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Analysis of Temperature Patterns in Channel Islands National Park

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Contents

Executive Summary

From April 2009 – September 2011, a research team coordinated jointly by the Nature Conservancy and the National Park Service deployed 95 temperature dataloggers on Santa Cruz and Santa Rosa Islands in Channel Islands National Park, California. After the project's completion, ***Walking Shadow Ecology*** was contracted to analyze the temperature data. After a detailed quality checking and data validation process, the data were made available through an automated, web-based interface (www.ClimateAnalyzer.org/dataloggers/map_html) that allows the user to make graphs, tables, and query the data in a variety of ways. In addition to describing the methods used in data analysis, this technical report provides instructions for use of the web interface. It also analyzes the influence of elevation and aspect on temperature throughout the islands, provides 47 pages of interpolated "heat maps" that graphically illustrate temperature patterns for each month, and makes recommendations for future study.

Introduction

From April 2009 – September 2011, a research team coordinated jointly by the Nature Conservancy and the National Park Service deployed 95 temperature dataloggers on Santa Cruz and Santa Rosa Islands in Channel Islands National Park, California. The total length of the temperature record was 15 – 26 months, depending on location. These dataloggers took measurements at recurring intervals that varied from 7 – 21 minutes. They were distributed evenly across the landscape and spanned an elevation range of 0 – 660 meters (Figure 1).

Figure 1. Map showing the locations of temperature dataloggers deployed in Channel Islands National Park during 2009 – 2011. White stars indicate temperature dataloggers deployed as part of the project described here. Red stars are permanent weather stations.

The objectives of the project were to supplement the temperature data provided by the Islands' weather stations (red stars in Figure 1), and to elucidate temperature patterns across the landscape.

After the project's completion, ***Walking Shadow Ecology*** was contracted to analyze the temperature data. Only basic summaries are provided here. Additional analysis and access to the quality-checked and synchronized data are available at www.ClimateAnalyzer.org/dataloggers/map_html. Menus on that web page provide daily values, monthly summaries, graphs, standard indices such as growing degree day estimates for each datalogger, and a query tool that determines which dates in the record exceeded user-defined temperature thresholds. Additional data and GIS layers can be downloaded from the links provided in the Results section of this report.

In addition to providing basic summaries of the data, this technical report provides interpretation of the spatial patterns observed and makes recommendations for future study.

Methods

Equipment and Siting

The dataloggers used in this study were “Hobo pendant temp/light” dataloggers, part # UA – 002 -64 (Figure 2), available from Onset Computing (www.Onsetcomp.com). According to the manufacturer, this device has an accuracy of +/- 0.53 degrees centigrade (+/- 0.95 degrees F) and provides resolution of 0.14 degrees C (0.25 F). The dataloggers were hung inside the canopy of vegetation (trees or bushes; Figure 2) and shade was provided by the leaves and branches in most locations during most typical days (see next section). The length of time between temperature measurements varied from 7 – 21 minutes depending on location. The first dataloggers were deployed during April 2009 on Santa Cruz Island and July 2009 on Santa Rosa Island. All dataloggers were removed from the field during July 2011. Temperatures were recorded in Degrees Fahrenheit, and because that temperature scale is more familiar to most residents of the United States, the data were not converted into metric (SI) units for this report.

Figure 2. LEFT: Manufacturer’s photograph of the datalogger model used in this study. RIGHT: A typical deployment location, marked with the orange flagging at the end of red arrow (National Park Service Photograph).

Initial Quality Checking and Removal of Bad Data Using Waveform Screening

The raw dataset consisted of roughly 10.2 million temperature measurement s in 197 separate files. Before these files could be synchronized and made commensurate with each other, it was necessary to remove errors in the data that were due to a number of common problems associated with temperature dataloggers. These problems include: (1) low battery conditions, which produce extreme temperature measurements or systematically biased data, (2) faulty thermistors or other damage to the datalogger, which produce erroneous and unpredictable readings, and finally, (3) solar heating due to lack of shade, which at some locations greatly inflated the temperature measurements. All of these problems have been encountered previously by the author of this report during projects that used the same model of datalogger.

Because the dataset was very large (approximately 10.2 million measurements), it was impossible to manually examine the plots for every day in the record. Instead, ***Walking Shadow Ecology*** developed custom software that analyzed the data from each datalogger in 24 hour steps and detected deviations from an expected diurnal temperature cycle. When the software detected suspected problems, it generated plots of the data for the suspect day as well as the days before and after the potential problem (Figure 3). Human screeners then examined the plots and deleted days as needed. Rather than attempting to edit out single points or to estimate missing values, entire 24 hour pieces of data were removed from the record and replaced with "9999" missing value symbols. This was done because the ultimate goal of the processing was to make the data from the present study commensurate with local weather stations, and since most weather stations (with the exception of Remote Automated Weather Stations) record only daily maximum and minimum values, a single erroneous or incorrectly estimated point in the datalogger record could introduce significant error into the daily record that is compared to the weather stations. Furthermore, since only daily maximum and minimum values were ultimately going to be extracted from the record (see next section), removing 24 hours of data resulted in the loss of only two data points from the final quality-checked dataset. The number of days deleted from a datalogger's record ranged from 0 – 34 days.

Figure 3 shows sample diagnostic plots from the screening process. Panel A contains a relatively clean diurnal temperature cycle with no abrupt increases or decreases, a high degree of waveform similarity to other days in the record (yellow and green dotted lines), and coincidence of increasing temperature with increasing light level. Panel B contains noisier data, with temperature spikes that coincide with spikes in light levels. Data of this type was rejected if it was unique in the record, but was retained if the same pattern of solar heating was seen in the majority of days at a particular location. Stricter quality checking procedures might justifiably reject data resembling that shown in Panel B, but such a procedure in the present study would have resulted in rejection of a large portion of the dataset, particularly on Santa Cruz Island. Without detailed knowledge of the location in which each datalogger was placed, “the benefit of the doubt” was exercised in assuming that the temperatures measured were representative of the habitat selected by the maintainers of the equipment, and that incident warming caused by changing sun angles are part of the conditions of interest. Panel C in Figure 3 shows an isolated spike that occurred in only a few days of the record and was consequently deleted. Panels D – F show examples of extreme values that were attributed to equipment faults and removed. Notice in Panels D and E that measurements ranging from – 20F to 800 F were encountered. When data of this type was found, the record from the datalogger containing it was given closer scrutiny to ensure that additional errors were not being missed by the screening.

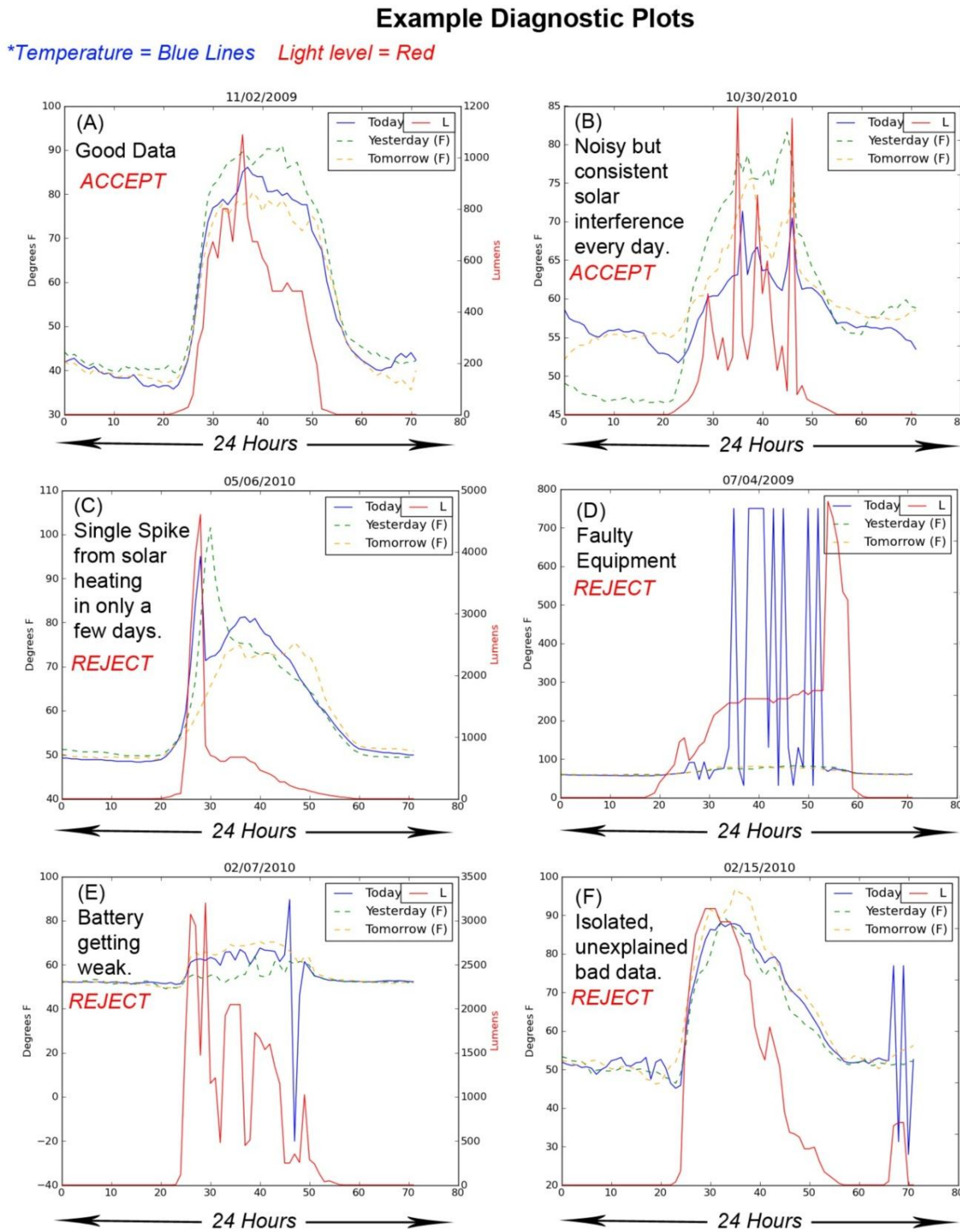


Figure 3. Example diagnostic plots generated as part of the data quality checking. Each plot shows 24 hours of data. Blue lines are temperature values for the date indicated in the title. Green dotted lines are temperatures for the previous day. Yellow dotted lines are temperatures for the next day. Red lines are light levels. “ACCEPT” or “REJECT” indicates whether the day’s data passed the QC.

Screening of Daily Maximum and Minimum Values

The next step in data processing consisted of extraction of the maximum and minimum value for each day and generation of a new set of diagnostic plots, which were manually screened for spikes and trends (Figure 4). This was accomplished by using automated scripts written in the Python programming language (www.python.org) that transformed the datalogger data into the format used by the Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) weather station network (http://www.wcc.nrcs.usda.gov/snow/) and subsequently plotting the data with the Climate Data Summarizer, an analysis tool that ***Walking Shadow Ecology*** offers as a free download at this web address: http://www.yellowstoneecology.com/research/COOP_data.html. Using this tool and the data files that accompany this report (see Results), anyone can reproduce or expand upon the daily screening described here.

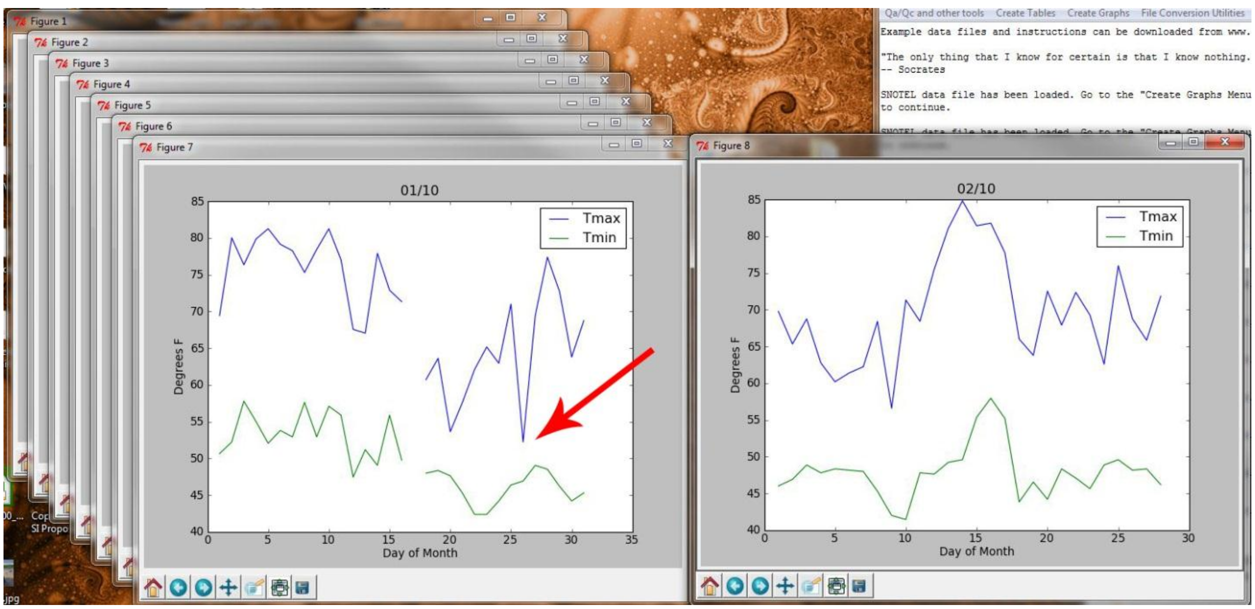


Figure 4. Screenshot of the daily screening process. The graph shown at left contains daily maximum (blue lines) and minimum (green lines) temperatures for January 2010. A break in the plot indicates data that was removed during the waveform screening (previous section of this report). The red arrow marks a dip in daily maximum temperature that is not matched by a dip in daily minimum temperature. This mismatch would merit closer examination of the original data for that day using the waveform methods described above.

As shown in Figure 4, days that showed abrupt deviations from the rest of the month were marked for re-examination with the waveform analysis methods illustrated in Figure 3. If diagnostic plots generated by that re-examination showed any of the faults shown in Figure 3, the day's data was deleted. Similarly, the daily plots were examined for a systematic, linear increase or decrease in temperature (encountered in data collected with the same model of datalogger as part of other field work conducted by ***Walking Shadow Ecology***). No such systematic biases were found in the present study.

Testing of Relationships Between Elevation, Aspect, and Monthly Average Temperatures

Using GPS coordinates provided by the Nature Conservancy and the National Park Service, the location of every datalogger was mapped in ArcGIS version 10 (www.ESRI.com), and elevation and aspect (direction in which the slope is facing, expressed as a compass heading in degrees) were extracted from a USGS 30 meter Digital Elevation Model (DEM). Average daily maximum temperature (Tmax) and average daily minimum temperatures (Tmin) were calculated for each month at each datalogger as the arithmetic mean of the maximum and minimum values for each day. Averages were not calculated for a datalogger during any month that had more than 5 missing days. Linear regressions and scatter plots were used to determine the strength of the relationship between the average temperatures and elevation or aspect. Following an initial investigation that included only elevation, more detailed scatter plots were performed on subsets of the data that were divided according to aspect and smaller regions within the islands. For this second analysis each datalogger was classified into North, South, East, or West facing slopes, using the compass heading ranges North = $316^{o} – 45^{o}$, East = $46^{o} – 135^{o}$, South = $136^{o} – 225^{o}$, West = $226^{o} – 315^{o}$. All regressions and scatter plots were performed with the R statistical programming language (http://www.r-project.org/). The R code used appears in Appendix 2. Lapse rates (rate of temperature increase or decrease as a function of elevation) are reported in units of Degrees F per 100m. Even though this mixing of imperial and scientific units may seem non-standard, it is adopted here because the two data sets (temperature readings from dataloggers or weather stations and elevation from Digital Elevation Models) are readily available to Channel Islands National Park staff in these units. Thus the results presented here can be interpreted in a GIS environment without manipulation.

