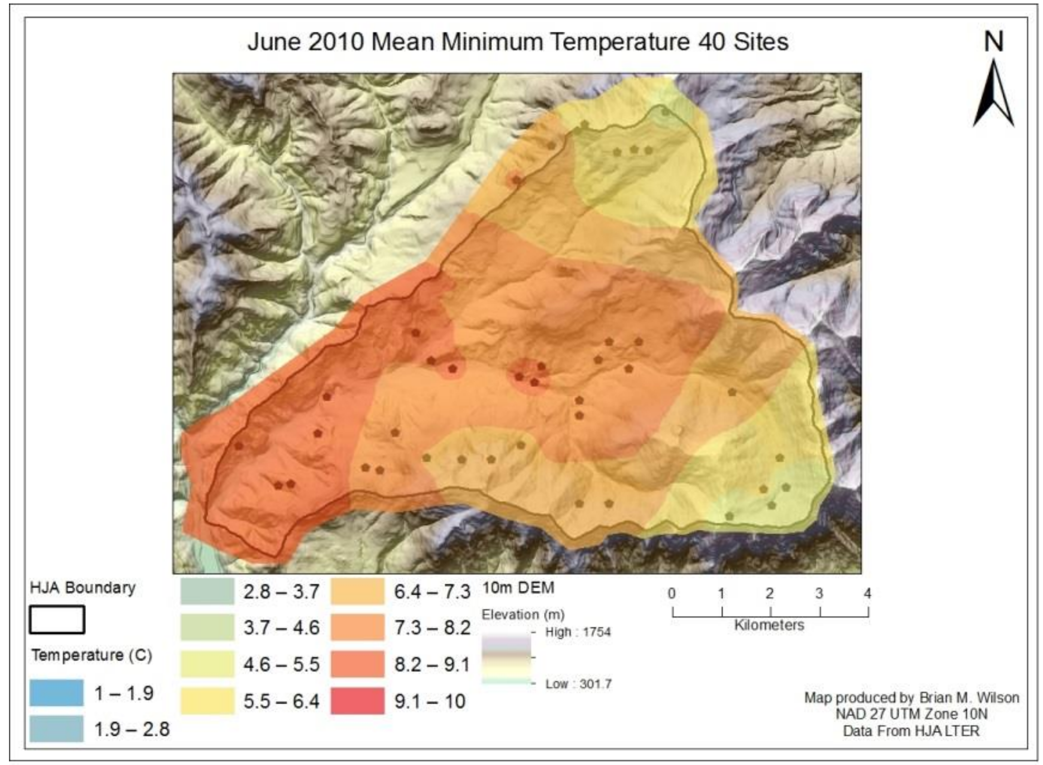
Mean Monthly Maximum Temperature 3 Consecutive Years June 2010 to June 2012 using 40 BIRD Sites.

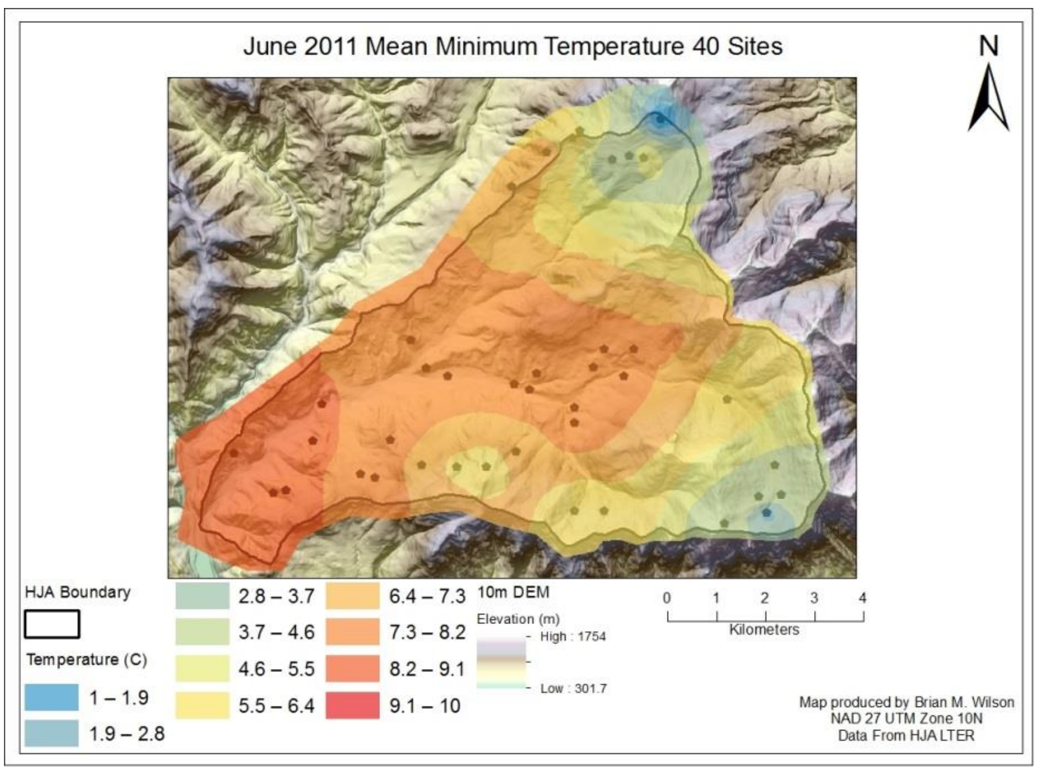


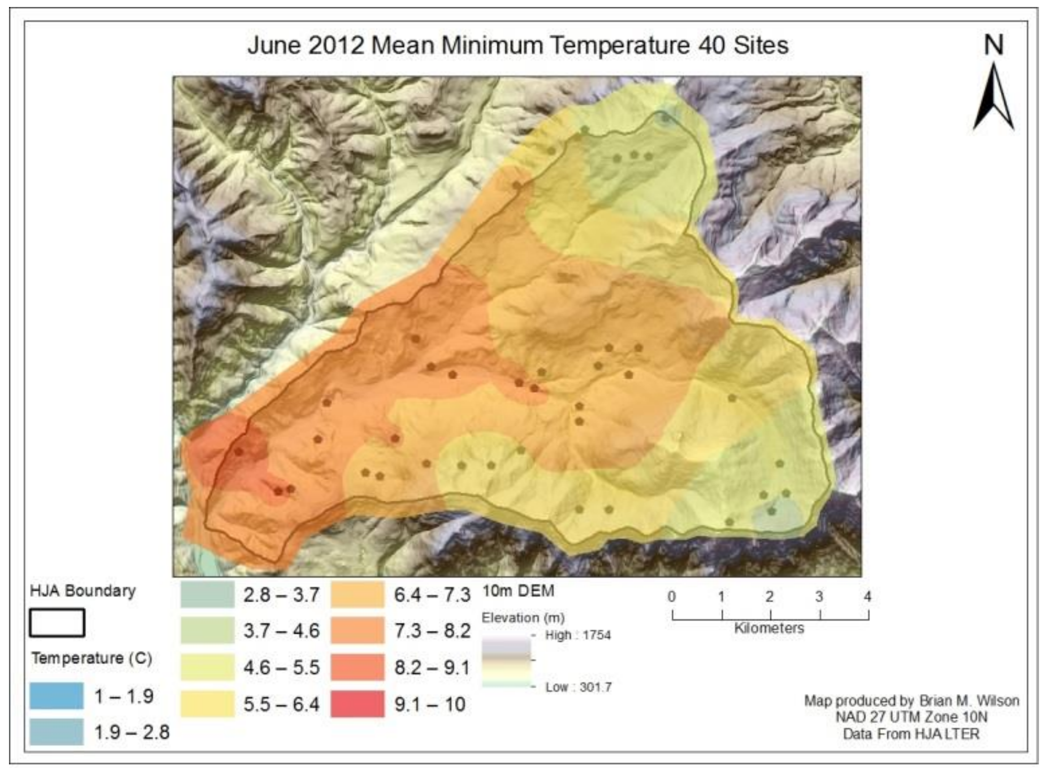




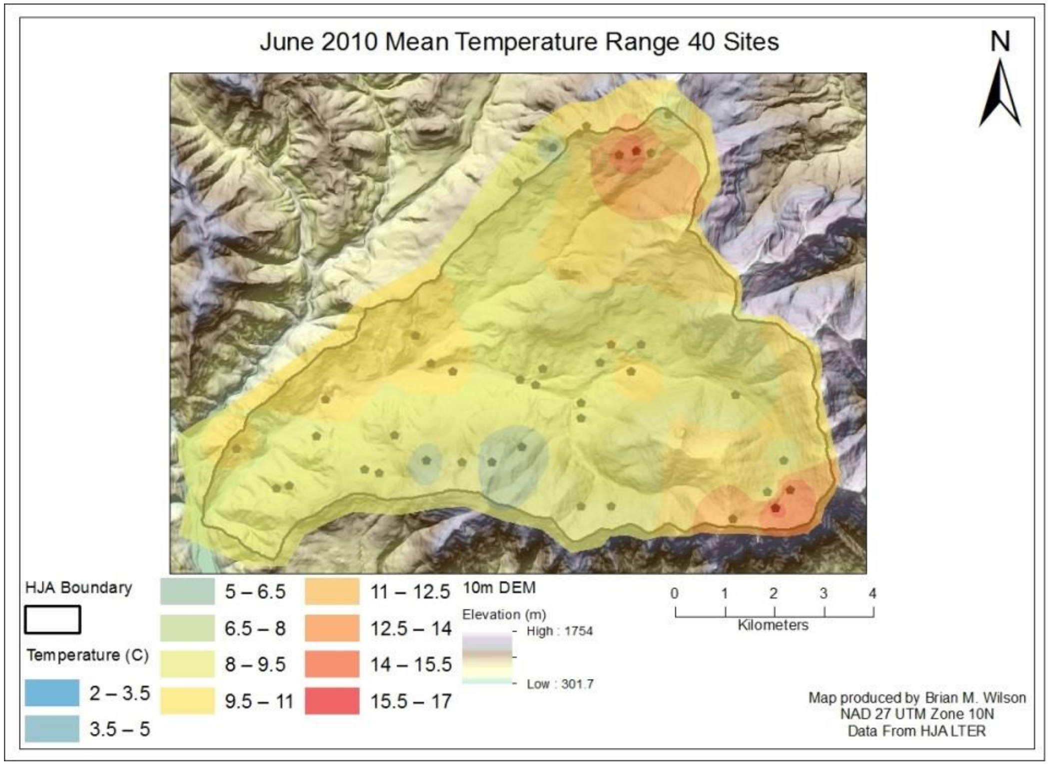
Mean Monthly Minimum Temperature 3 Consecutive Years June 2010 to June 2010 using 40 BIRD Sites.