Interpolation of Monthly Temperature Averages and Creation of "Heat Maps"

Monthly averages for each datalogger were imported to ArcGIS, joined to the appropriate point location, and interpolated using Inverse Distance Weighting (IDW). A range of input settings for the IDW algorithm were tested on the July 2009 Tmin data from Santa Cruz Island until settings were chosen that minimized the difference between the value predicted for the raster cell (gridded map location) containing the island's Remote Automated Weather Station (RAWS) and the actual monthly average calculated from the weather station's recorded data. During July 2009, the Santa Cruz Island RAWS reported average daily minimum temperature (Tmin) of 51.94 F (http://www.climateanalyzer.org/medn/raws/santa_cruz_raws/) and the predicted July

2009 Tmin value for the raster cell containing the RAWS was 57.43 F. The IDW used to generate the raster was programmed to include at least 6 surrounding dataloggers and to dilute the effect of each datalogger on a raster cell as function of the horizontal distance between the cell and the datalogger raised to the fourth power. The differences between the predicted temperatures from the raster cells generated by IDW and the actual readings from official weather stations are elaborated in the Discussion section of this report. It is important to note that this interpolation method does not account for air flow patterns or topography. It uses a weighted average that considers only the horizontal distance between the raster cells and the dataloggers included in the average.

Results

Web Access to the Data

Only basic summaries are provided in this report. Readers interested in obtaining the daily data for each datalogger, monthly averages, Accumulated Growing Degree Day (AGDD) estimates, and other summaries, can visit the web interface available at this address: http://www.climateanalyzer.org/dataloggers/map_html

Clicking on the map provided by that web page will lead the user to the data for each datalogger as shown in Figure 5.

Figure 5. Screenshot of the map-based web access to the datalogger data available from www.ClimateAnalyzer.org. The map can be moved and zoomed. Clicking on one of the green symbols leads the user to the data for a particular location. The other symbols on the map are official weather stations, which can be summarized and queried in the same way as the dataloggers.

After navigating through the menu options that follow the map, the user can generate a variety of tables and graphs, including a query of the data that provides the dates that exceed user defined temperature thresholds. For example, Table 1 shows the dates at datalogger 2323001 that had minimum temperature less than 40 F or maximum temperature greater than 80 F.

Datalogger 2323001

Year	Total # Days (consecutive or not) with Tmin <= 40 (F)	Consecutive dates with Tmin <= 40 (F)	Total # Days (consecutive or not) with Tmax >= 80 (F)	Consecutive Dates with Tmax >= 80 (F)
2009	Insufficient Data	12/09;	Insufficient Data	04/18 - 04/21; 05/01; 06/04; 06/13 - 06/14; 06/16; 06/18; 06/24; 07/04; 07/07 - 07/08; 07/11; 07/15; 07/19; 07/26; 07/30; 08/22; 08/26 - 08/30; 09/01 - 09/04; 09/07; 09/09 - 09/10; 09/15 - 09/16; 09/18 - 09/19; 09/23 - 09/26; 09/30 - 10/02; 10/05 - 10/07; 10/10 - 10/11; 10/15 - 10/17; 10/20 - 10/26; 10/29 - 11/03; 11/05; 11/07 - 11/08; 11/10; 11/19; 11/24 - 11/26; 12/19;
2010	6	11/24; 11/28 - 11/29; 12/29 - 12/31;	160	01/03; 01/06; 01/27 - 01/28; 02/03; 02/12; 02/14 - 02/17; 03/15 - 03/17; 03/19 - 03/20; 03/27 - 03/28; 04/06 - 04/07; 04/18 - 04/19; 04/25; 05/03; 05/15 - 06/23; 06/27 - 06/28; 06/30 - 07/02; 07/09; 07/11 - 07/25; 07/28 - 08/10; 08/12 - 08/27; 08/31 - 09/06; 09/10 - 09/18; 09/20; 09/23 - 10/03; 10/08 - 10/14; 10/20; 11/01 - 11/05; 11/12; 11/14 - 11/16; 11/18;
2011	Insufficient Data	01/01; 01/03; 01/09 - 01/10; 02/17; 02/19 - 02/24; 02/26 - 03/01; 03/20 - 03/22; 03/24; 04/07 - 04/10; 04/13;	Insufficient Data	01/15 - 01/18; 01/22; 01/24 - 01/25; 01/28; 02/04 - 02/07; 02/12 - 02/13; 03/04 - 03/05; 03/09 - 03/10; 03/30 - 04/01; 04/16 - 04/17; 04/30 - 05/06; 05/12 - 05/13; 06/14 - 06/15; 06/20 - 06/27; 06/30 - 07/10; 07/18 - 07/26;

** 'Insufficient Data' indicates that there were more than 5 days of temperature measurements missing in at least one month of the year. Lists of dates exceeding the threshold are still presented but they are likely not complete during years with insufficient data.

Table 1. Example output from a query performed by www.ClimateAnalyzer.org on the data from the present study.

Using ClimateAnalyzer.org, monthly averages can be graphed within a single year as shown in Figure 6, or averages can be compared across years, as shown in Figure 7. Additionally, all the same tables and graphics can be generated for the official weather stations on the islands (see map symbols in Figure 5), allowing for easy comparisons between datalogged and official data.

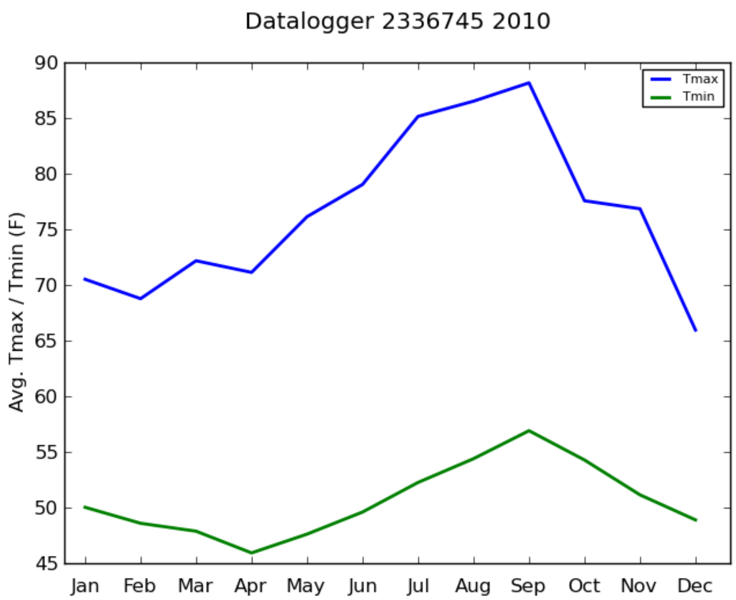


Figure 6. Example graph showing monthly averages during 2010 for a datalogger on Santa Rosa Island. Generated from a menu – based query on www.ClimateAnalyzer.org.

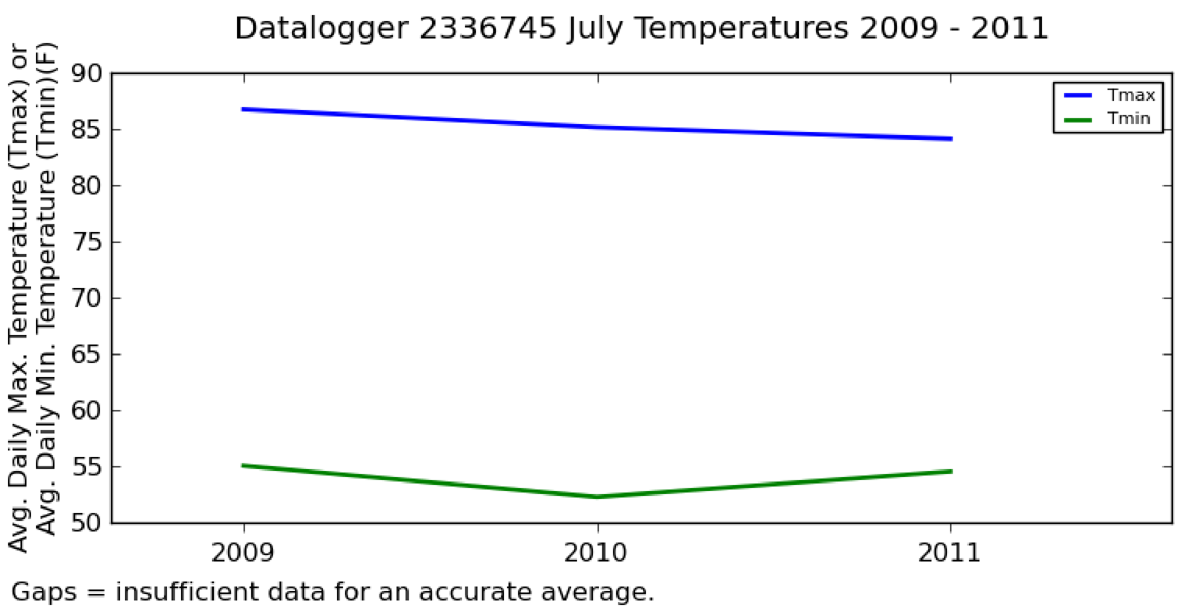


Figure 7. Example graph showing a multi-year comparison of July temperatures for a datalogger on Santa Rosa Island. Generated from a menu – based query on www.ClimateAnalyzer.org.

Relationships Between Average Monthly Temperatures and Elevation / Aspect

There is no single, simply expressed relationship between temperature and elevation. Tmax and Tmin exhibit different patterns, and each month of the year requires separate analysis. Furthermore, many of the effects of elevation on temperature are not apparent until the data are divided into subsets that were collected from North, South, East, and West facing slopes, and different regions within the islands appear to have different temperature – elevation relationships.

An initial exploration of the relationships between elevation and monthly average daily maximum (Tmax) and monthly average daily minimum temperature (Tmin) suggested that during April – July on both islands Tmin decreased as a function of elevation and Tmax increased with elevation. All the other months in the year had non-significant linear regressions. Figure 8 shows a sample subset of the scatterplots and regressions that were performed during this early stage of analysis. It is important to note that Figure 8 is misleading, and is presented here only as an example of what should not be repeated in the future.

Further investigation revealed that the seemingly simple relationships presented in Figure 8 mask the effects of aspect (the direction in which a slope is facing expressed as a compass heading) and the effects of local variability among different locales in the island. Figure 9 shows the data collected by dataloggers located only on north-facing (north-aspect) slopes on Santa Rosa Island. The overall pattern in panel A of this figure might seem to suggest that Tmin during February 2010 has a weak negative relationship with elevation, like the relationship shown in the bottom panel of Figure 8. Progressing from left to right through the points labeled in red, then through points labeled blue and green, and finally to the single yellow point located bottom right in panel A, temperatures appear to gradually decrease. However, plots of residuals from a linear regression of the data in panel A (not shown) reveal that, just as in Figure 8, a linear model including all the points in Figure 9A is not a good fit. The true pattern is revealed by plotting the dataloggers onto a map (Figure 9C) and observing how geographically nearby loggers vary as a function of elevation and how these relationships change from month to month.

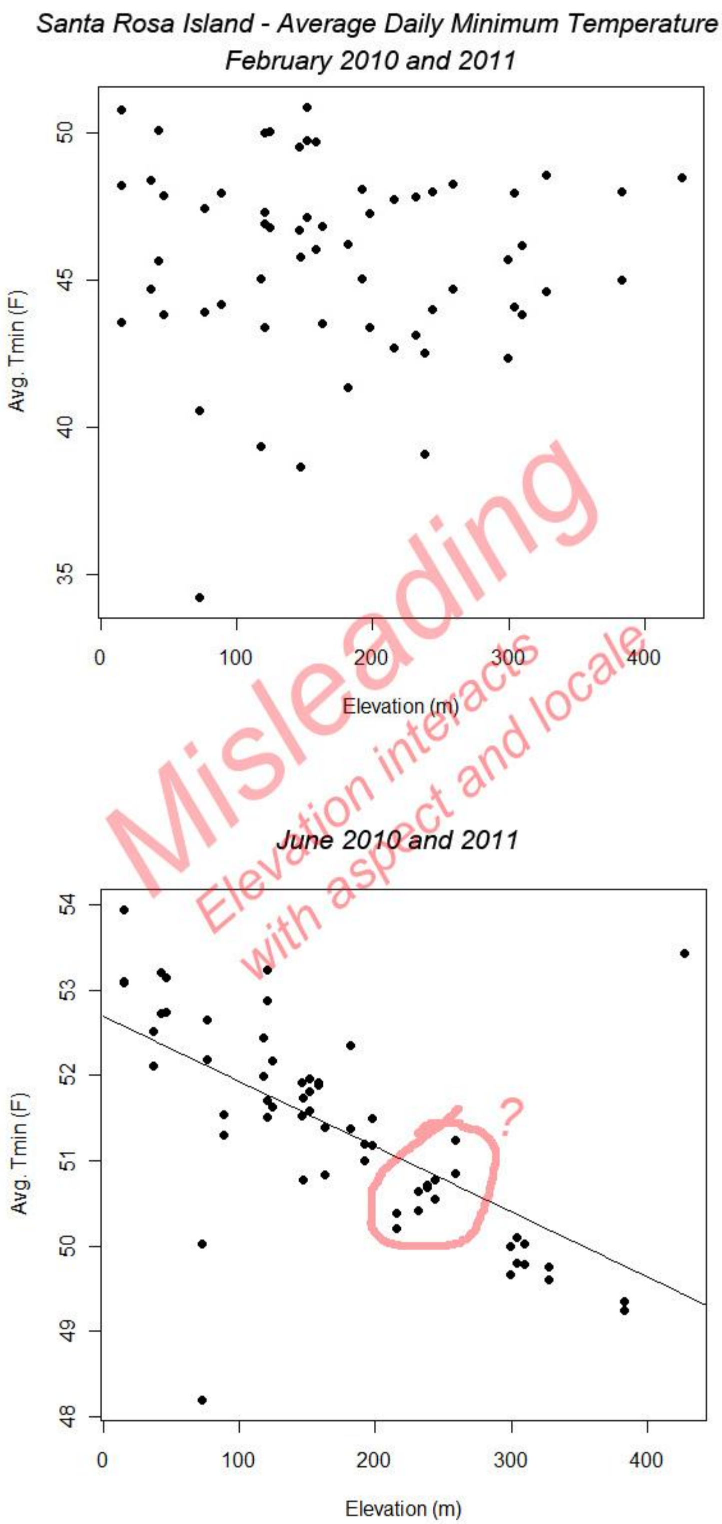


Figure 8. Sample scatterplots and a sample linear regression from an initial exploration of the relationships between elevation and average monthly temperatures on Santa Rosa Island. Plots like these were performed for every month for both Tmax and Tmin on each island. According to those plots, April – July showed Tmin decreasing and Tmax increasing significantly as a function of elevation, as shown in the bottom panel of this figure. Other months in the year did not have significant regressions between elevation and temperature, as shown in the top panel of this figure. This figure is misleading because there actually are significant relationships to be gleaned between elevation and temperature during the winter months, and the relationships during the summer are not as straight forward as the one shown in the bottom panel here. This figure is presented as an example of what should not be naively repeated in the future. The red points circled in the bottom panel are a clue that the regression shown is not very accurate. As a subset, the circled points increase as a function of elevation in opposition to the overall pattern shown here. Plots of residuals (not shown) confirm that this linear model is a poor fit even though it is significant ($p < .01$). Figure 9 examines a subset of this data more closely, showing the true relationships.