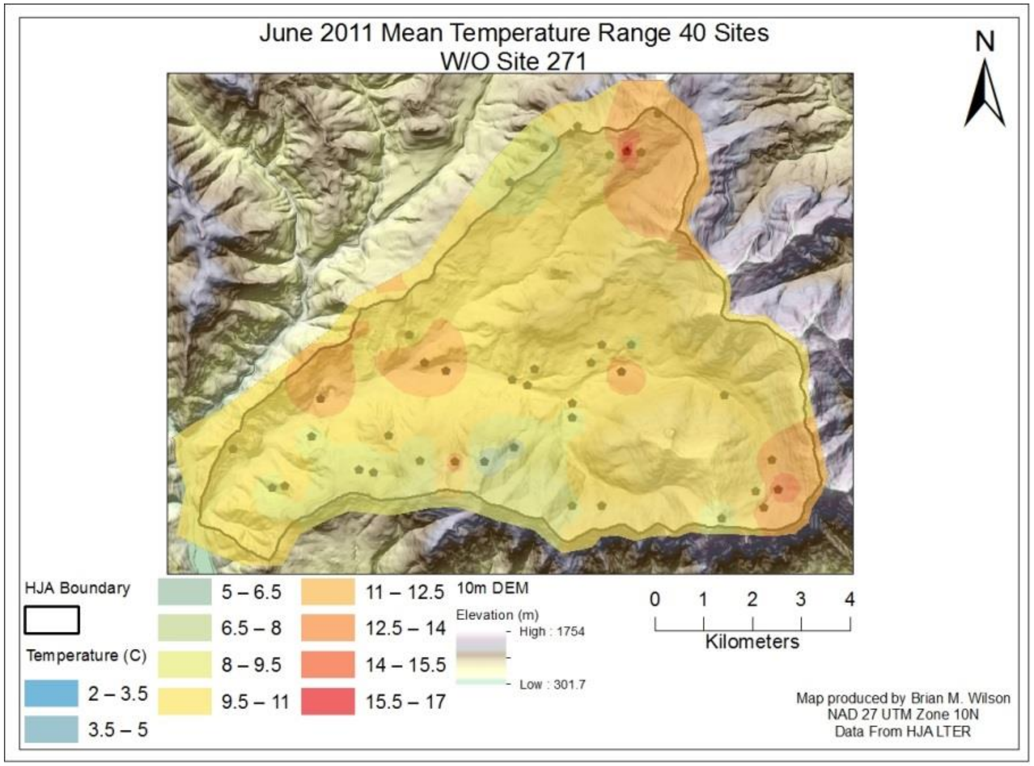


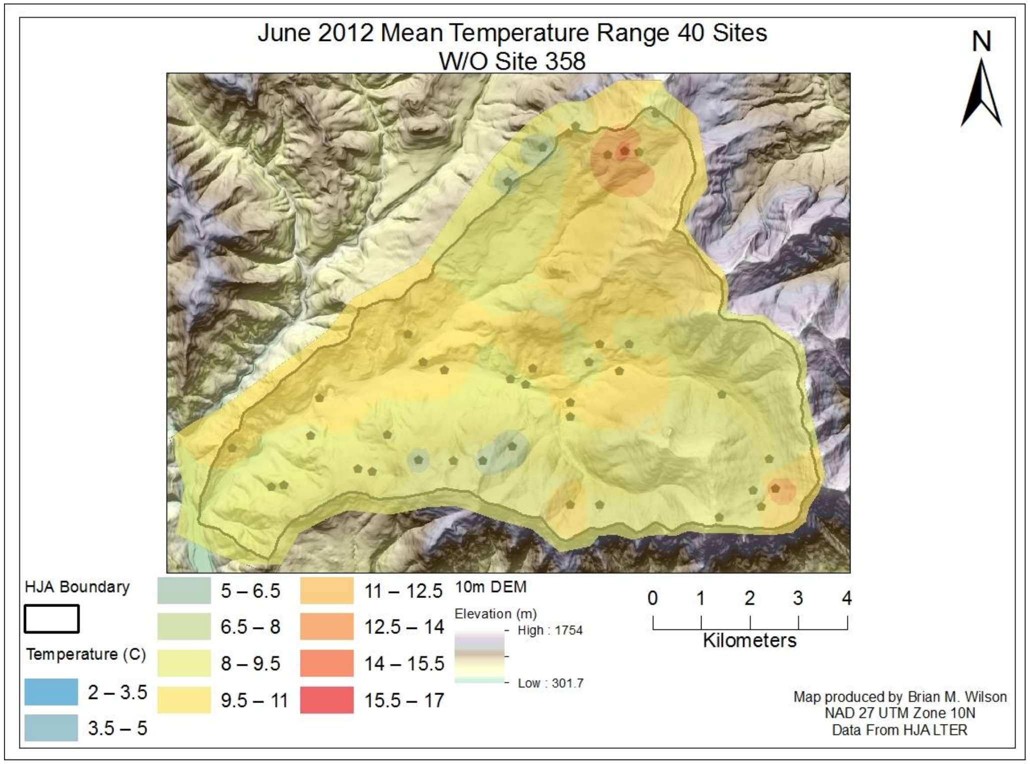




Mean Monthly Temperature Range 3 Consecutive Years June 2010 to June 2012 using 40 BIRD Sites.





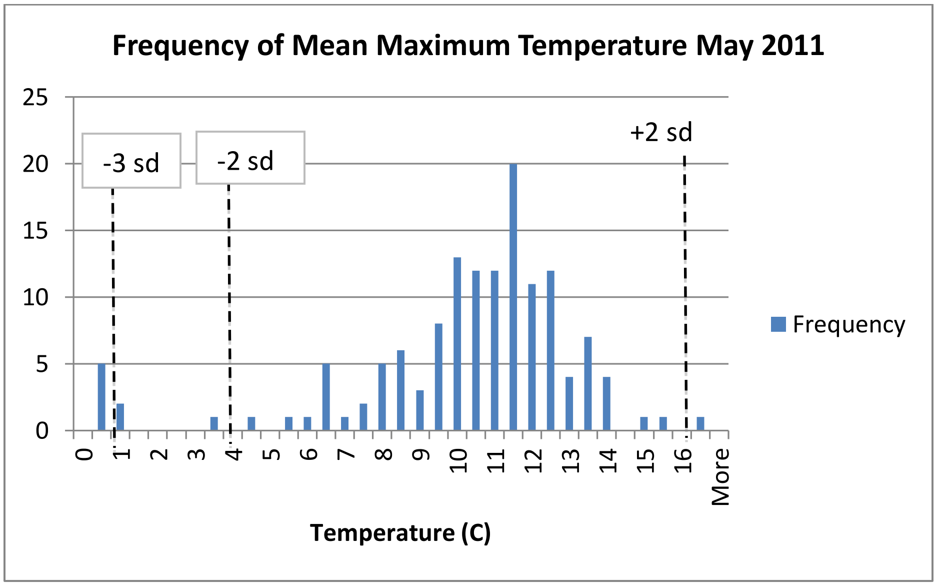


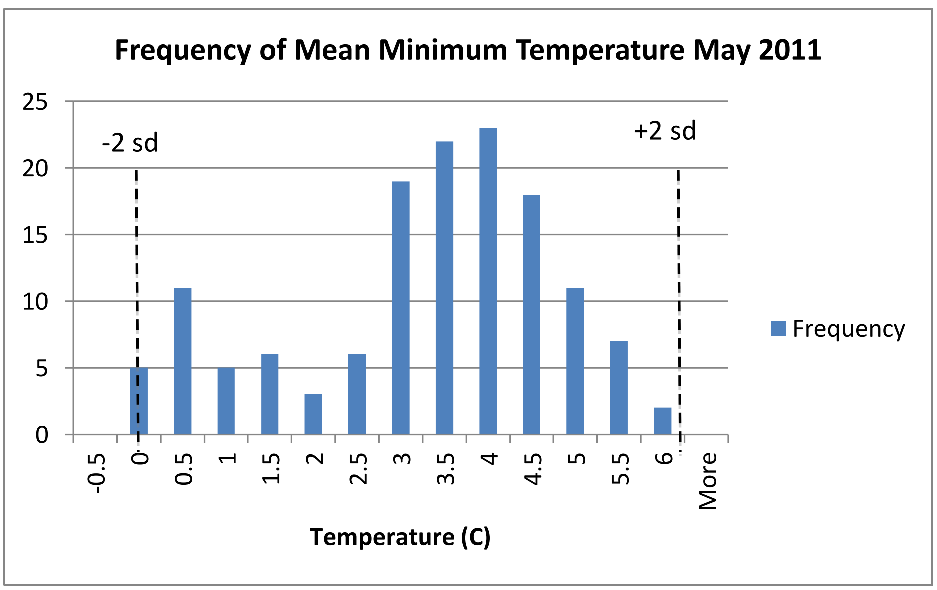
11. Appendices

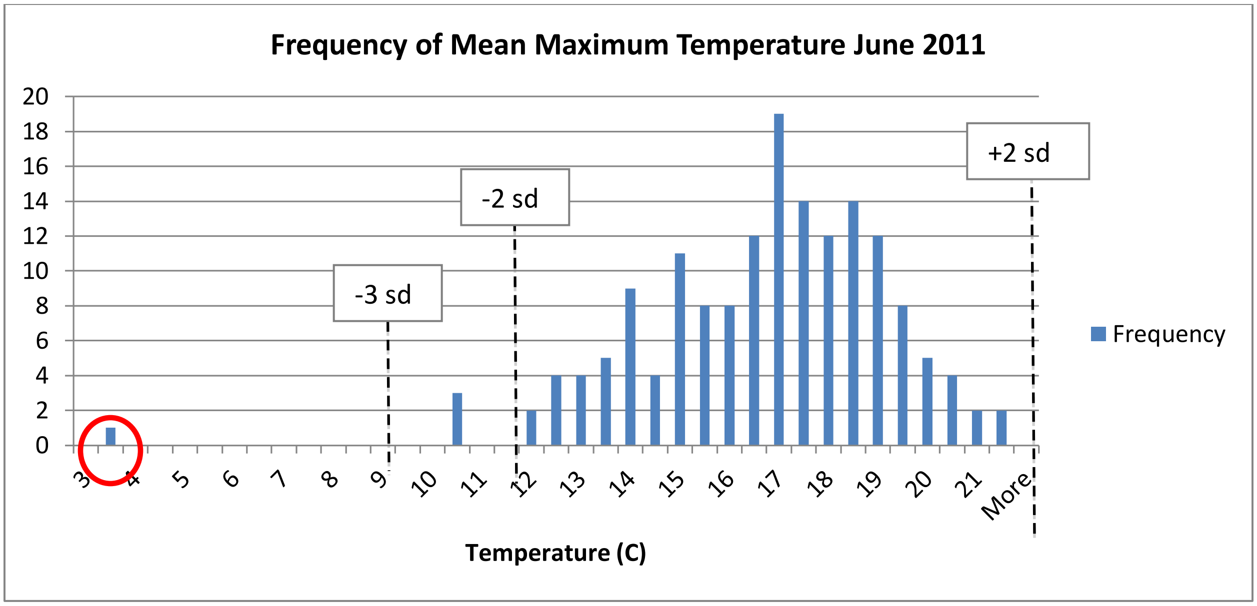
Appendix A. HJ Andrews Temperature Histograms for Mean maximum and Minimum Temperature 166 Sites May 2011 to June 2012 with Standard Deviation (sd) Bars from +/- 2 up to +/- 3 Standard Deviations from the Mean.