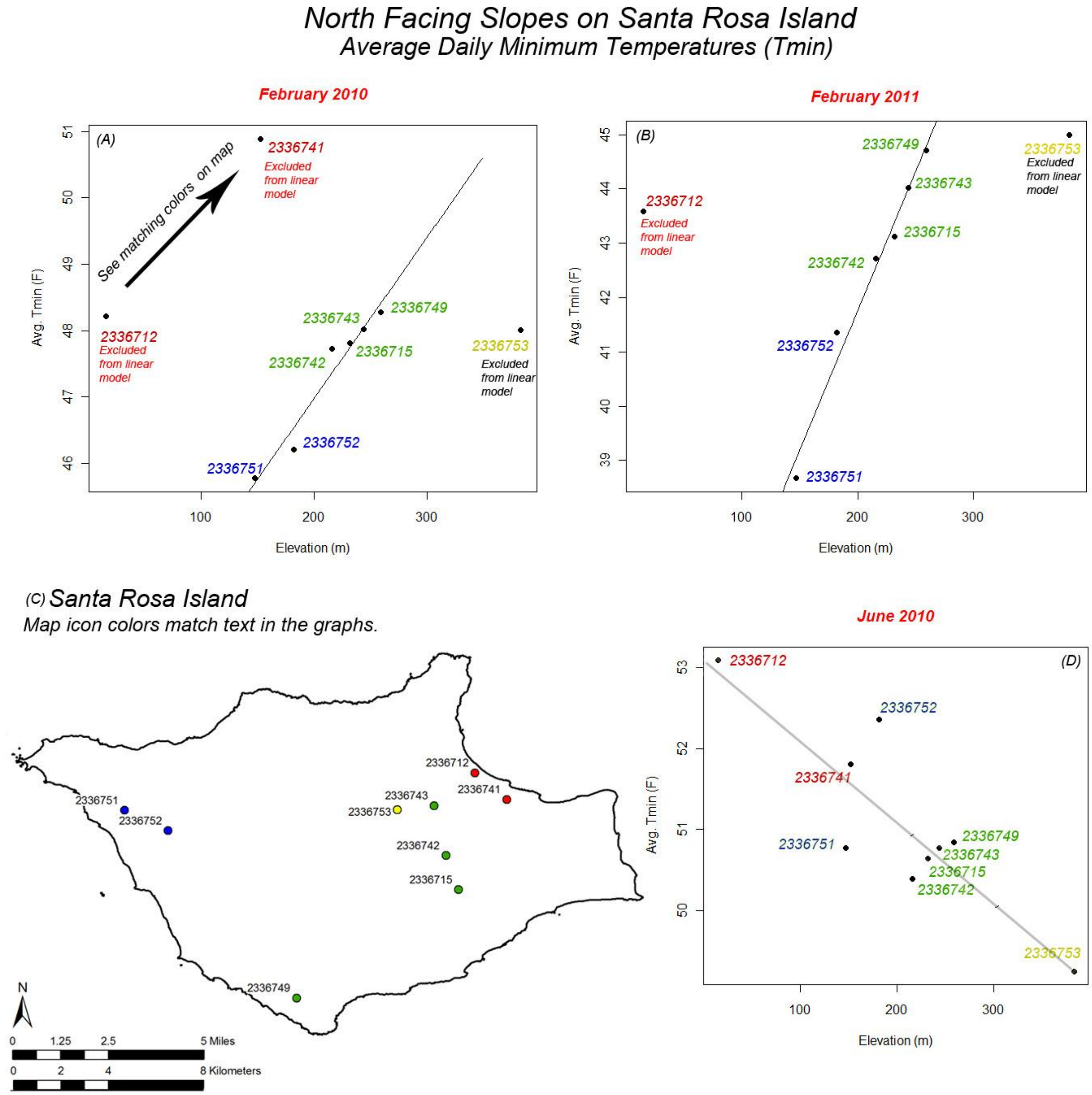


Figure 9. A closer look at a subset of the data presented in Figure 8 showing only data from north facing slopes on Santa Rosa Island. All north-facing dataloggers are shown here. Colored labels in the scatterplots (A,B,D) correspond with colors on the map (C). Straight lines in the scatterplots are linear regressions, details of which are presented in the text. In panels A and B, the regressions include only the points labeled green and blue. In Panel D the regression includes all points, but note that the points labeled green and blue in D show an increasing pattern in opposition to the overall pattern indicated by the straight line. The arrow in panel A indicates an increase of temperature as a function of elevation among eastern dataloggers (red) that differs from the increase shown among the blue – green dataloggers (straight line).

In Figure 9A, the dataloggers labeled blue and green exhibit a strongly significant ($p < .001$, $F = 182.1$ on 1,4 DF) increase in February 2010 Tmin as a function of elevation, and linear regression (indicated by the line in Figure 9A) shows that elevation explains 98% of the variance among these points (Figure 9A, $R^2 = 0.9785$). The same relationship is seen in Figure 9B for February 2011 Tmin, with elevation in this case explaining 94% of the variance among points labeled blue and green (Figure 9B, $R^2 = 0.9379$, $P < .001$, $F = 76.55$ on 1,4 DF). The blue and green labeled points just mentioned stand in contrast to the red-labeled points in Figures 9A and 9B, which are grouped together on the eastern coast of the island (Figure 9C) and <u>*also show an increase in temperature as a function of elevation, but with an intercept that differs from the blue-green pattern*</u> (see arrow in Figure 9A). During February 2010, average daily minimum temperatures (Tmin) increase at a rate of about 2 degrees F per 100m increase in elevation, and this lapse rate (regression slope) is the same for both the blue – green and red points in Figure 9A. The regression equation for blue – green points in Figure 9A is Tmin = 31.5 + .05(elevation), where elevation is expressed in meters. The same equation can be used for the red points in Figure 9A by replacing 31.5 with 47.9. During February 2011 (Figure 9B) the slope among blue –green points is about half as steep (roughly 2 degrees F increase per 100m). The regression equation for blue-green points in Figure 9B is Tmin = 42.1 + .02(elevation).

Figure 9D shows an apparent decrease in temperature as a function of elevation during June, in agreement with the pattern that was initially discovered in the bottom panel of Figure 8, but the colors in Figure 9D show that geographically coherent groups continue to exhibit an increase rather than a decrease of temperature as a function of elevation. In Figure 9D, the green-labeled points group separately from the blue-labeled points, but both groups show an increase of temperature as elevation increases. In contrast, the red-labeled points in Figure 9D show a decrease of temperature as a function of elevation during June 2010, and the highest elevation location (2336753,yellow) has the lowest Tmin. In Figure 9D, Tmin for the green points increases at a rate of about 1 degree F per 100m. For the blue points, the increase is about 4.5 degrees F per 100m. Among the red points, Tmin <u>*decreases*</u> at a rate of about 0.9 degrees F per 100m.

In order to examine whether there is an overall pattern among groups of dataloggers or regions of the island that can be explained consistently by elevation during all months, the north-facing Santa Rosa dataloggers were averaged into groups that correspond to the colors in Figure 9, and the relationships among the groups were plotted as shown in Figure 10 for every month during 2010. (Data for 2009 and 2011 are incomplete but the patterns shown in Figure 10 are the same seen for extant months in those years.) The dataloggers were grouped this particular way because (a) they form cohesive units geographically, and (b) the analysis in Figure 9 demonstrated that dataloggers within these groups vary similarly together. In Figure 10, the red line (Zone 1) is the average of the data from the red dataloggers (2336712, 2336742) in Figure 9. Similarly, the blue, green, and yellow lines are the averages from the blue, green, and yellow labeled dataloggers in Figure 9. If the relationship among these datalogger groups were constant from month to month, the lines in Figure 10 would not cross. Instead, they show varying relationships throughout the year and cross each other in complex ways. Furthermore, the color order in Figure 10 often does not correspond to elevation. Arranged in order of elevation from lowest to highest, the colors (datalogger groups) in Figure 10 are red-blue, green, yellow (compare to Figure 9). In contrast, Figure 10, bottom panel (Tmax) shows the colors during January – July, for example, arranged from top to bottom as blue, green, red, yellow, which in terms of elevation could be expressed as “medium-high,” medium-low,” “low,” “high” (compare colors in Figure 10 to Figure 9). Similarly, in Figure 10, top panel, the Tmin pattern from top to bottom during many months is red, green / yellow, blue, which in terms of elevation is “low,” “medium-high to high,” “medium-low.”

Comparison Between Official Weather Station and Datalogger Data

Datalogger #2336753 was deployed in the same location as the Santa Rosa Island “Black Mountain” Remote Automated Weather Station. Comparison between the two data sets shows that the datalogger measurements are usually warmer than those from the weather station, particularly during the summer. Average daily minimum temperatures (Tmin) were an average of 1 degree warmer during the study and average daily maximum temperatures (Tmax) were an average of 3 degrees warmer (Table 2). During April – August 2010, Tmax measurements from the datalogger were about 5 degrees F warmer on average than Tmax measurements from the adjacent weather station.

Interpolated Heat Maps

Due to the large number of heat maps (47 pages), they have been moved to Appendix 1. In general, Santa Cruz Island exhibited greater spatial heterogeneity in temperature than Santa Rosa Island. Average daily maximum temperatures (Tmax) exhibited greater spatial heterogeneity than average daily minimum temperatures (Tmin), and Tmax had generally larger ranges of temperatures within a given month. Summer temperatures were also generally more heterogeneous and covered a wider range than temperatures during winter. For example, Tmax during September on Santa Cruz Island spanned roughly 30 degrees (67 – 97 degrees F) while Tmin during that month spanned only 20 degrees (49 – 69 degrees F). During January, Santa Cruz Island Tmax ranged over 15 degrees (59 – 84 F) and Tmin during that month had a span of 13 (43 – 56 F).

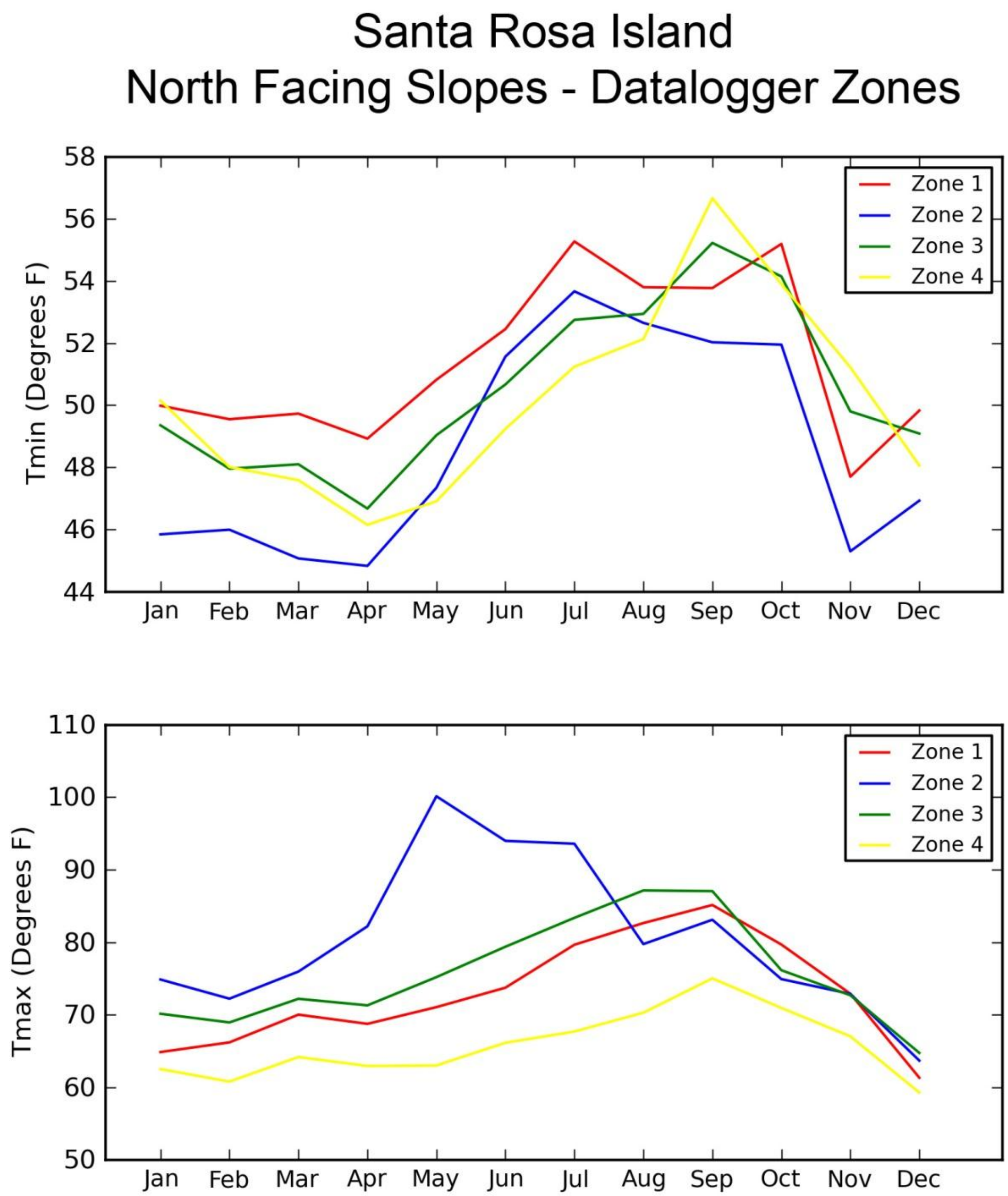


Figure 10. Monthly temperature averages for groups of dataloggers on north-facing slopes on Santa Rosa Island. Colors correspond to map symbols in Figure 9C and to labels in Figures 9A, 9B, and 9D. Tmin = average daily minimum temperature. Tmax = average daily maximum temperature.

Santa Rosa Island	Avg. Daily Minimum Temperature (Tmin)				Avg. Daily Maximum Temperature (Tmax)		
Month	Datalogger 2336753	Weather Station	Tmin Difference		Datalogger 2336753	Weather Station	Tmax Difference
July 2009	52.6	51.2	*1.5*		76.4	71.0	*5.4*
August 2009	56.1	54.5	*1.6*		76.7	72.4	*4.3*
September 2009	59.6	58.4	*1.2*		79.5	78.0	*1.5*
October 2009	54.3	53.0	*1.3*		70.5	69.2	*1.4*
November 2009	53.3	52.3	*1.0*		67.1	68.1	*-1.0*
December 2009	47.3	46.0	*1.3*		59.4	58.4	*0.9*
January 2010	50.2	49.0	*1.1*		62.5	62.7	*-0.1*
February 2010	48.0	46.9	*1.2*		60.8	59.0	*1.7*
March 2010	47.6	47.3	*0.3*		64.2	61.2	*3.0*
April 2010	46.2	45.6	*0.5*		62.9	57.8	*5.1*
May 2010	46.9	45.9	*1.0*		63.0	58.9	*4.1*
June 2010	49.2	48.1	*1.2*		66.1	61.3	*4.8*
July 2010	51.2	49.9	*1.3*		67.7	62.5	*5.2*
August 2010	52.1	51.0	*1.2*		70.3	65.6	*4.7*
September 2010	56.7	55.9	*0.8*		75.0	72.4	*2.6*
October 2010	53.9	53.0	*0.9*		70.9	67.6	*3.4*
November 2010	51.2	50.7	*0.5*		67.0	64.6	*2.5*
December 2010	48.1	47.4	*0.6*		59.3	58.2	*1.1*
January 2011	50.2	49.7	*0.4*		66.9	64.6	*2.4*
February 2011	45.0	44.5	*0.5*		60.4	58.2	*2.2*
March 2011	46.7	45.7	*1.0*		61.6	57.5	*4.1*
April 2011	46.3	45.0	*1.3*		62.6	57.1	*5.5*
May 2011	47.4	46.5	*0.9*		65.8	58.9	*6.8*
June 2011	49.4	48.3	*1.1*		65.8	60.2	*5.6*
July 2011	53.8	52.7	*1.1*		68.2	65.5	*2.6*
August 2011	52.4	50.8	*1.6*		62.4	63.7	*-1.3*
Average	**50.6**	**49.6**	**1.0**		**66.6**	**63.6**	**3.0**

Table 2. Comparison of monthly average temperatures in Degrees Fahrenheit collected from datalogger 2336753 and from the Santa Rosa Island “Black Mountain” Remote Automated Weather Station, which was at the same location during the study. Data from the weather station is available at http://www.climateanalyzer.org/medn/raws/santa_rosa_island/. All values are rounded to 0.1 degree, which creates small discrepancies between the raw values and calculated differences, e.g., first line of table 52.6 – 51.2 = 1.4.