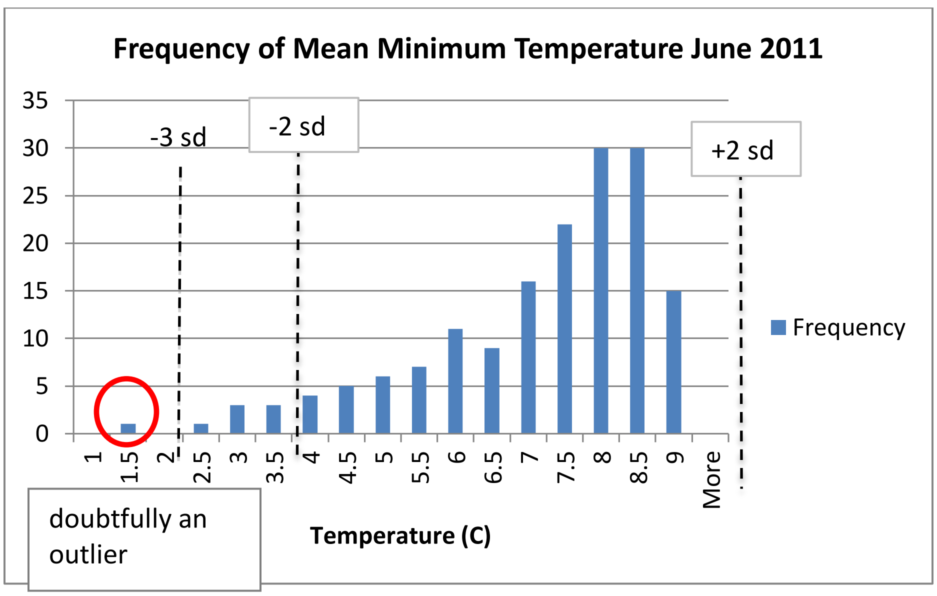
Appendix B - sensor calibration.

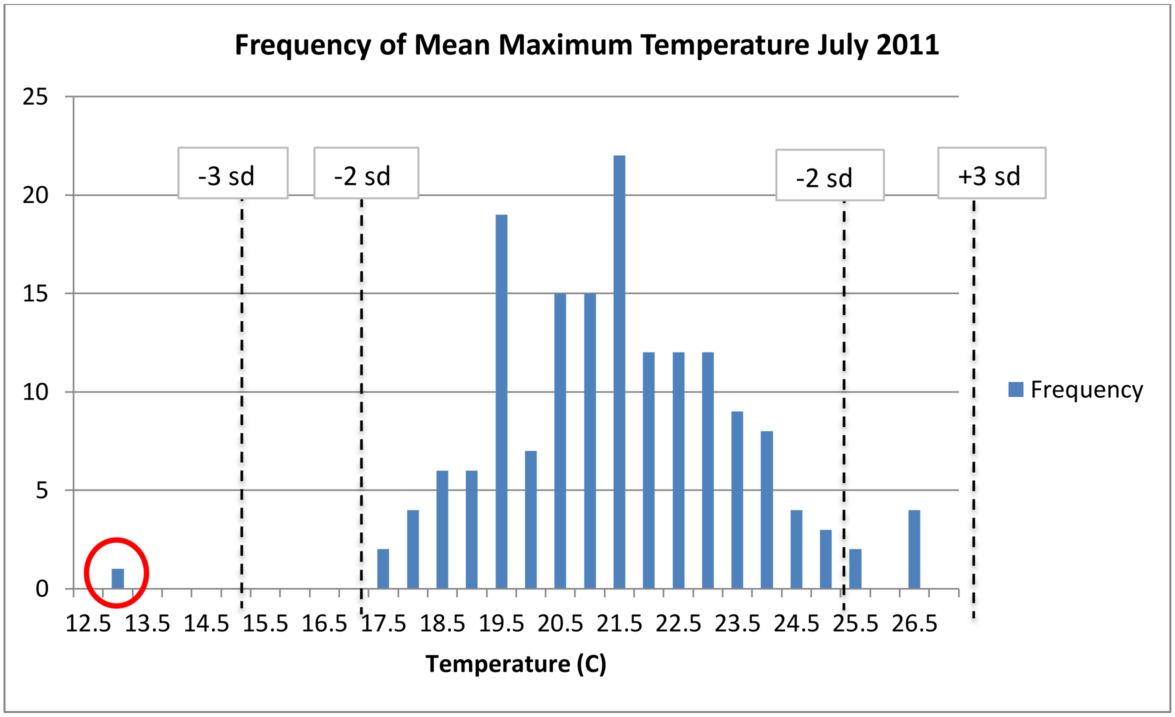
Appendix A. HJ Andrews Temperature Histograms for Mean maximum and Minimum Temperature 166 Sites May 2011 to June 2012 with Standard Deviation (sd) Bars from +/- 2 up to +/- 3 Standard Deviations from the Mean