Download of the Data

Readers wanting to perform their own analysis on the data can use the download links provided below:

All the daily data in one synchronized file: Santa Cruz Island Santa Rosa Island
All monthly averages in one synchronized file: Santa Cruz Island Santa Rosa Island
All of the raster files (GIS data) used to produce the heat maps: Both Islands

Discussion

Working together, the Nature Conservancy and the National Park Service have assembled a large and impressive dataset. If applied correctly, it will be of great value to natural resource managers and scientists in Channel Islands National Park. In particular, the present study is of value in identifying regions within the islands that are consistently warmer or cooler than others, such as the western peninsula of Santa Rosa Island or the northern coast of Santa Cruz Island, which are both often cooler than the rest of the islands (Appendix 1). Spatial patterns in temperature like these might be compared to species distribution maps or used as a source of covariates that explain other resource patterns on the islands. Using monthly data from this study, researchers will also be able to estimate localized lapse rates that allow for the prediction of temperature as a function of elevation within sub-regions of each island. As additional covariates become available, new analysis will quite likely reveal new patterns in the temperature data presented here. The remainder of this report provides some basic interpretation of the results presented here and offers recommendations / cautions regarding how the data might be applied as part of future research.

The easiest way to access the data from this study and make queries or summaries is through the web portal that has been built at this address:
http://www.climateanalyzer.org/dataloggers/map_html.

Data Accuracy and Comparison to Official Weather Stations

The temperature measurements taken by the dataloggers in this study appear to be systematically warmer than measurements taken by official weather stations, and this pattern is quite likely true across the entirety of the islands, even in areas where no weather stations are currently located. There are three lines of evidence for this statement. First, a datalogger deployed at the same location as the Santa Rosa Island Remote Automated Weather Station measured an average of 1 degree F above the average daily minimum temperature from the weather station and an average of 3 degrees F warmer than the average daily maximum temperature (Table 2). Second, diagnostic screening revealed that many of the datalogger files on Santa Cruz Island contained spikes similar to those shown in Figure 3B that were caused by intermittent heating of the instrument by solar radiation. This pattern was not common on Santa Rosa Island. More stringent quality checking might have removed the data containing those spikes, but such a procedure would have removed enough data to degrade the present dataset's usefulness in elucidating spatial patterns. Third, using the heat map raster dataset (Appendix 1), and comparing the raster grid cell from the location that contains the automated weather station on Santa Cruz Island to official data (http://www.climateanalyzer.org/medn/raws/santa_cruz_raws/) revealed a discrepancy that was similar to the one presented in Table 2. The predicted Tmax from the raster file was 2 – 5 degrees F warmer than the corresponding official monthly values and Tmin was 0 – 3 degrees warmer.

The patterns just described that suggest that Tmin values from this study are generally more accurate than Tmax values. This is likely due in part to the fact Tmin was not subject to the intermittent solar radiation spikes illustrated in Figure 3B. Happily, the patterns just described do not invalidate the data for many purposes, in particular the elucidation of spatial patterns and the identification of regions that are consistently cooler or warmer than others. Since the quality-checking methods used left in only spikes that were seen consistently throughout the record of a particular datalogger, the bias caused by solar radiation will be largely systematic throughout the dataset and measurements taken from different locations will often suffer from a similar amount of bias. It is also worth considering that the dataloggers in this study measured Tmax values that represent what would have been experienced by a plant or animal in the habitat occupied by the datalogger. From this perspective, the Tmax values from this study might be viewed as "biologically realistic" measurements rather than meteorological measurements that should be compared to a weather station. In summary, the data are likely useful for biological or natural resource applications, but they probably should not be used in studies that make comparisons to historical meteorological data (from, e.g., now defunct weather stations) or in studies that make statements about climate change. This last caution is reinforced by the fact that the dataloggers used in this study have an accuracy of +/- 0.95 F, which is greater than the global average warming seen during the 20th century (Solomon et al. 2007).

Relationships Between Temperature and Elevation / Aspect

The analysis presented in Figures 8 – 10 suggests that there is no single, simply expressed relationship between average temperature and elevation. Tmax and Tmin exhibit different patterns, and each month of the year requires separate analysis. Furthermore, many of the effects of elevation on temperature are not apparent until the data are divided into subsets that were collected from North, South, East, and West facing slopes, and different regions within the islands appear to have different temperature – elevation relationships. Once all these factors (aspect, month, locale, Tmax vs. Tmin) are considered and the data are properly partitioned, it is possible to develop excellent linear models of average temperature as a function of elevation. The linear regressions in Figures 9A and 9B suggest that, at least within selected locales of Santa Rosa Island, elevation explains 95% - 98% of the variability in Tmin.

To calculate estimates of lapse rates (rates of temperature change as a function of elevation) that would be accurate for natural resource applications, it would be best to select the geographic area of interest within a particular island and perform an analysis similar to the one presented in Figure 9. The locations of each datalogger in such an analysis should be mapped, and careful attention should be given to groups of dataloggers that vary together and comprise cohesive geographic units. Notice, for example, that during June 2011, two dataloggers on the northeast coast of Santa Rosa Island (labeled red in Figure 9D) had temperatures decreasing as a function of elevation, while during the same month two other groups of inland dataloggers (blue and green in Figure 9D) had the opposite pattern, increasing temperature with elevation. I contrast, during February (Figure 9A) the red-labeled dataloggers had temperatures increasing as a function of elevation, like all the other north-facing dataloggers in the analysis.

In order to fully elucidate the effects of elevation and aspect on temperature, a very large number of analyses *could be* performed, but it is probably wiser to calculate lapse rates only for particular geographic regions or species habitats of interest. If all possible analyses were performed there would be at least 12 months X 2 Islands X 4 Aspects (N-S-E-W) X 2 variables (Tmax vs. Tmin) = 192 linear regressions. Quite likely, some of these analyses would exhibit similar patterns, but many would also reveal geographic regions ("locales") on each island that had unique patterns, and that the relationships among locales vary from month to month (Figure 10). In order to facilitate future analyses of this type, Appendix 2 provides the analytical code that was used to produce Figure 9, along with brief instructions on its use.

Heat Maps

The interpolation method used to produce the heat maps in Appendix 1 calculated predicted temperatures for each grid cell as a simple function of the horizontal distance between the cell and nearby dataloggers. Importantly, it did not take into account the effects of topography, air currents, or other factors that may affect temperatures in the areas between sampling locations. Nevertheless, the spatial sampling density of dataloggers in this study was great enough to reveal consistent patterns. In particular, the same regions of the islands were consistently warmer or cooler than each other from month to month, and the same month in subsequent years (e.g. February 2010 and February 2011) exhibited similar gradients, even if the absolute magnitude of temperatures differed from year to year (Appendix 1).

In general, Santa Cruz Island had more spatial heterogeneity than Santa Rosa Island and summer months had more heterogeneity than winter months (Appendix 1). One factor contributing to these patterns is likely the wind. Redmond and McCurdy (2005) state that days with calmer winds have greater spatial heterogeneity in temperature on the Channel Islands. In general, Santa Rosa Island is windier than Santa Cruz Island, and summer months have higher winds than winter (Figure 11). For example, maximum wind speeds on Santa Cruz Island were 13 – 19 miles per hour (MPH) during March 2011 and only 8 – 13 during July 2011. In contrast, Santa Rosa Island had maximum winds of 39 – 47 MPH during March 2011 and 25 – 32 MPH during July (Figure 11). A more detailed analysis of the effects of air currents and wind direction on the temperature patterns in the present dataset may be an interesting topic for future study.

For the reasons given in the first part of this Discussion, the best application for these maps is likely to be as a source of temperature covariate data that explain spatial patterns in species or resource distributions. They are not well suited to comparisons with meteorological data.

Future Research

If research of this type is continued on the islands, managers might consider using a datalogger that measures relative humidity. Low cost options can be obtained from Onset Computing, the same manufacturer that provided the instruments for this study. Combining humidity data with temperature measurements would make it possible to quantify the frequency and duration of fog events, which are of particular interest to researchers on the islands (NPS staff, personal communication). In addition, it would be worth the extra cost to install specially- manufactured sun shades with each datalogger to mitigate the effects of solar radiation discussed above. Various options are available from datalogger manufacturers. They are typically either white or reflective and have baffles or vents that allow free movement of air past the instrument while at the same time shading it from the sun. Finally, now that the importance of slope aspect has become apparent, the design for future studies should explicitly take this factor into account by distributing deployment sites equally among slopes that face all four cardinal directions.

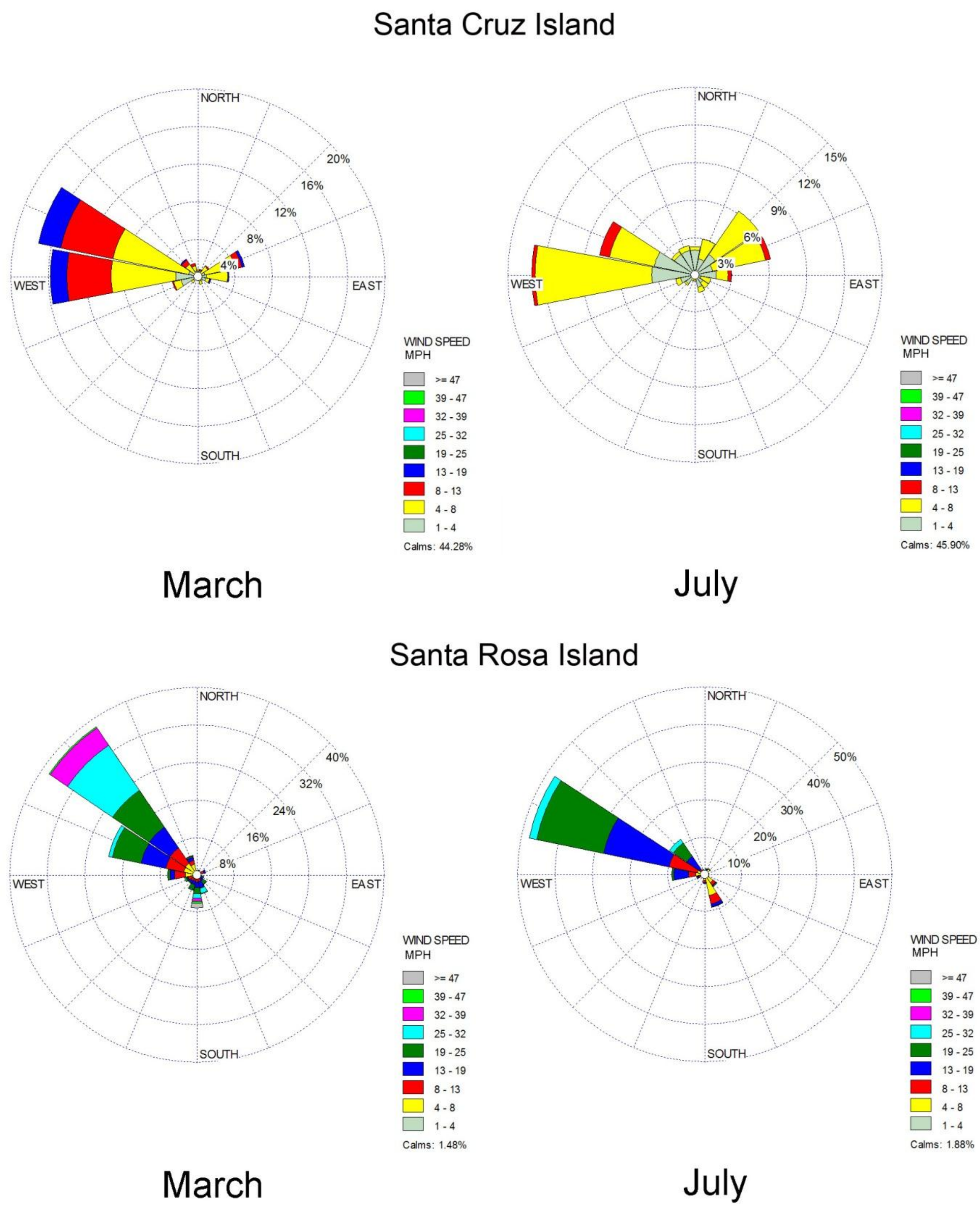


Figure 11. Wind roses for weather stations in Channel Islands National Park. The orientation of a spoke indicates wind direction (compass heading, degrees from which the wind originated), and the length of a spoke indicates the amount of time (%) that wind from a given direction occurred. Colors within the spokes express the amount of time (%) that wind from each direction had the indicated velocity.

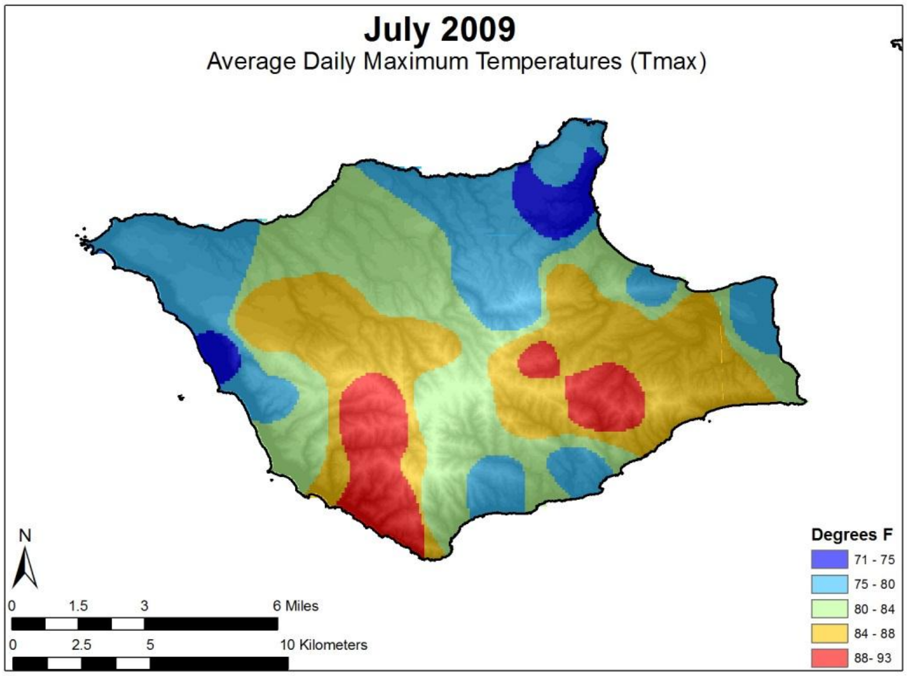
Literature Cited

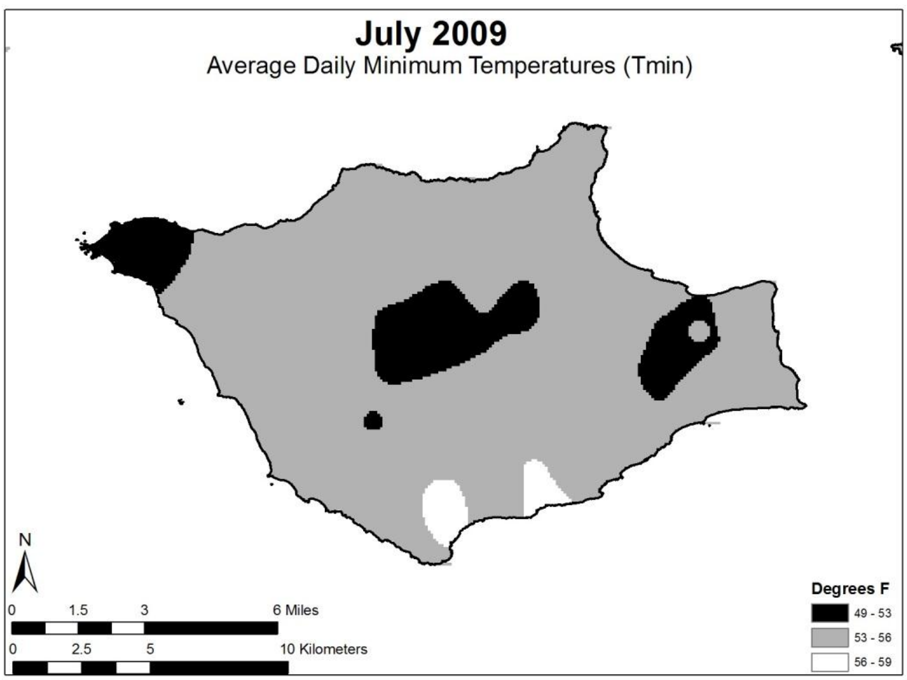
Redmond, K. and G. McCurdy. 2005. Channel Islands National Park: Design considerations for weather and climate monitoring. Technical report submitted to the National Park Service. Western Regional Climate Center, Reno, Nevada.

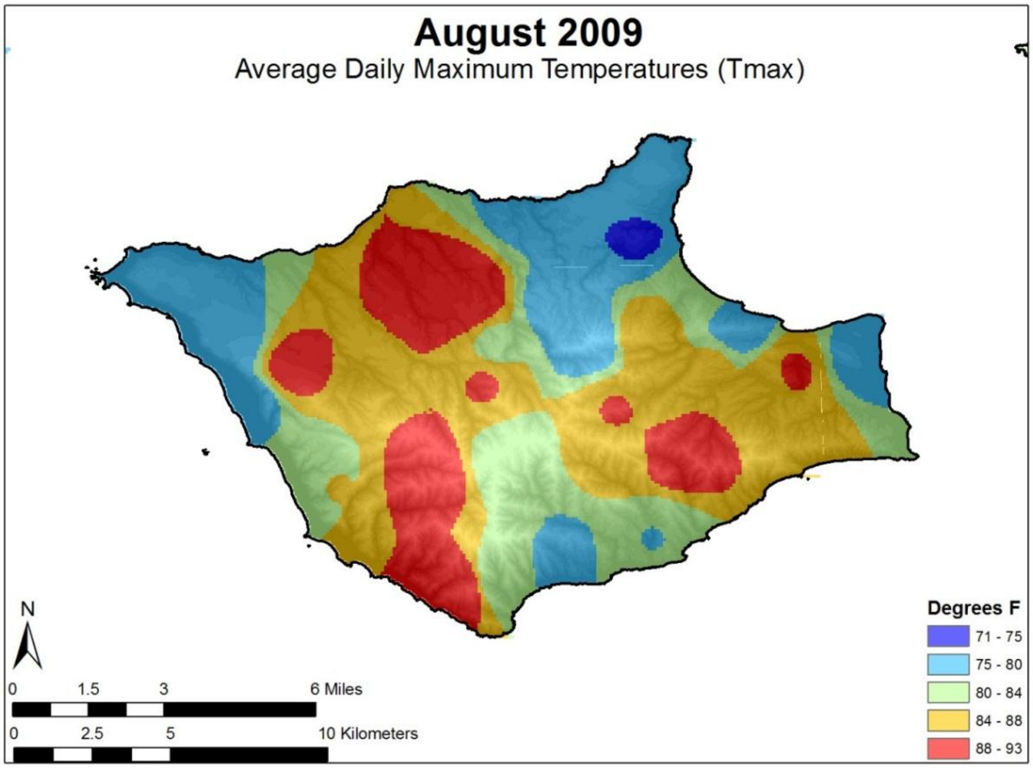
Solomon, S., and many co-authors. 2007. Climate Change 2007: The Physical Science Basis. Technical Summary, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). (Available in PDF format online at http://www.ipcc.ch)

Appendix 1 – Heat Maps

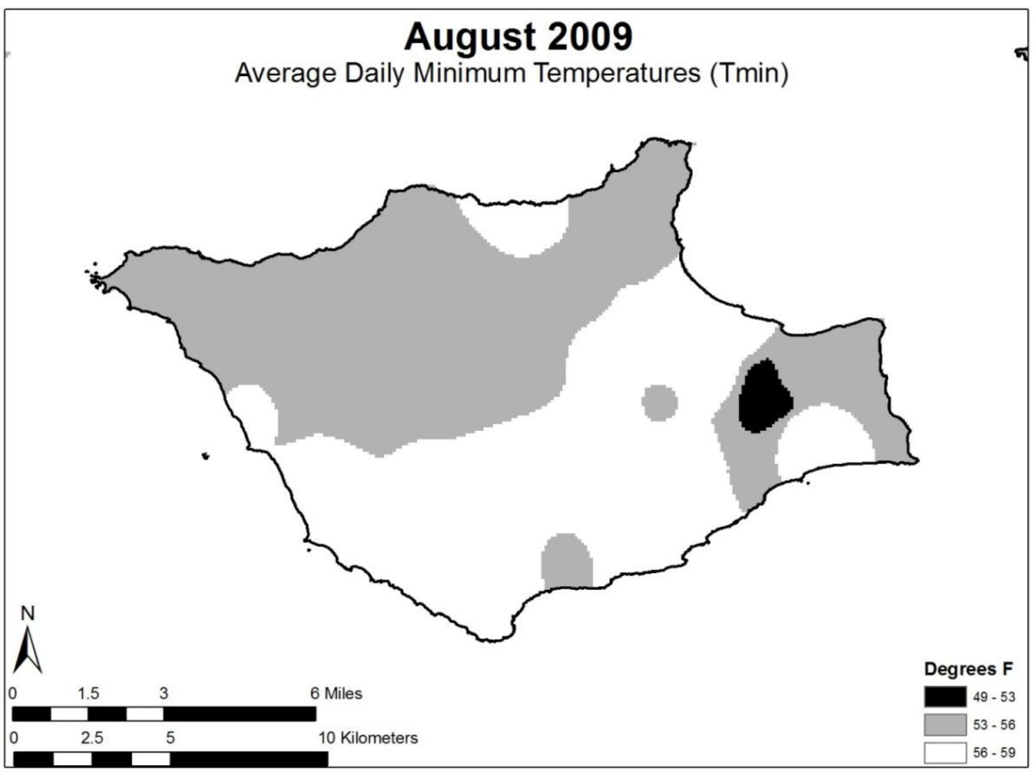
Santa Rosa Island



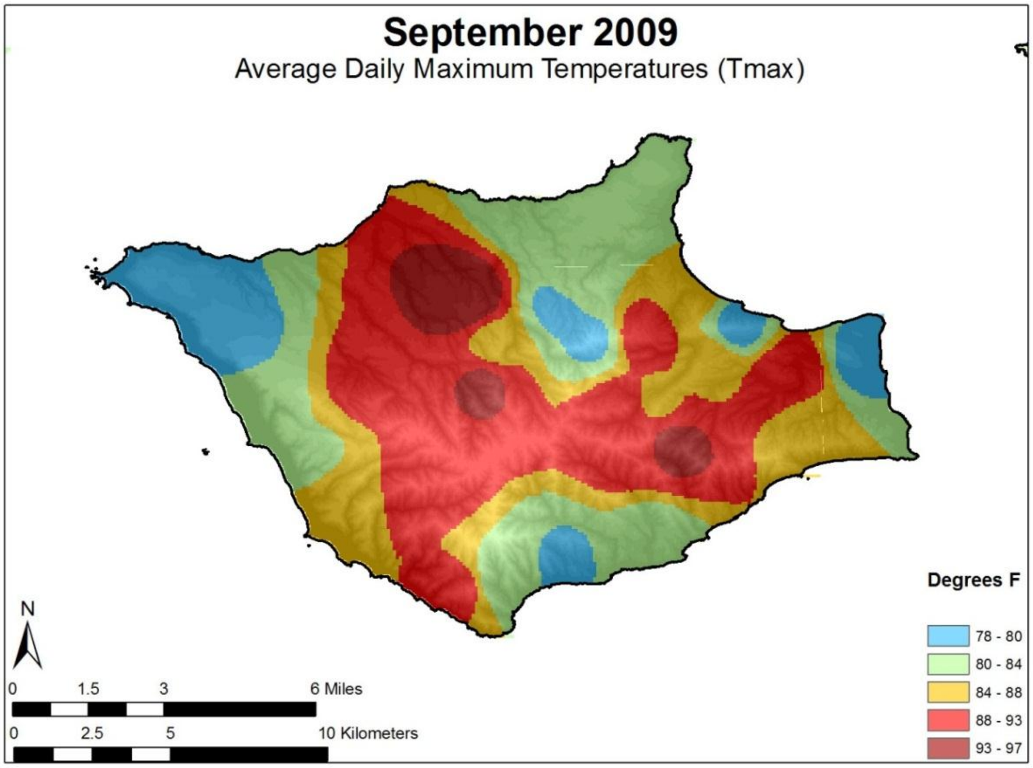


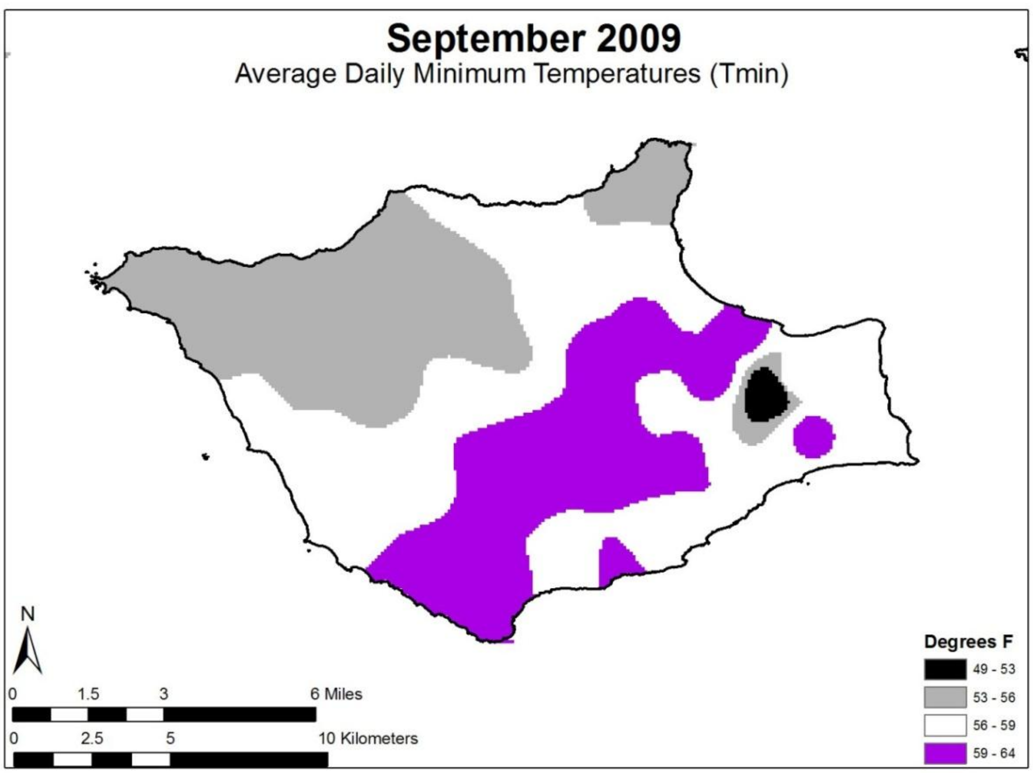


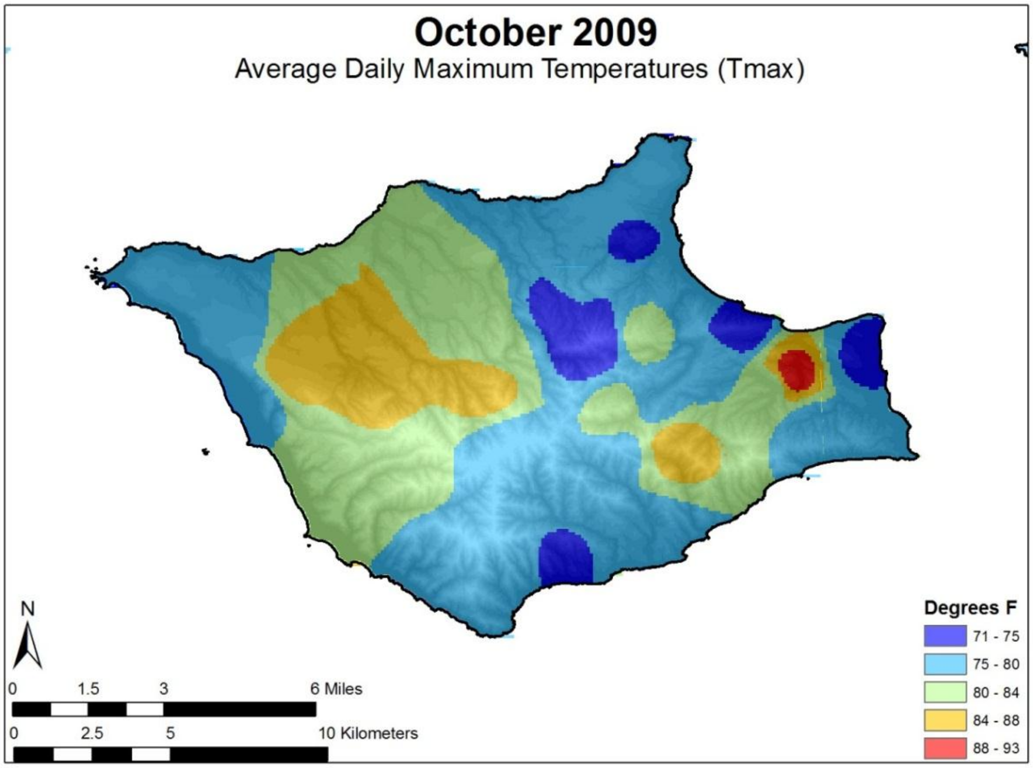
August 2009
Average Daily Maximum Temperatures (Tmax)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93