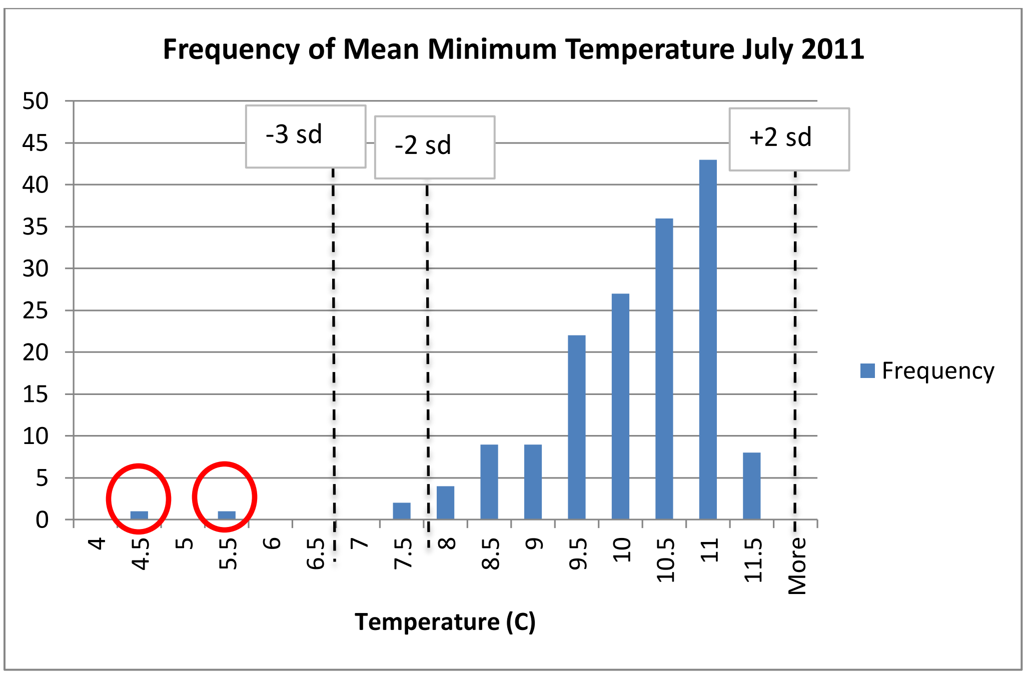


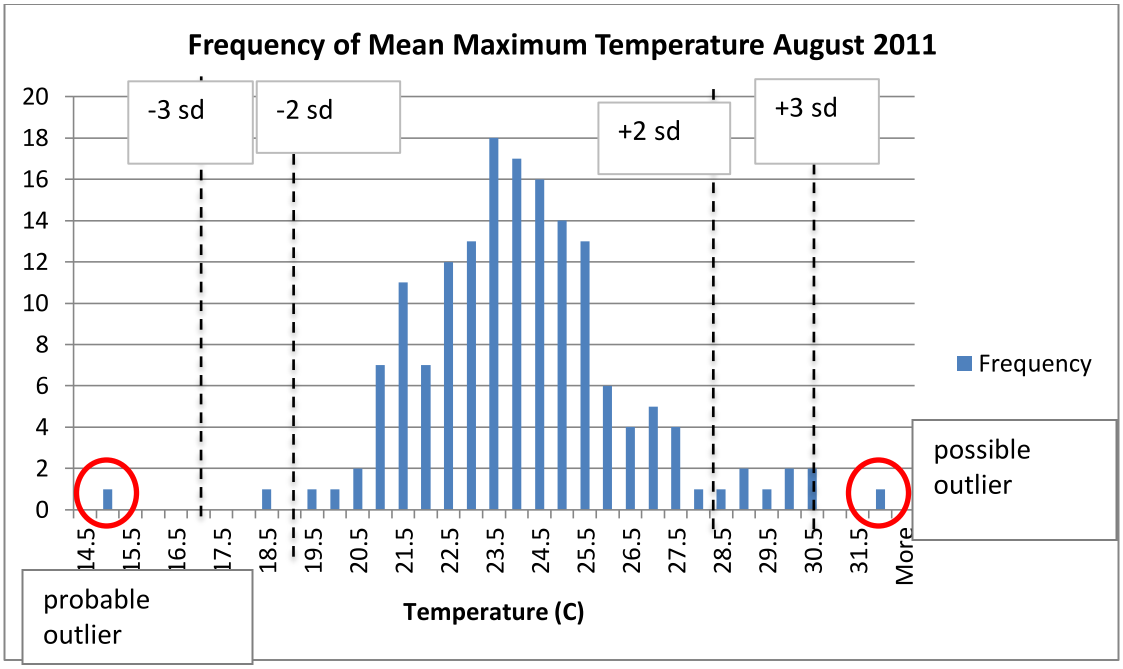


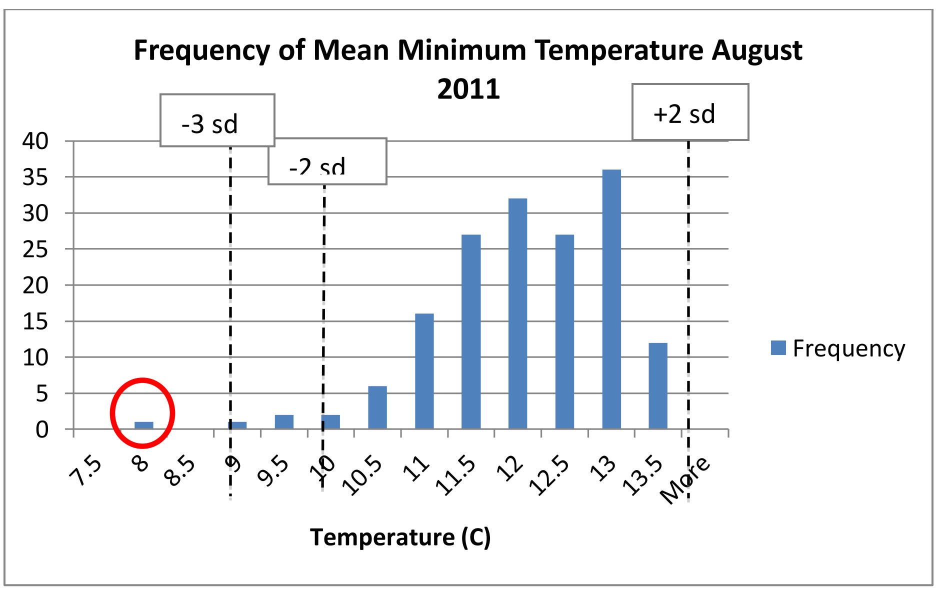

Frequency of Mean Maximum Temperature June 2011
20
18
16
14
12
10
8
6
4
2
0
-3 sd
-2 sd
+2 sd
Frequency
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
More
Temperature (C)

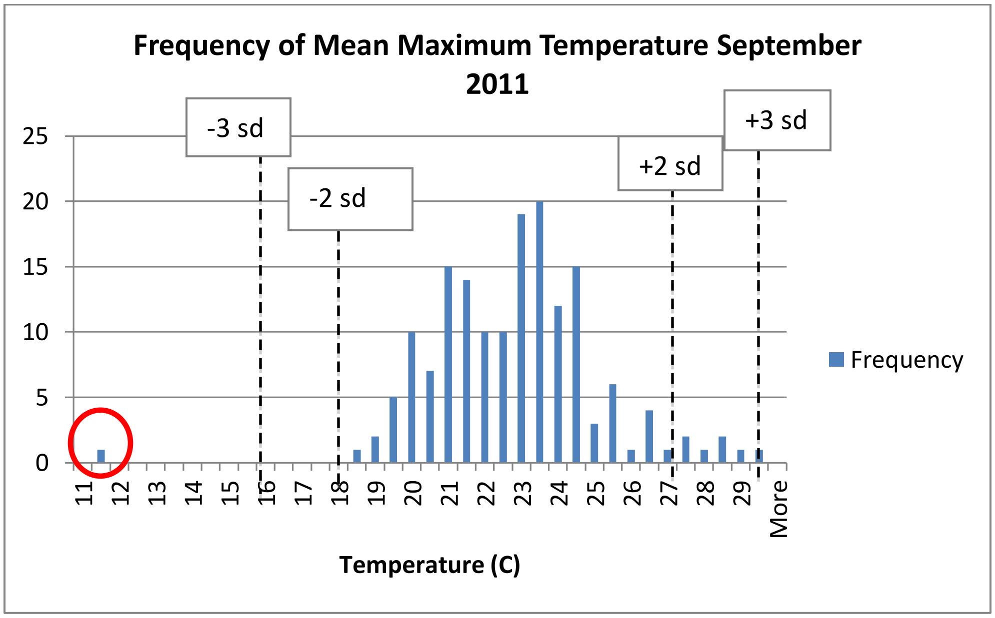

Frequency of Mean Minimum Temperature June 2011
35
30
25
20
15
10
5
0
-3 sd
-2 sd
+2 sd
Frequency
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
More
doubtfully an outlier
Temperature (C)

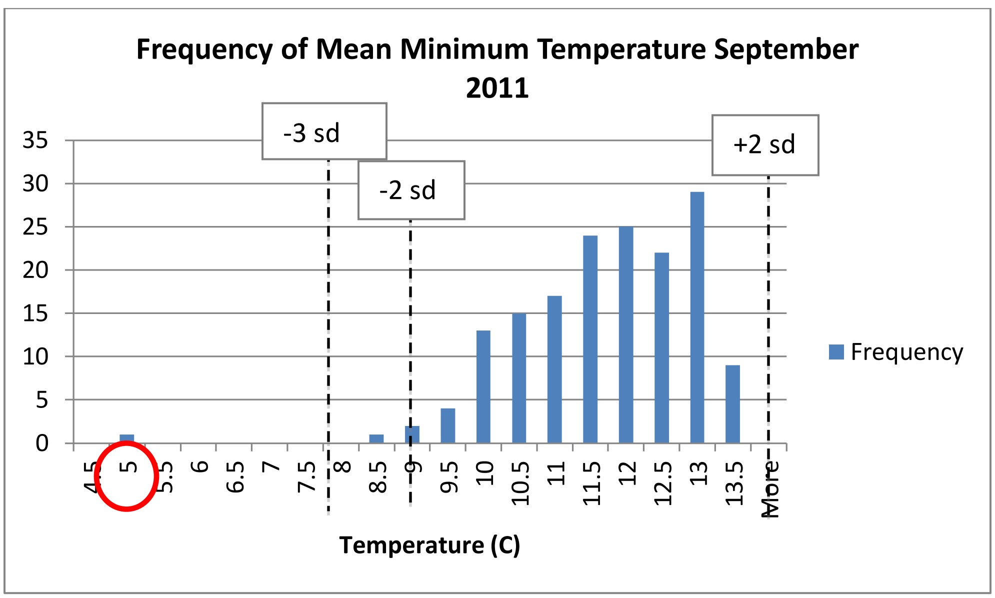

Frequency of Mean Maximum Temperature July 2011
25
20
15
10
5
0
-3 sd
-2 sd
-2 sd
+3 sd
Frequency
12.5 13.5 14.5 15.5 16.5 17.5 18.5 19.5 20.5 21.5 22.5 23.5 24.5 25.5 26.5
Temperature (C)

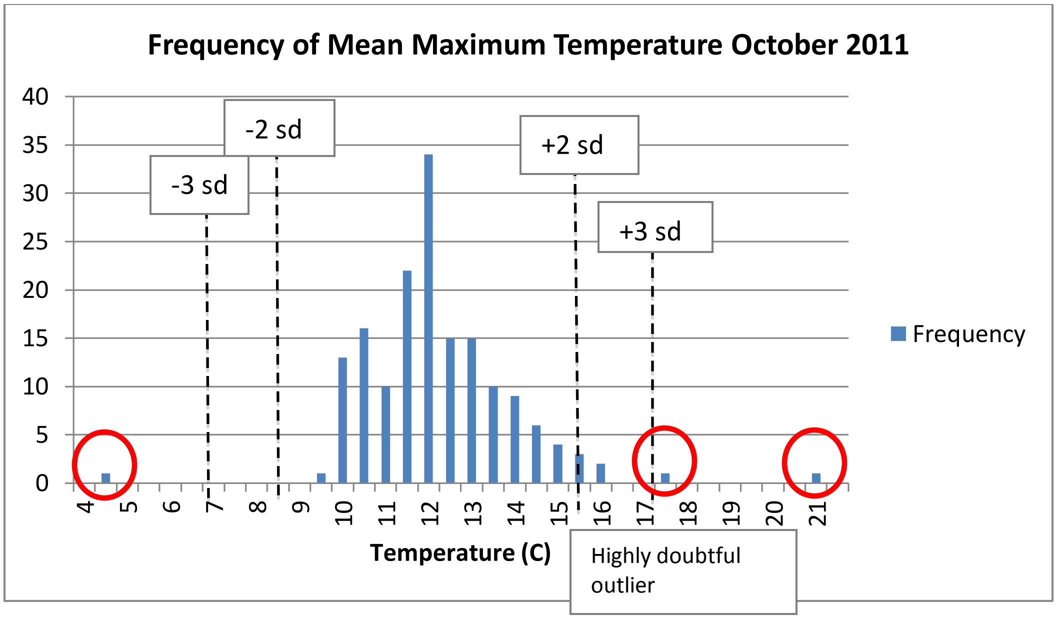

Frequency of Mean Minimum Temperature July 2011
50
45
40
35
30
25
20
15
10
5
0
-3 sd
-2 sd
+2 sd
Frequency
4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10 10.5 11 11.5 More
Temperature (C)

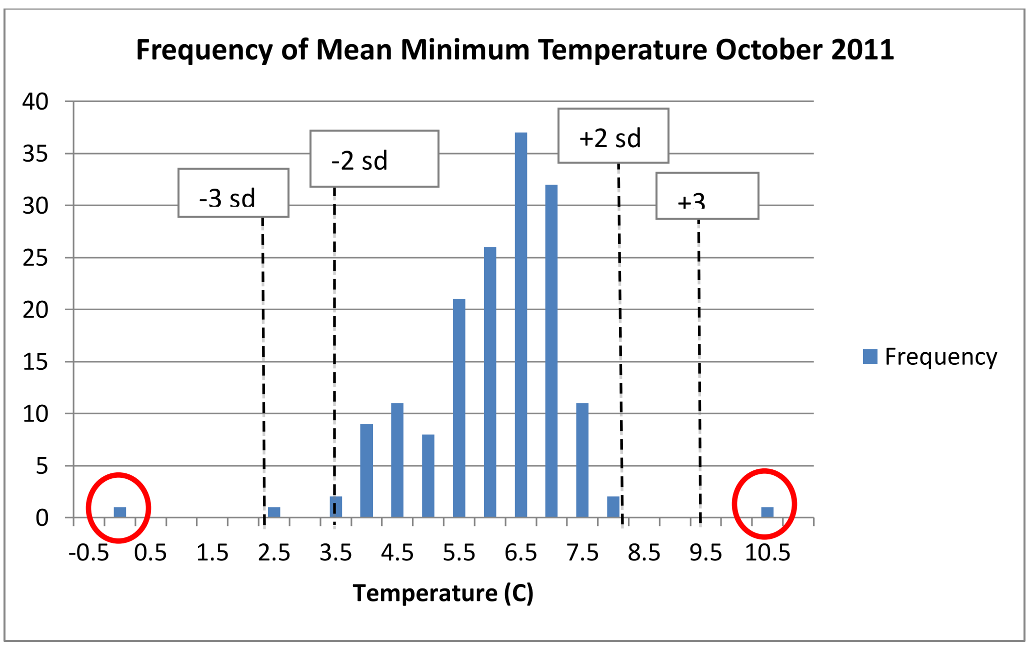

Frequency of Mean Maximum Temperature August 2011
-3 sd
-2 sd
+2 sd
+3 sd
20
18
16
14
12
10
8
6
4
2
0
14.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
22.5
23.5
24.5
25.5
26.5
27.5
28.5
29.5
30.5
31.5
More
Frequency
possible outlier
probable outlier
Temperature (C)