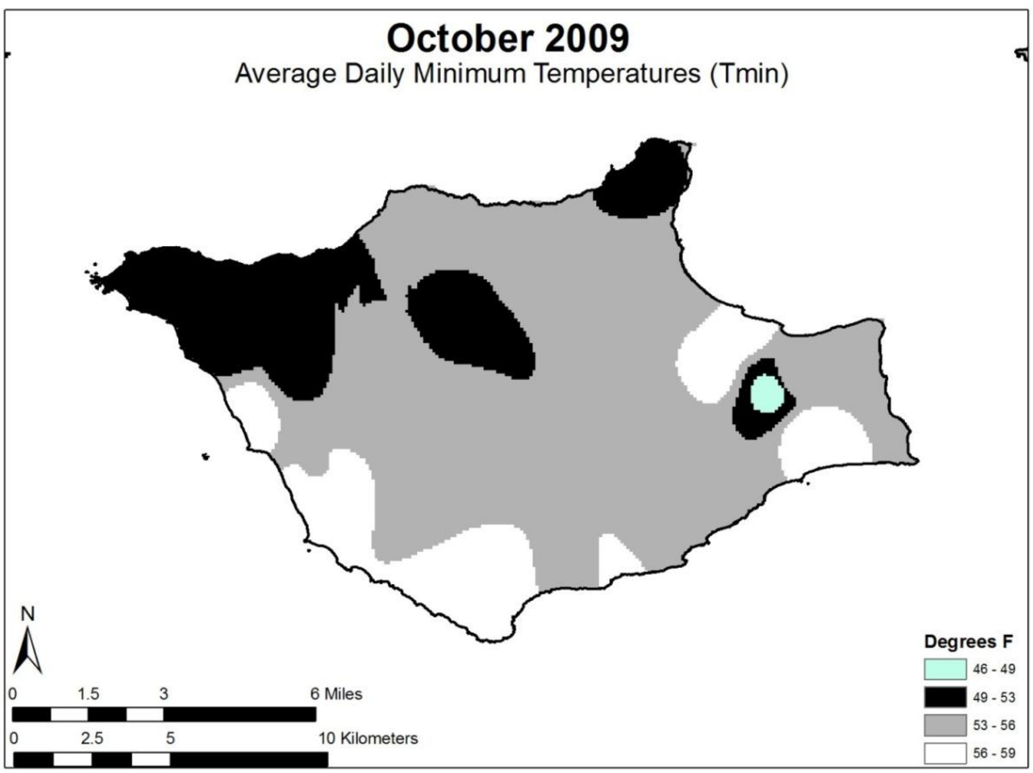


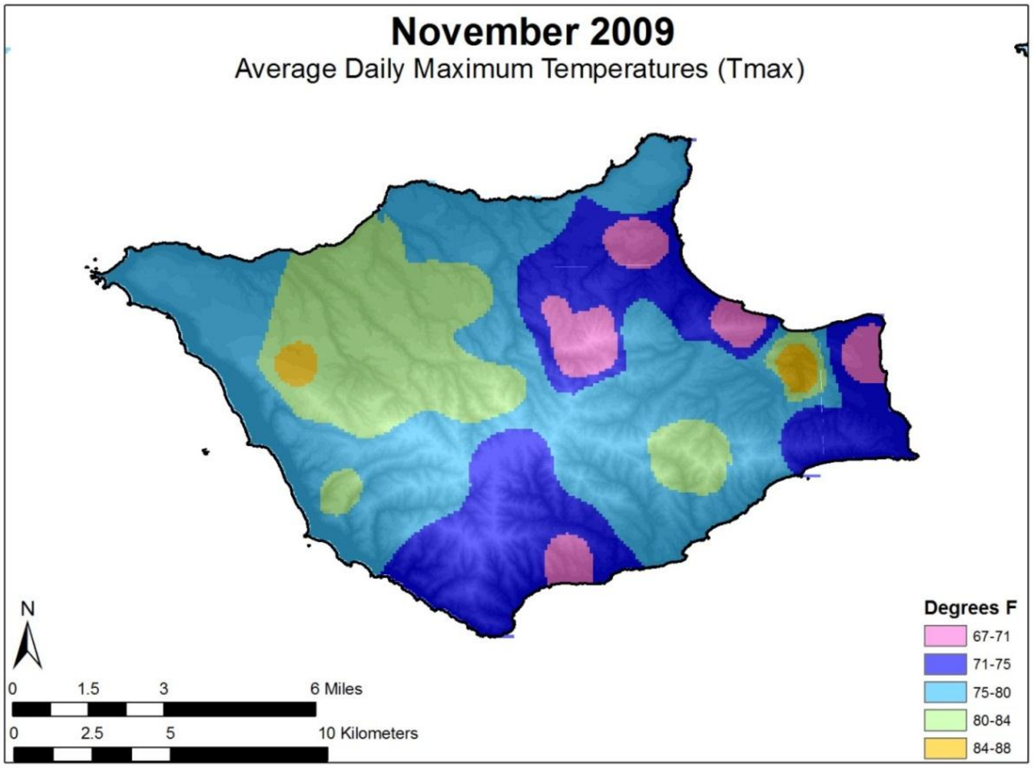
August 2009
Average Daily Minimum Temperatures (Tmin)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
49 - 53
53 - 56
56 - 59

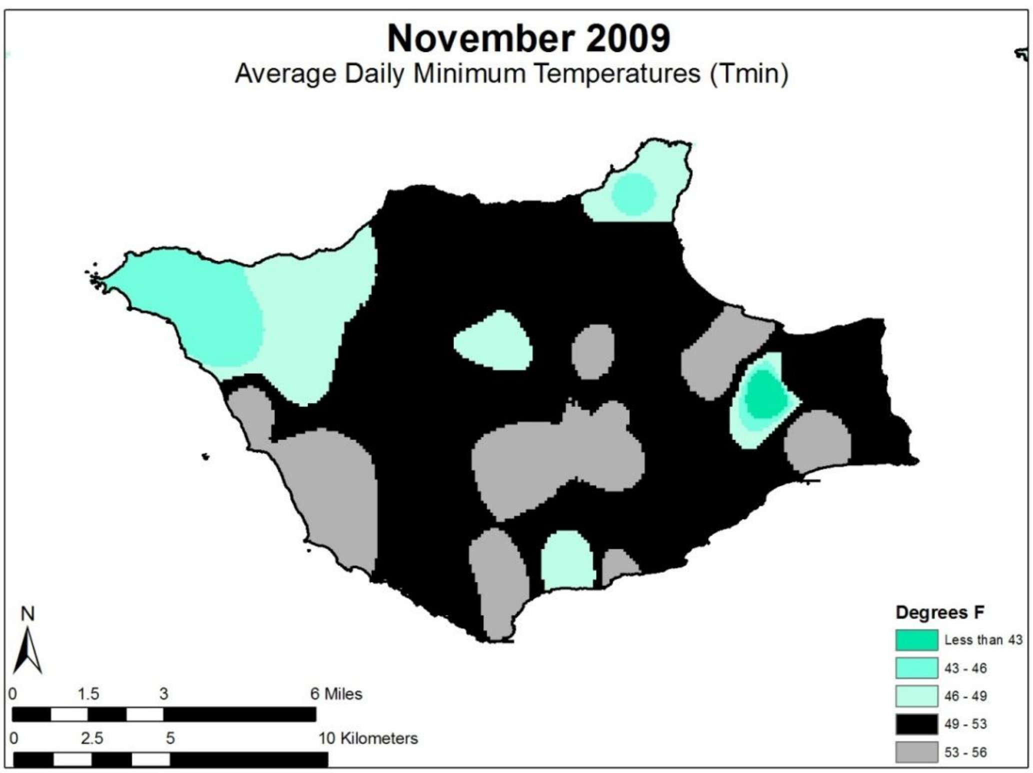

September 2009
Average Daily Maximum Temperatures (Tmax)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
78 - 80
80 - 84
84 - 88
88 - 93
93 - 97

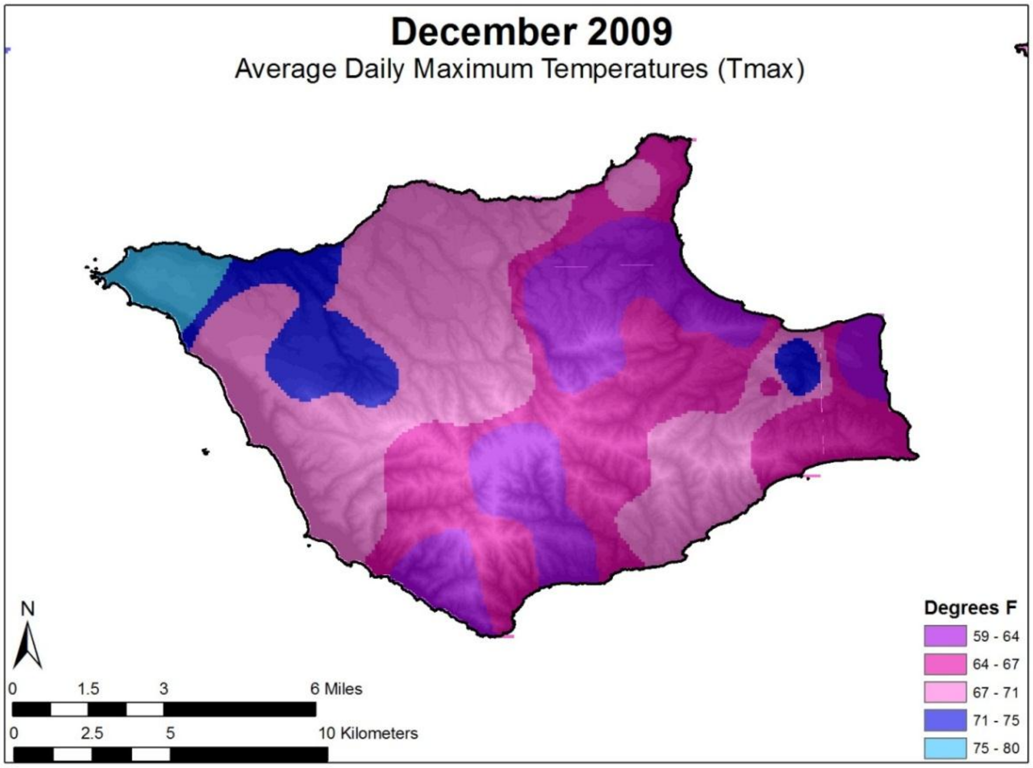

September 2009
Average Daily Minimum Temperatures (Tmin)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
49 - 53
53 - 56
56 - 59
59 - 64

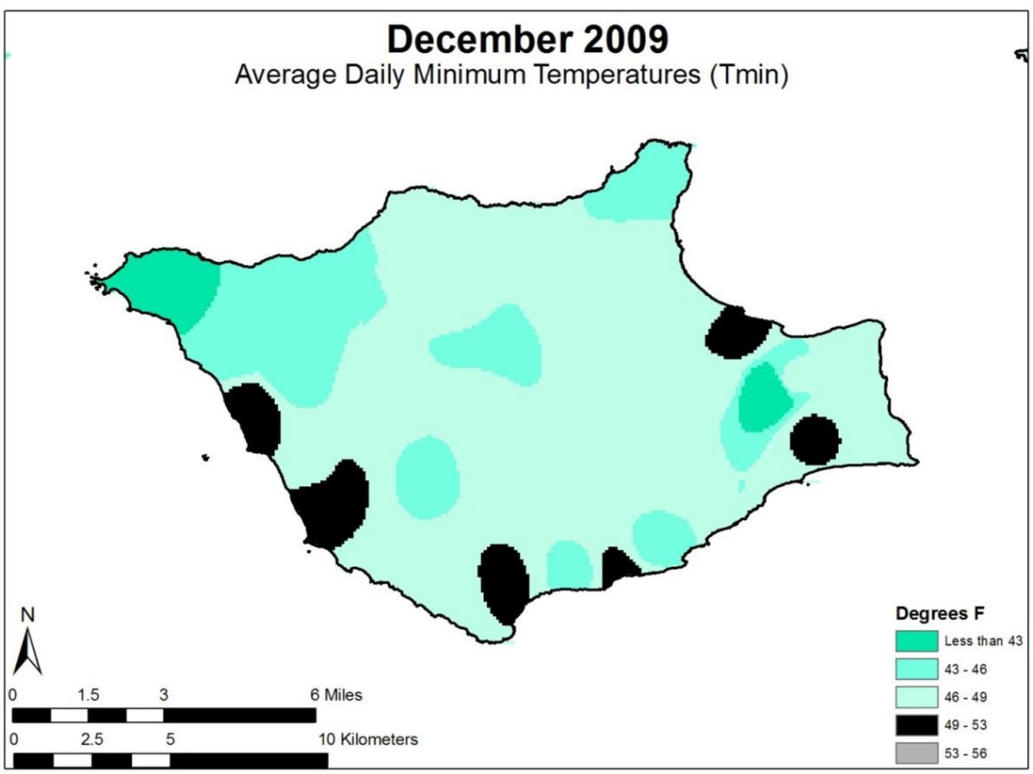

October 2009
Average Daily Maximum Temperatures (Tmax)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93

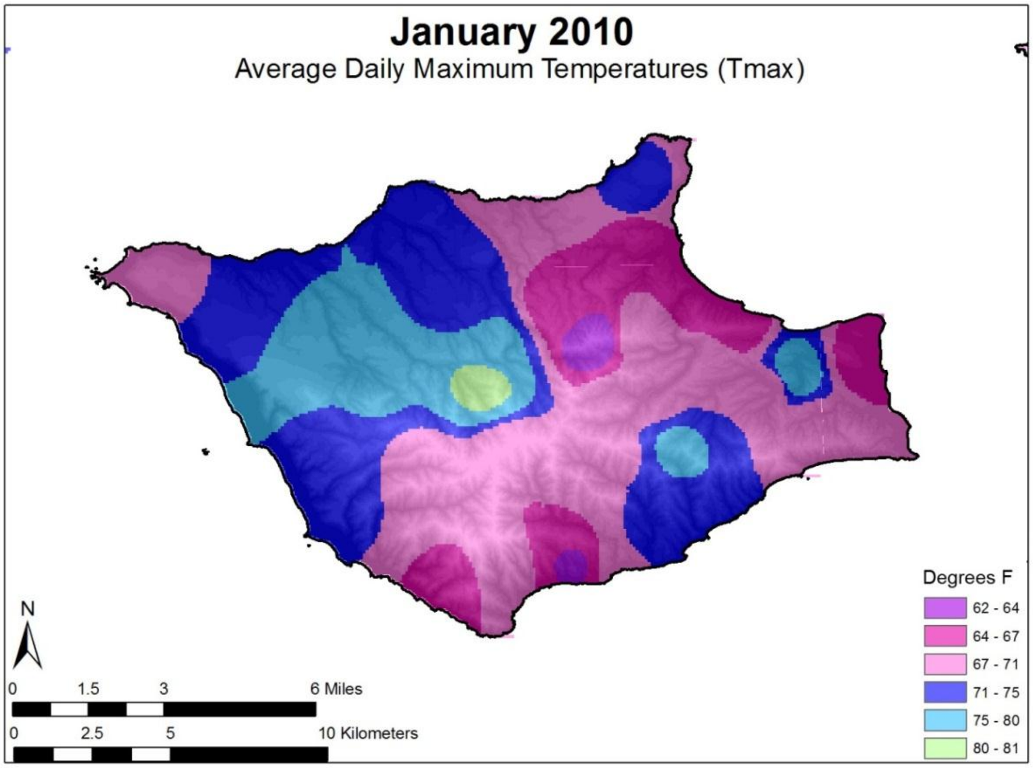

October 2009
Average Daily Minimum Temperatures (Tmin)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
46 - 49
49 - 53
53 - 56
56 - 59


November 2009
Average Daily Maximum Temperatures (Tmax)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
67-71
71-75
75-80
80-84
84-88

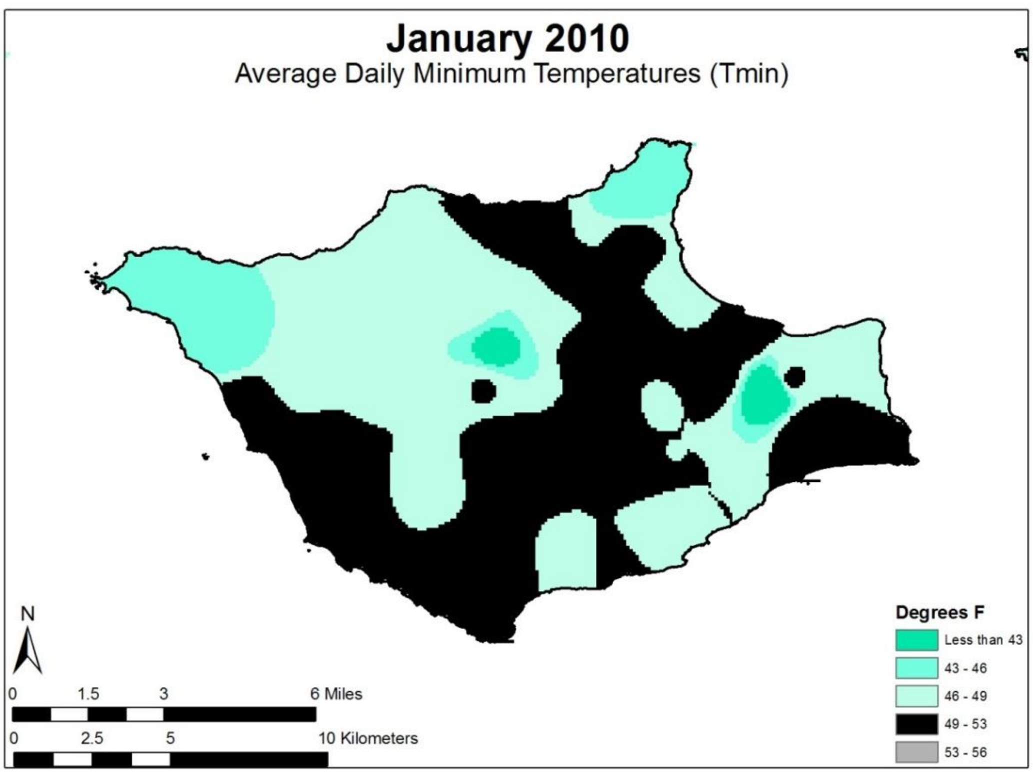

November 2009
Average Daily Minimum Temperatures (Tmin)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56


December 2009
Average Daily Maximum Temperatures (Tmax)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
59 - 64
64 - 67
67 - 71
71 - 75
75 - 80

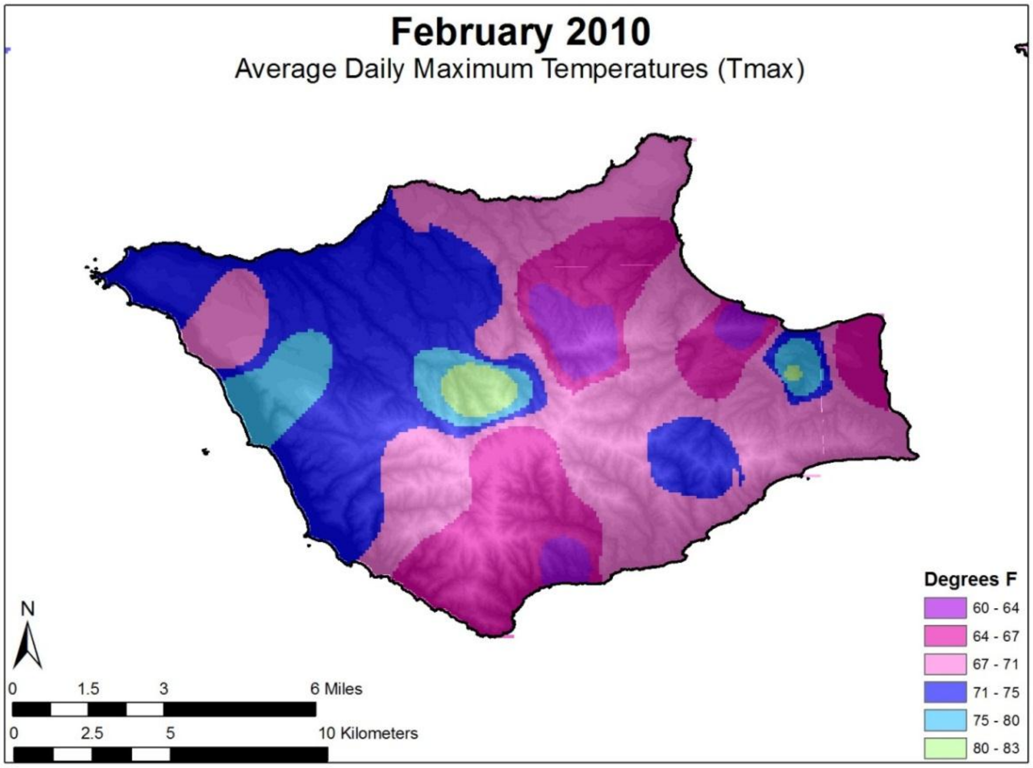

December 2009
Average Daily Minimum Temperatures (Tmin)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56

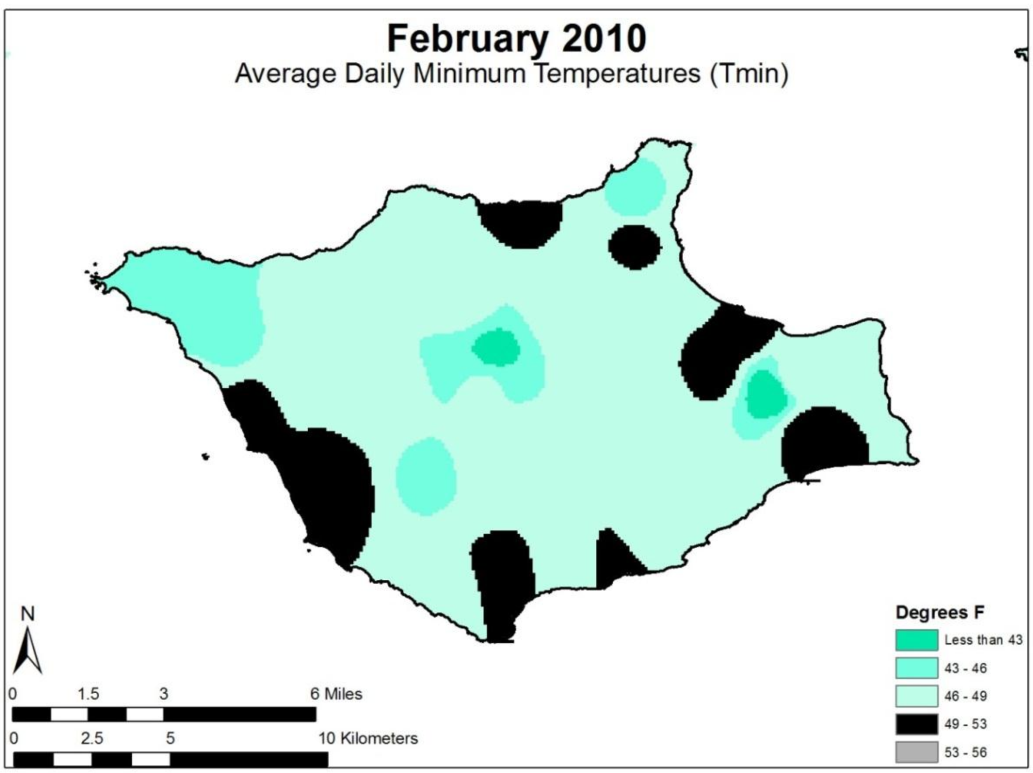


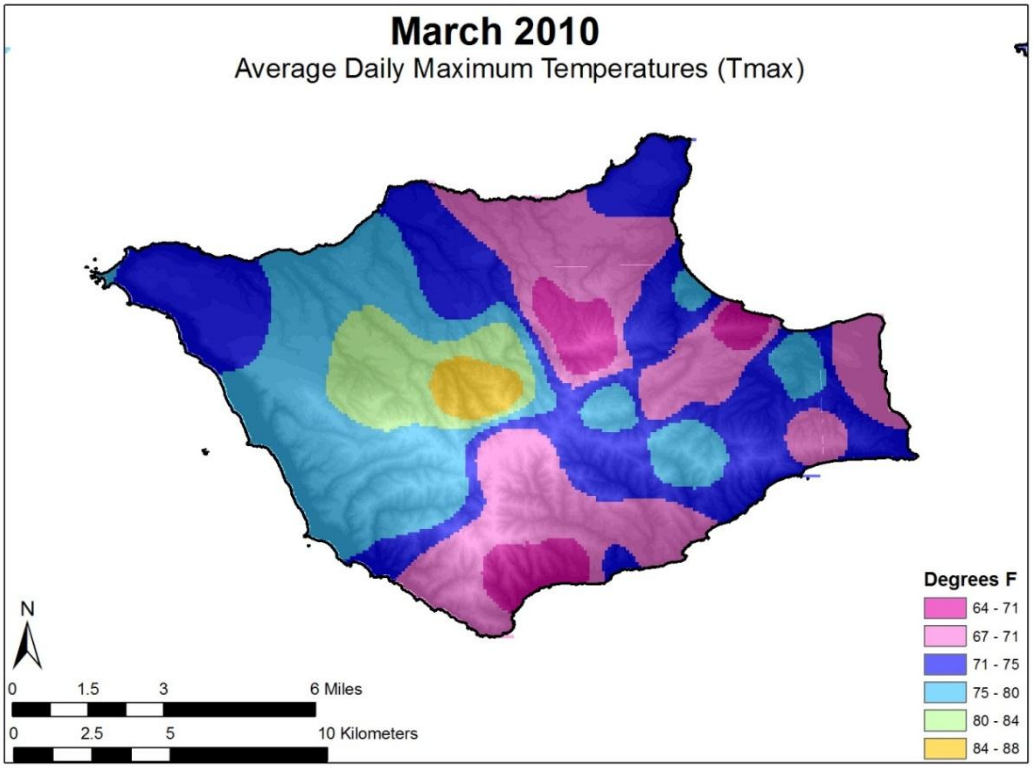
January 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 81
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers

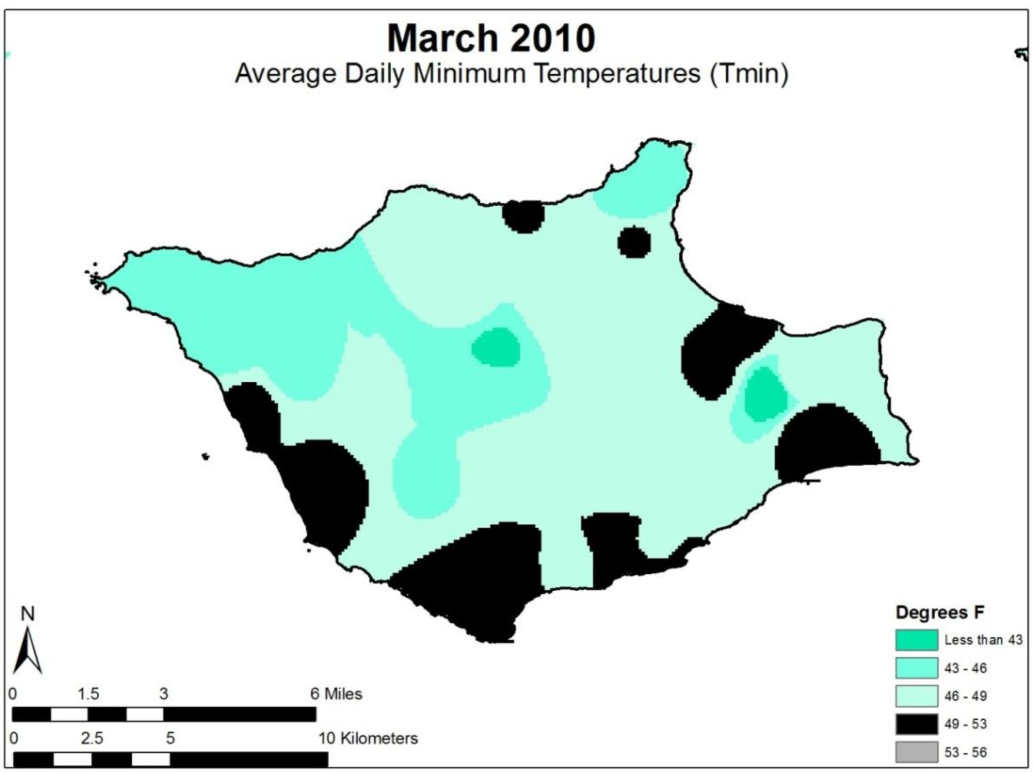


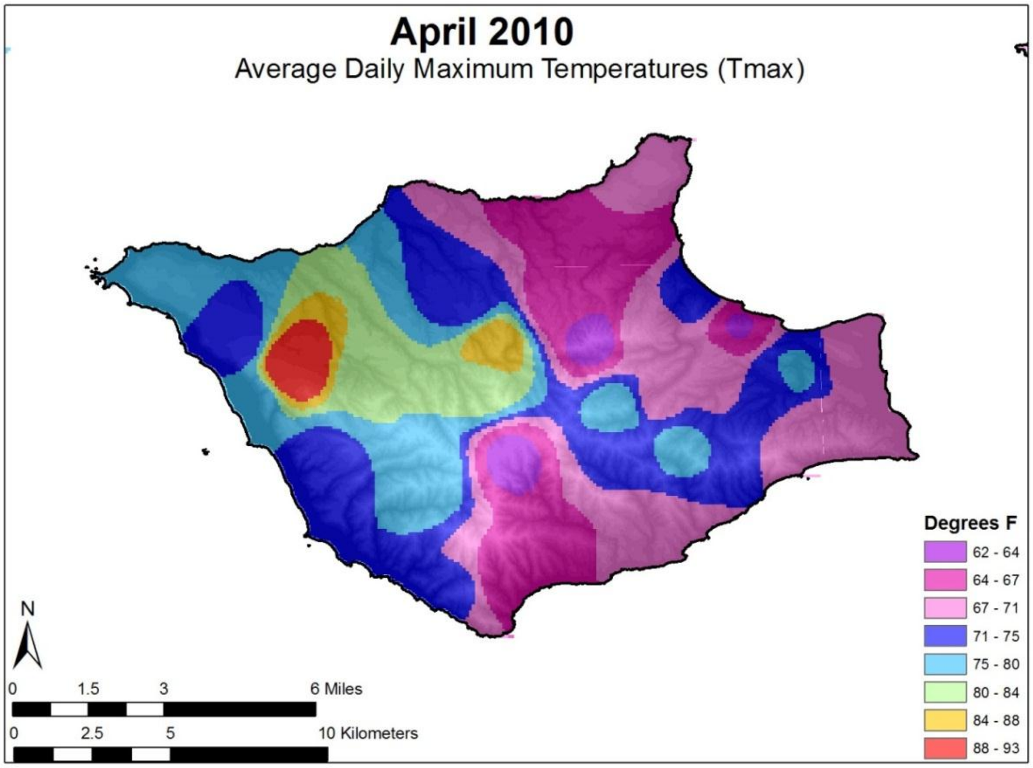
January 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers