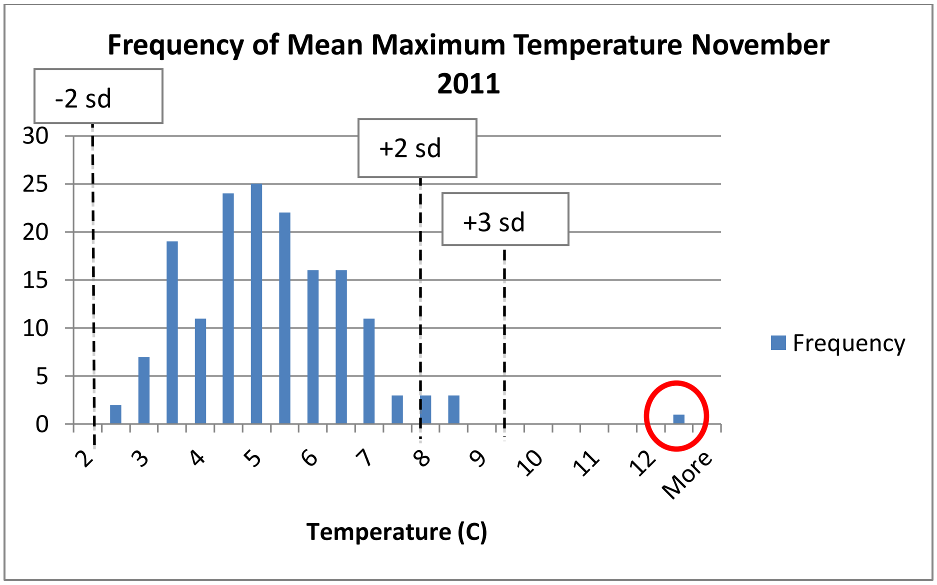

Frequency of Mean Minimum Temperature August 2011
-3 sd
-2 sd
+2 sd
40
35
30
25
20
15
10
5
0
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13
13.5
More
Frequency
Temperature (C)

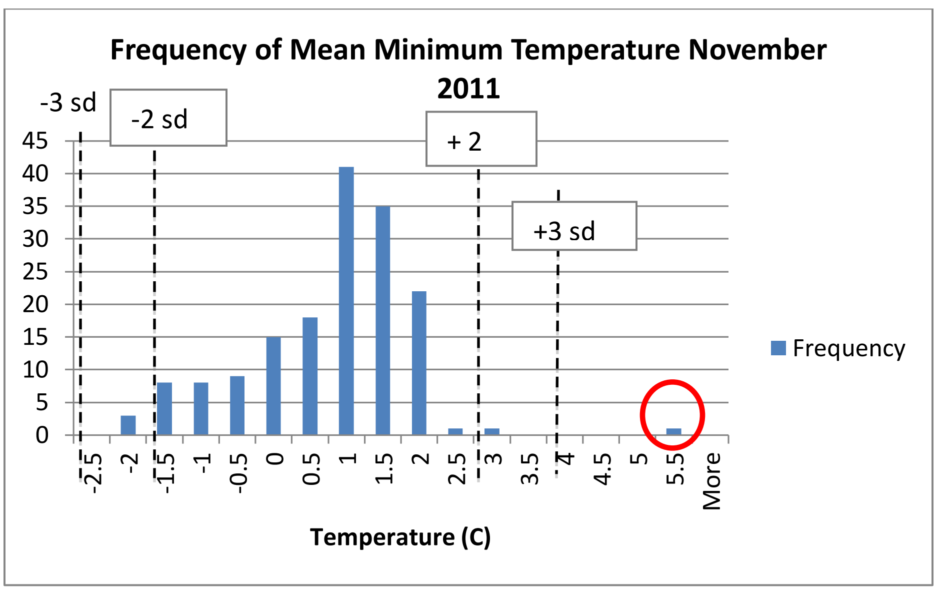

Frequency of Mean Maximum Temperature September 2011
-3 sd
-2 sd
+2 sd
+3 sd
25
20
15
10
5
0
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
More
Frequency
Temperature (C)

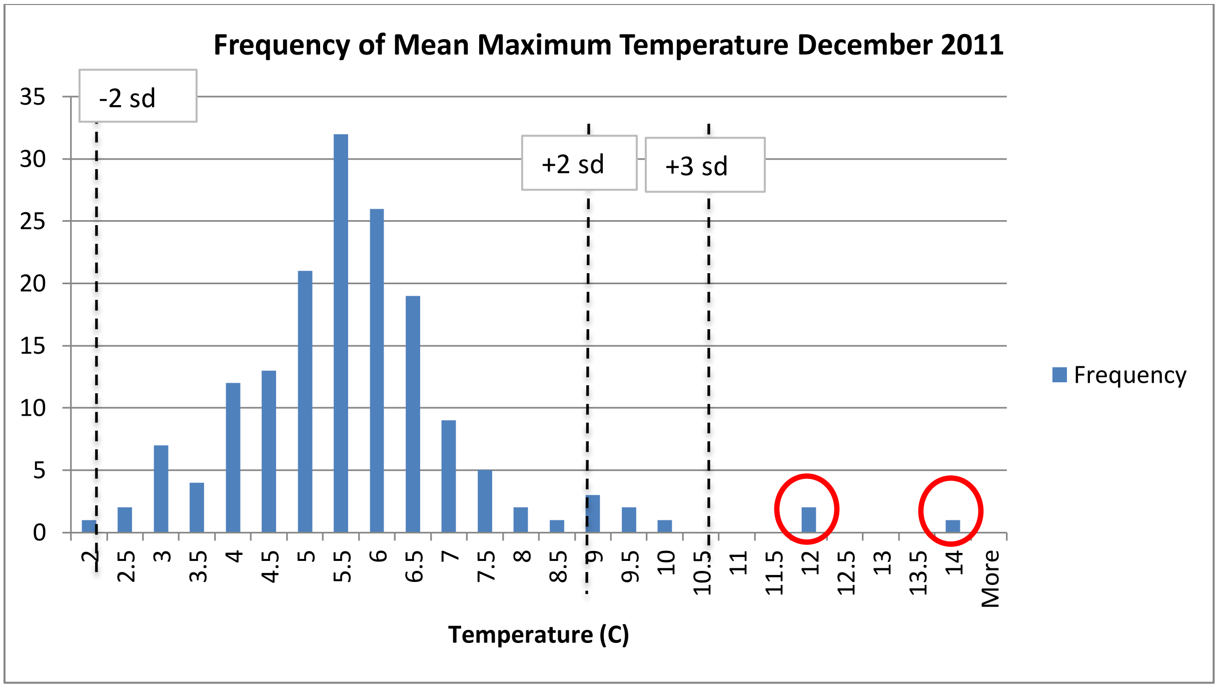

Frequency of Mean Minimum Temperature September 2011
-3 sd
-2 sd
+2 sd
35
30
25
20
15
10
5
0
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13
13.5
More
Frequency
Temperature (C)

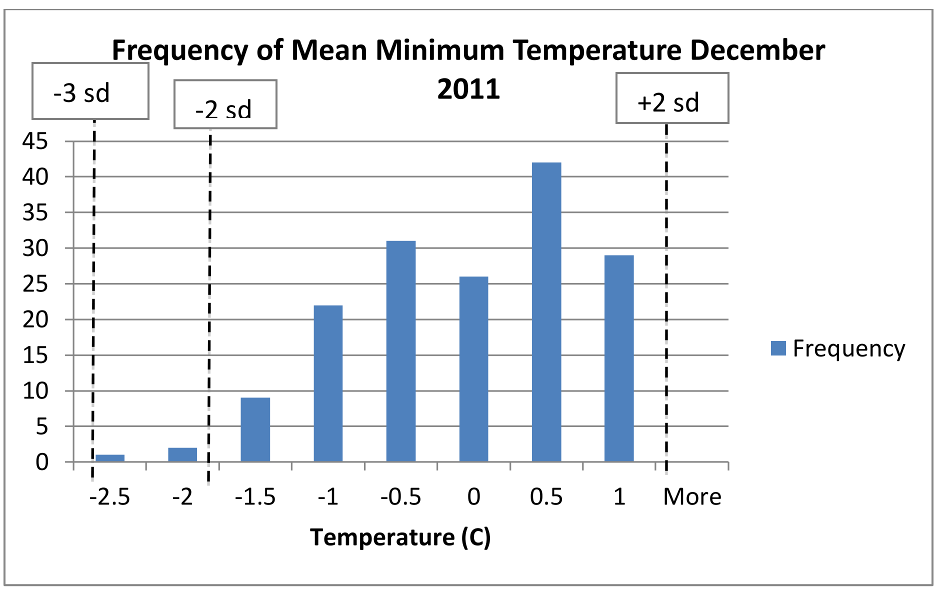

Frequency of Mean Maximum Temperature October 2011
40
35
30
25
20
15
10
5
0
-3 sd
-2 sd
+2 sd
+3 sd
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Temperature (C)
Frequency
Highly doubtful outlier

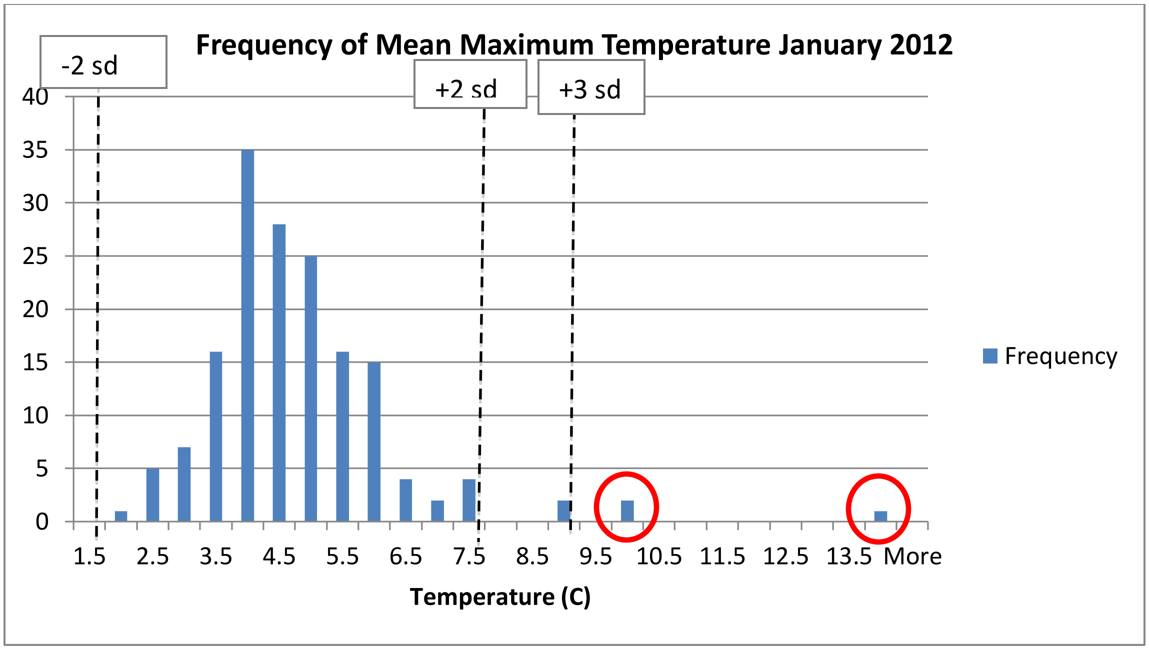

Frequency of Mean Minimum Temperature October 2011
40
35
30
25
20
15
10
5
0
-3 sd
-2 sd
+2 sd
+3
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
Temperature (C)
Frequency

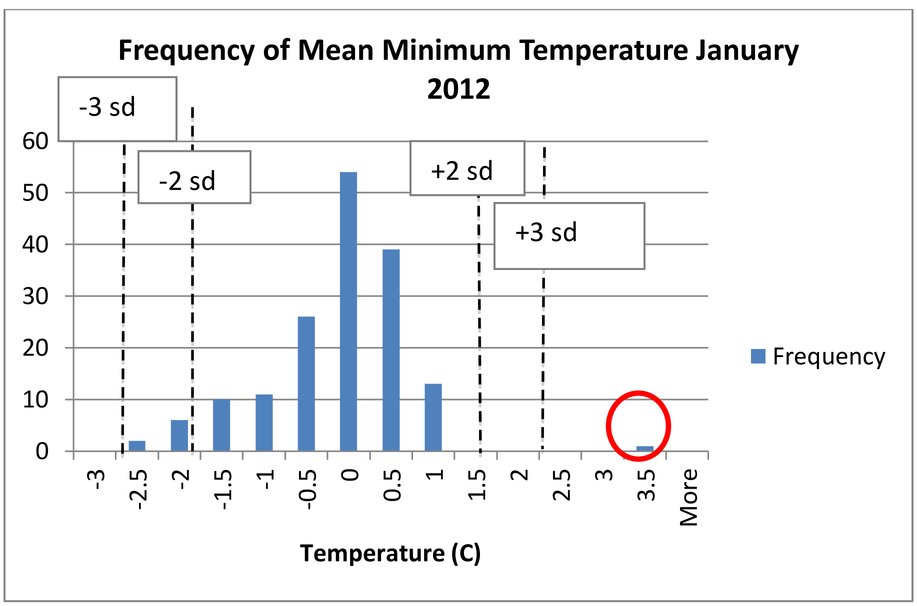

Frequency of Mean Maximum Temperature November 2011
-2 sd
+2 sd
+3 sd
30
25
20
15
10
5
0
2
3
4
5
6
7
8
9
10
11
12
More
Temperature (C)
Frequency

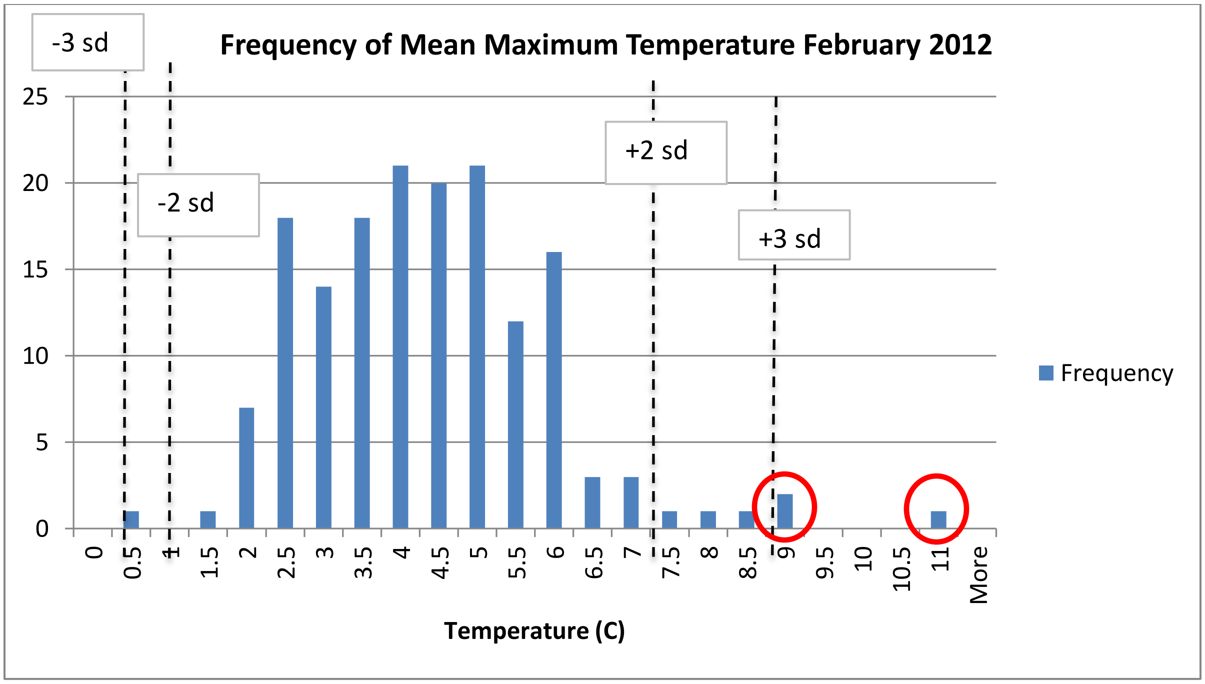

Frequency of Mean Minimum Temperature November 2011
-3 sd
-2 sd
+ 2
+3 sd
45
40
35
30
25
20
15
10
5
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
More
Temperature (C)
Frequency

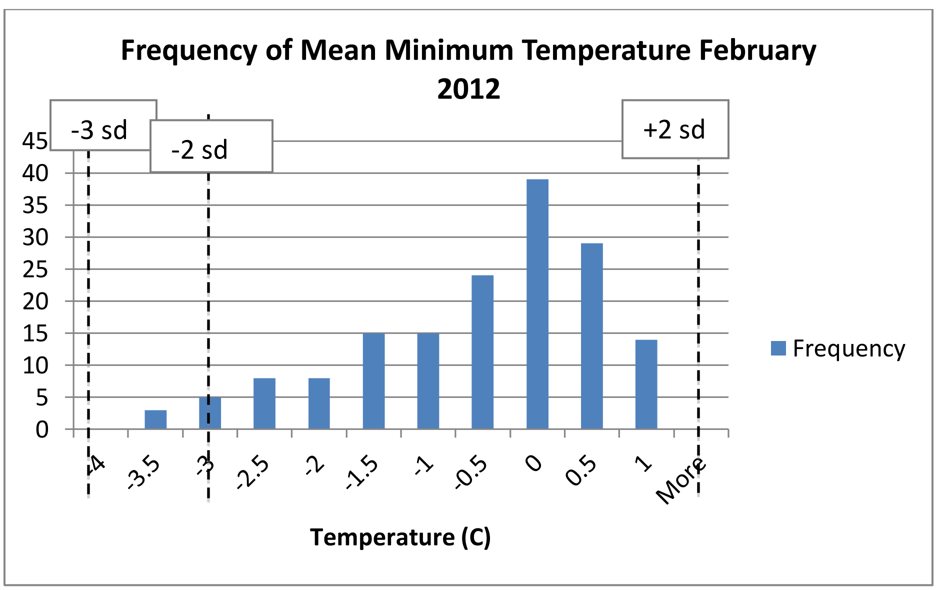

Frequency of Mean Maximum Temperature December 2011
-2 sd
+2 sd
+3 sd
35
30
25
20
15
10
5
0
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13
13.5
14
More
Temperature (C)
Frequency

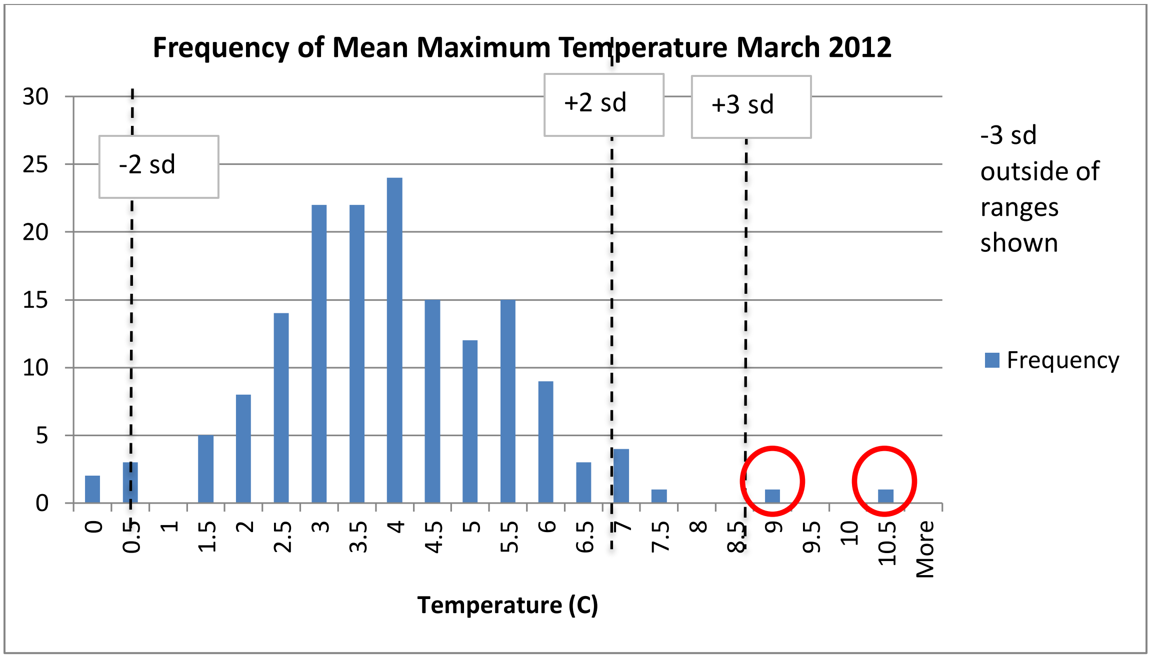

Frequency of Mean Minimum Temperature December 2011
-3 sd
-2 sd
+2 sd
45
40
35
30
25
20
15
10
5
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
More
Temperature (C)
Frequency

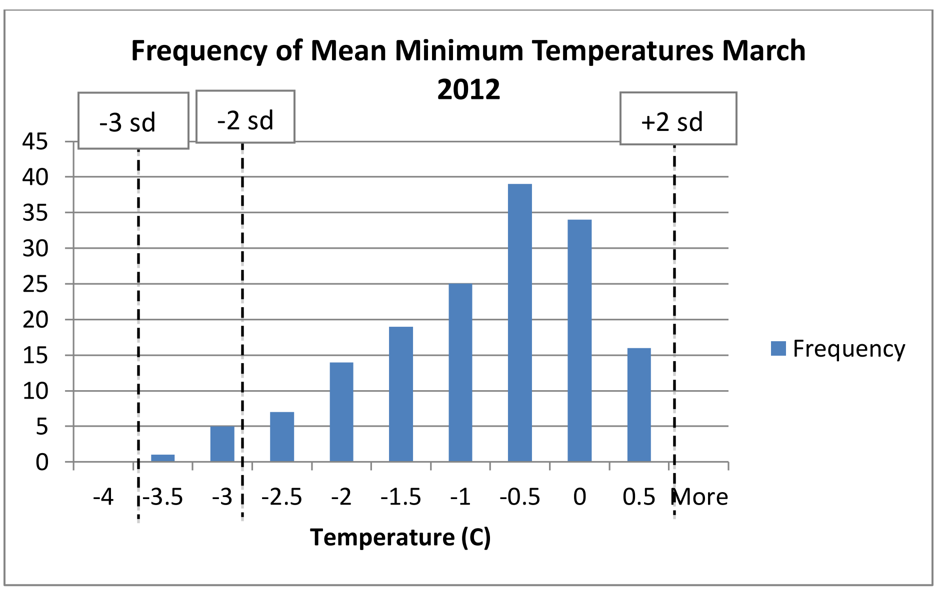

Frequency of Mean Maximum Temperature January 2012
-2 sd
+2 sd
+3 sd
40
35
30
25
20
15
10
5
0
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
More
Temperature (C)
Frequency

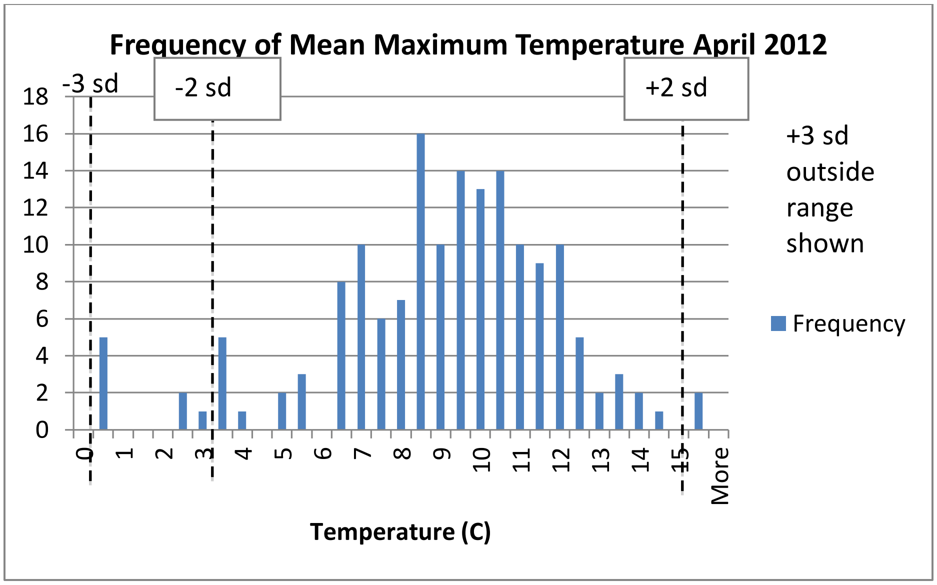

Frequency of Mean Minimum Temperature January 2012
-3 sd
-2 sd
+2 sd
+3 sd
60
50
40
30
20
10
0
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
More
Temperature (C)
Frequency


Frequency of Mean Maximum Temperature February 2012
-3 sd
-2 sd
+2 sd
+3 sd
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
More
Temperature (C)
Frequency

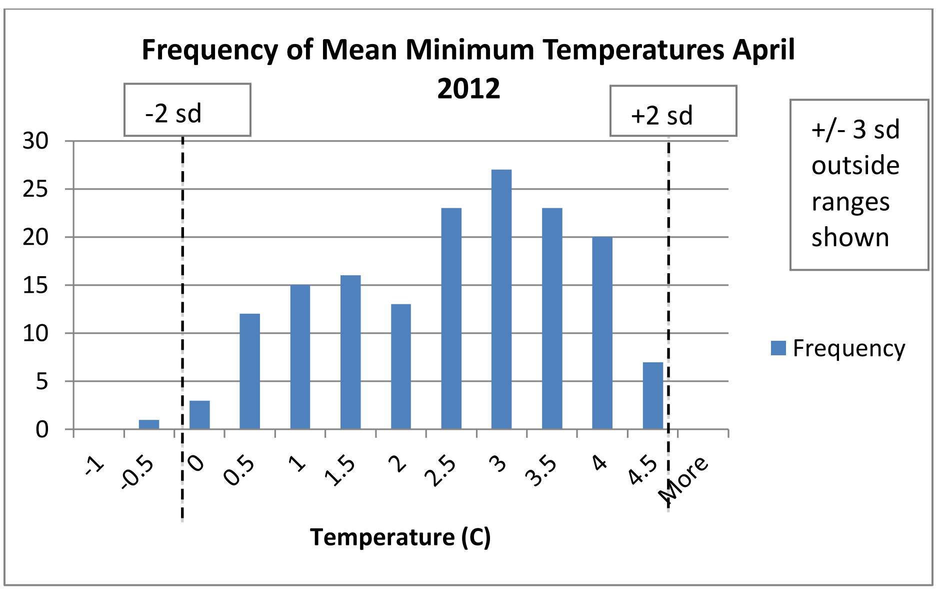

Frequency of Mean Minimum Temperature February 2012
-3 sd
-2 sd
+2 sd
45
40
35
30
25
20
15
10
5
0
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
More
Temperature (C)
Frequency


Frequency of Mean Maximum Temperature March 2012
30
25
20
15
10
5
0
-2 sd
+2 sd
+3 sd
-3 sd outside of ranges shown
Frequency
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
More
Temperature (C)

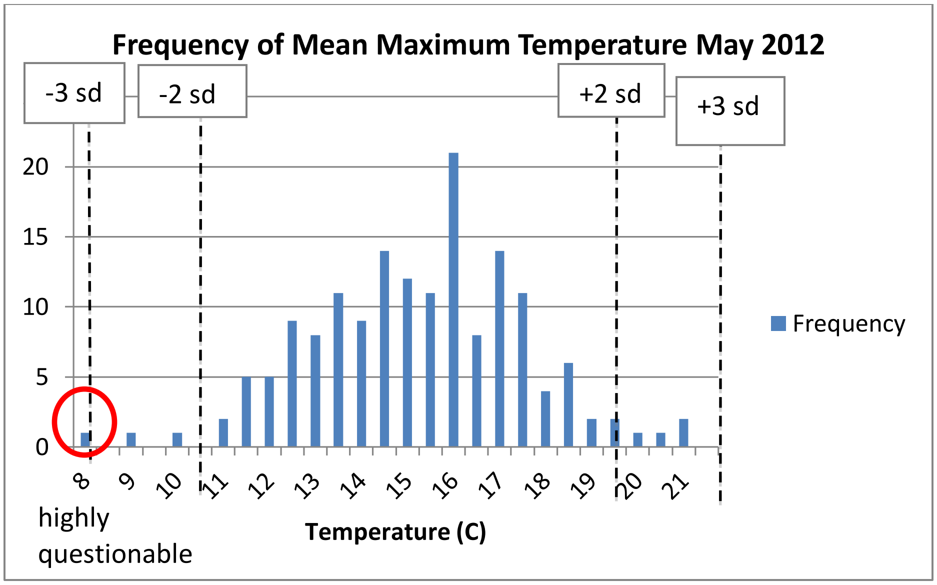

Frequency of Mean Minimum Temperatures March 2012
-3 sd
-2 sd
+2 sd
45
40
35
30
25
20
15
10
5
0
Frequency
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
More
Temperature (C)

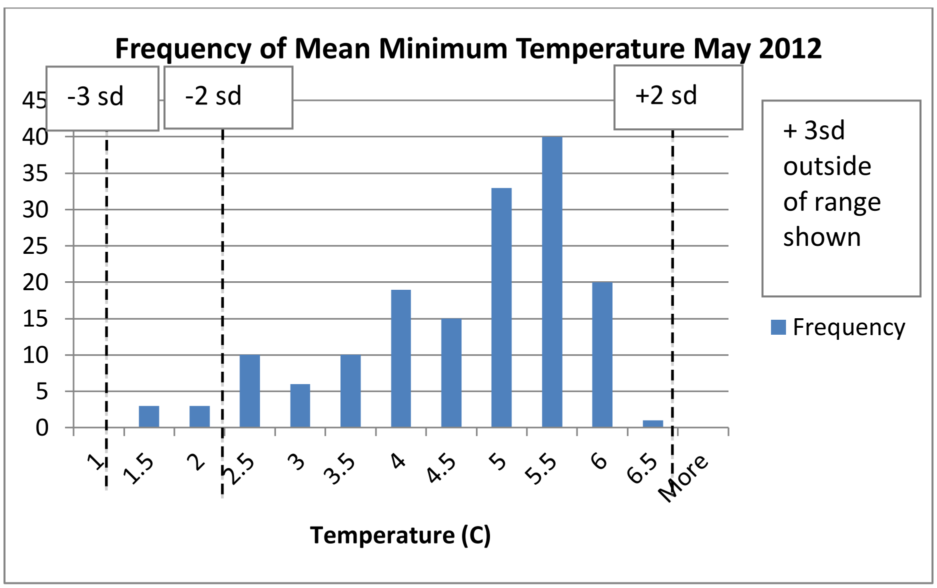


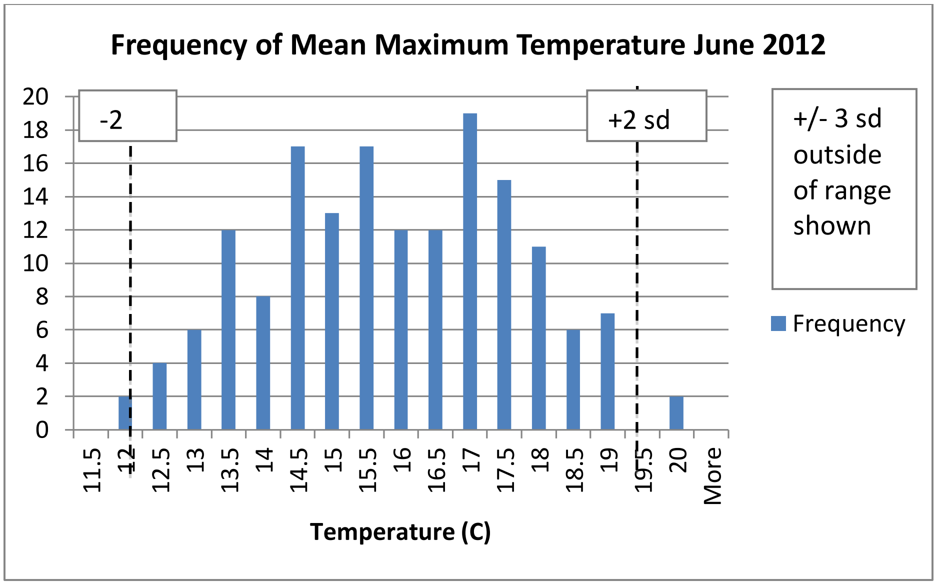
Frequency of Mean Maximum Temperature April 2012
-3 sd
-2 sd
+2 sd
+3 sd outside range shown
Frequency
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
More
Temperature (C)



Frequency of Mean Minimum Temperatures April 2012
-2 sd
+2 sd
+/- 3 sd outside ranges shown
Frequency
30
25
20
15
10
5
0
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
More
Temperature (C)


Frequency of Mean Maximum Temperature May 2012
-3 sd
-2 sd
+2 sd
+3 sd
20
15
10
5
0
8
9
10
11
12
13
14
15
16
17
18
19
20
21
highly questionable
Temperature (C)
Frequency

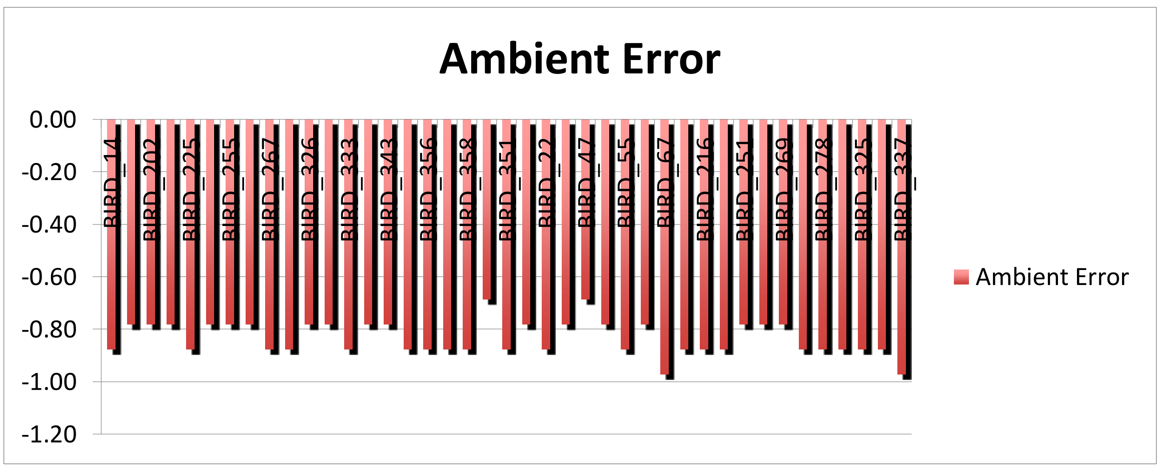

Frequency of Mean Minimum Temperature May 2012
-3 sd
-2 sd
+2 sd
+ 3sd outside of range shown
45
40
35
30
25
20
15
10
5
0
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
More
Temperature (C)
Frequency

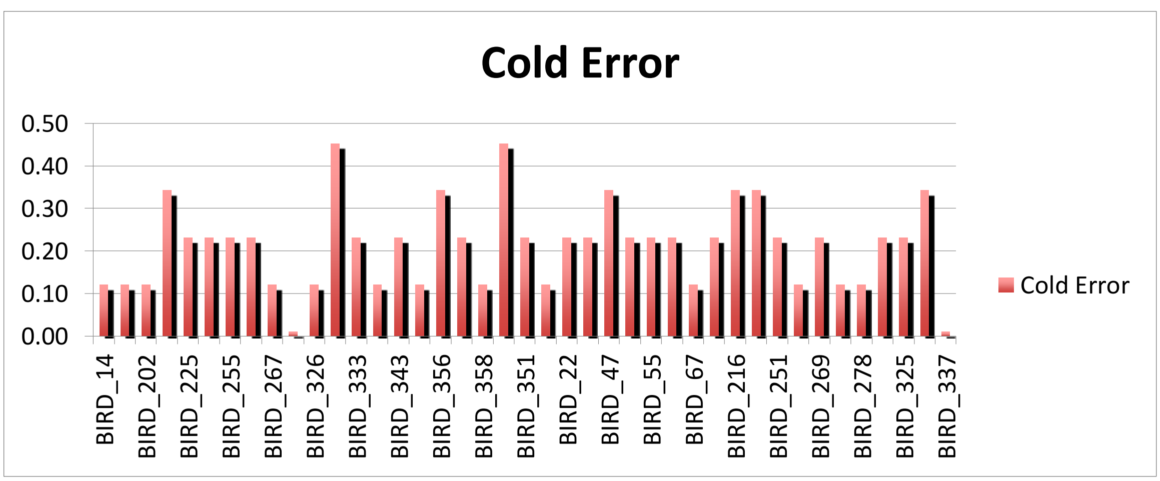

Frequency of Mean Maximum Temperature June 2012
20
18
16
14
12
10
8
6
4
2
0
-2
+2 sd
+/- 3 sd outside of range shown
Frequency
11.5
12
12.5
13
13.5
14
14.5
15
15.5
16
16.5
17
17.5
18
18.5
19
19.5
20
More
Temperature (C)

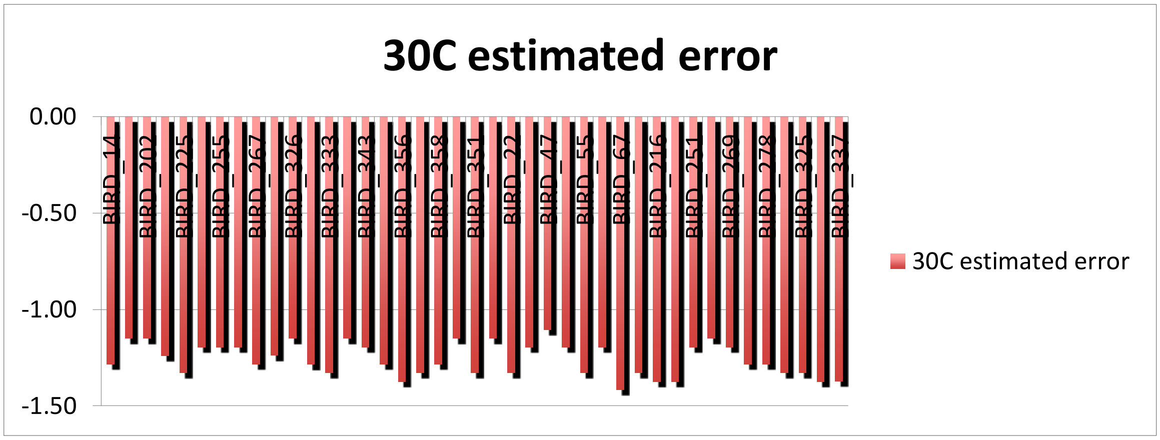
Appendix B - sensor calibration.

The Hobo temperature sensors were calibrated at the HJA Headquarters overnight before being replaced back to the BIRD sites the following day. The calibration consisted of an ice bath and a room-temperature comparison. The instrument used in the calibration was a Fluke thermometer Type K with an accuracy of +/- 0.05 percentage of reading + 0.5 degrees Fahrenheit and a resolution of 0.1. Evan Miles assisted in the calibration and analyzed the results and found that all sensors were accurate within +/- 0.5^{o} C within three standard deviations of the mean.

Figure B-1. (a) Ambient error. Difference between sensor reading and calibrated ambient air temperature (21.3 °C). (b) Cold error. Difference between sensor reading and ice bath temperature (0 °C). (c) 30 °C error. Extrapolated difference between sensor reading and 30°C air temperature, based on slope of error at 0°C and 21.3°C. Calculations by Evan Miles. Measurements made by Brian Wilson and Evan Miles July 21, 2011.






30C estimated error
0.00
-0.50
-1.00
-1.50
BIRD_14
BIRD_202
BIRD_225
BIRD_255
BIRD_267
BIRD_326
BIRD_333
BIRD_343
BIRD_356
BIRD_358
BIRD_351
BIRD_22
BIRD_47
BIRD_55
BIRD_67
BIRD_216
BIRD_251
BIRD_269
BIRD_278
BIRD_325
BIRD_337
30C estimated error