February 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
60 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 83
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

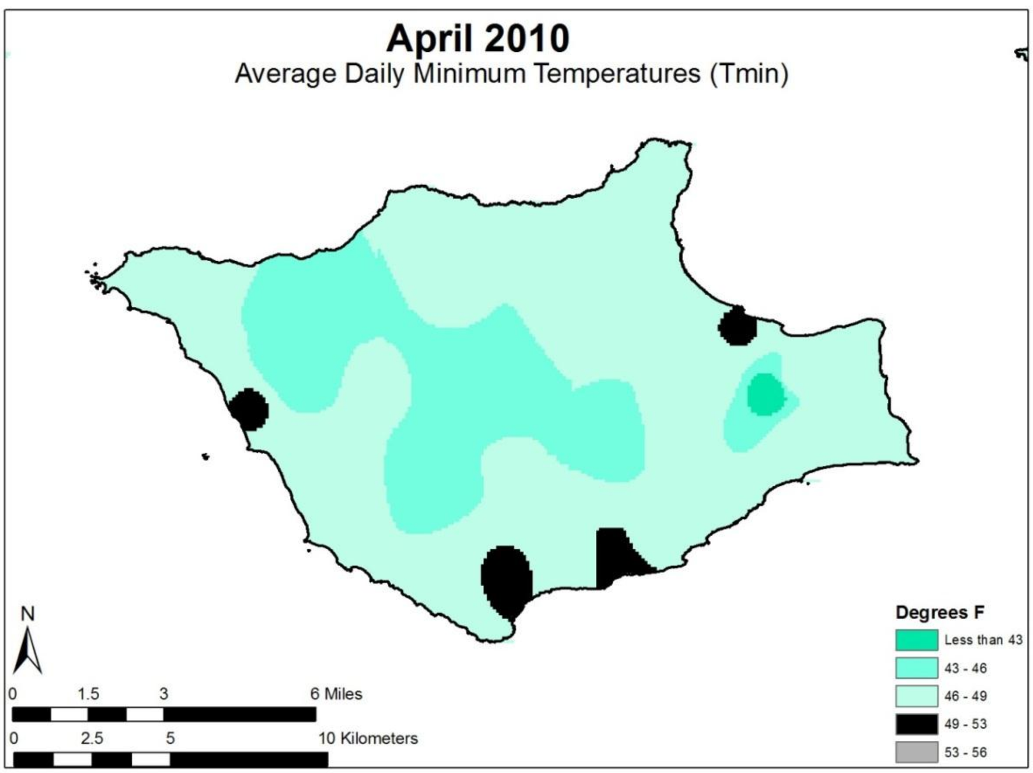

February 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers


March 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
64 - 71
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

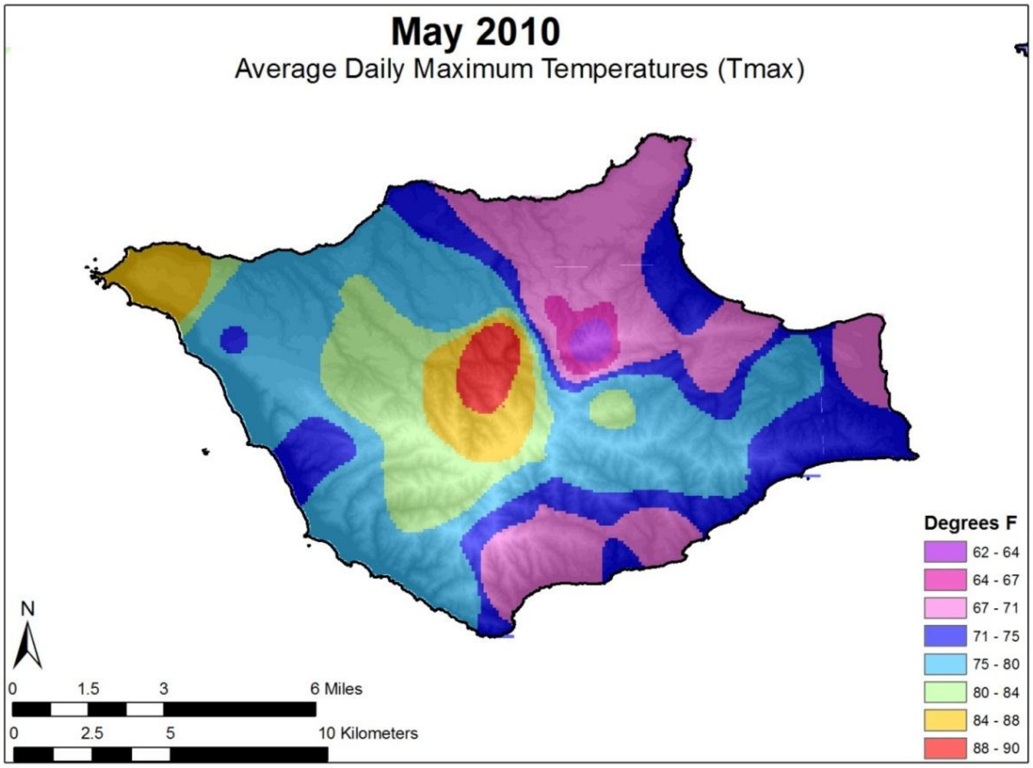

March 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

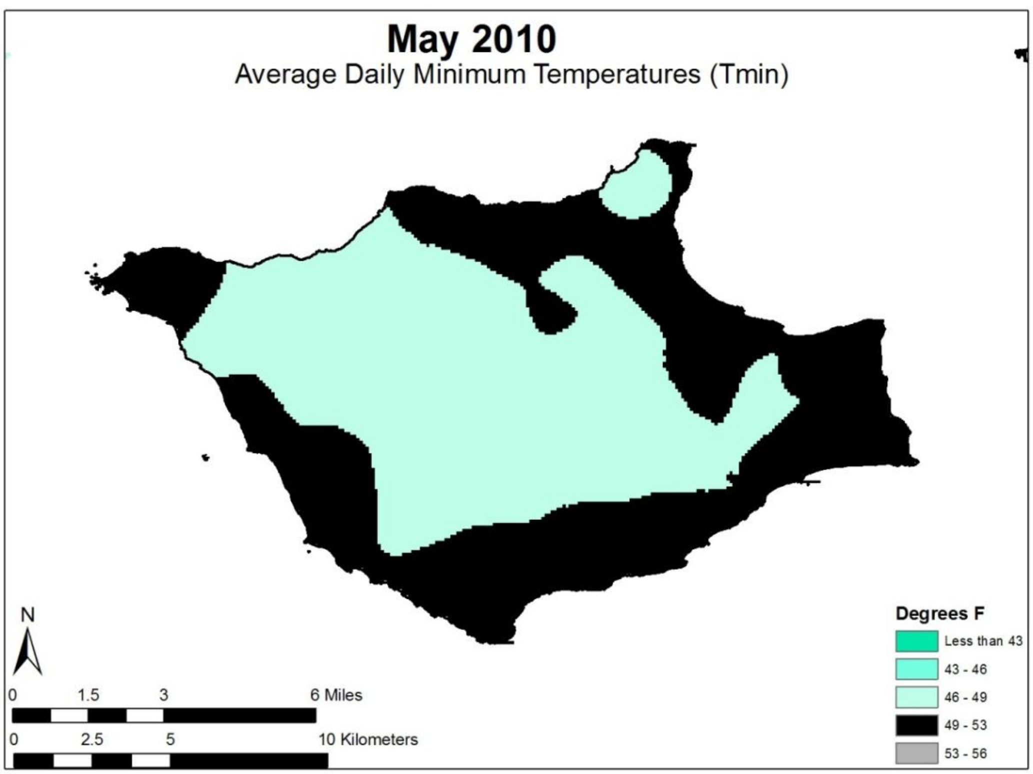


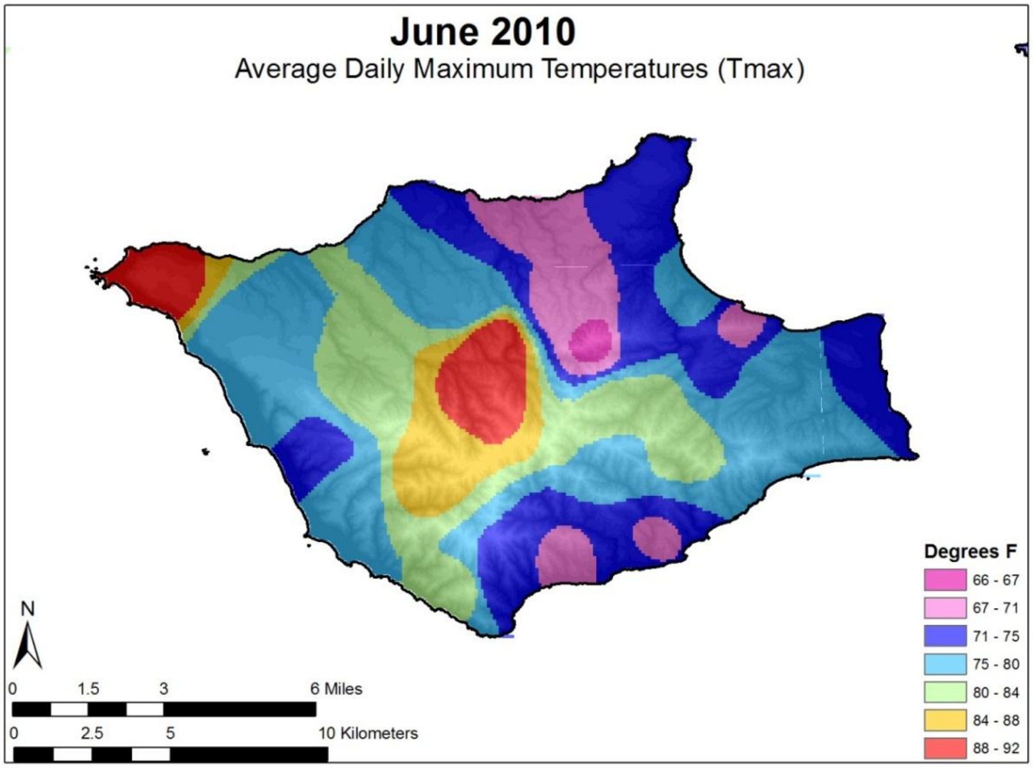
April 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers



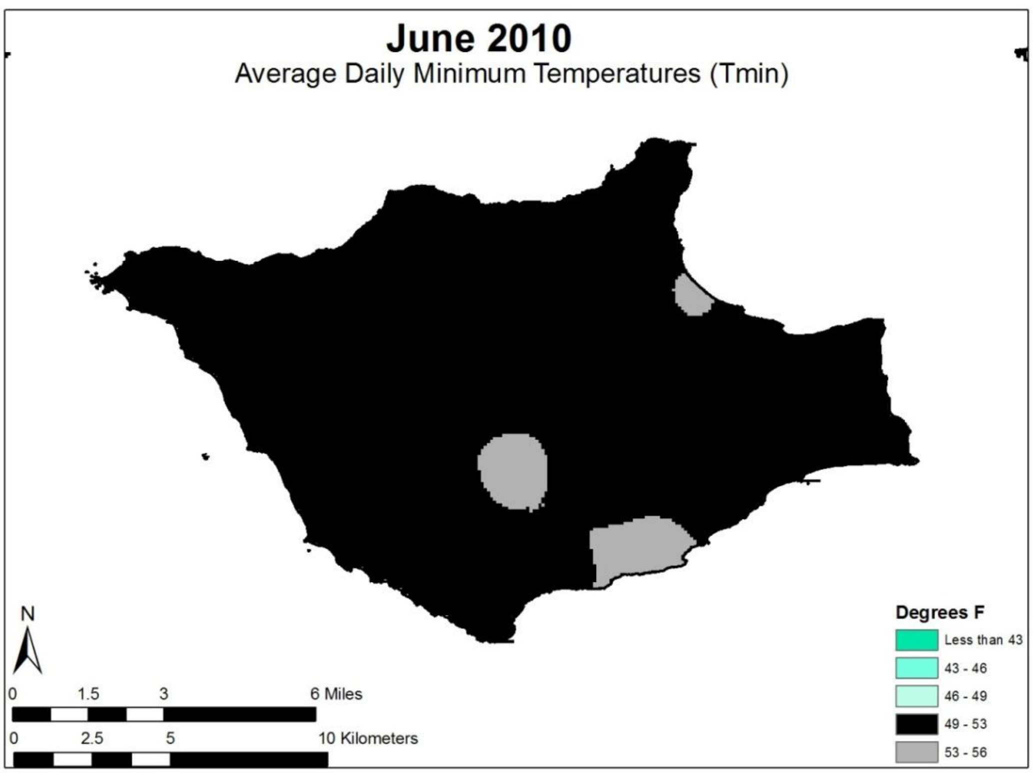
April 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers


May 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 90
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers

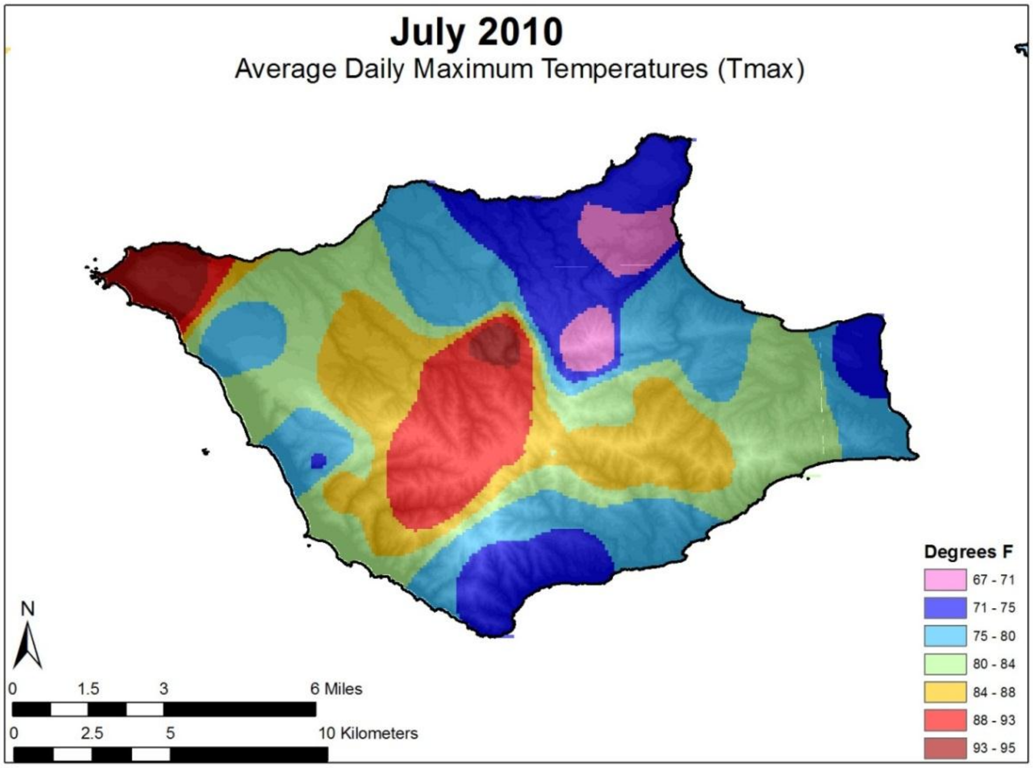

May 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers



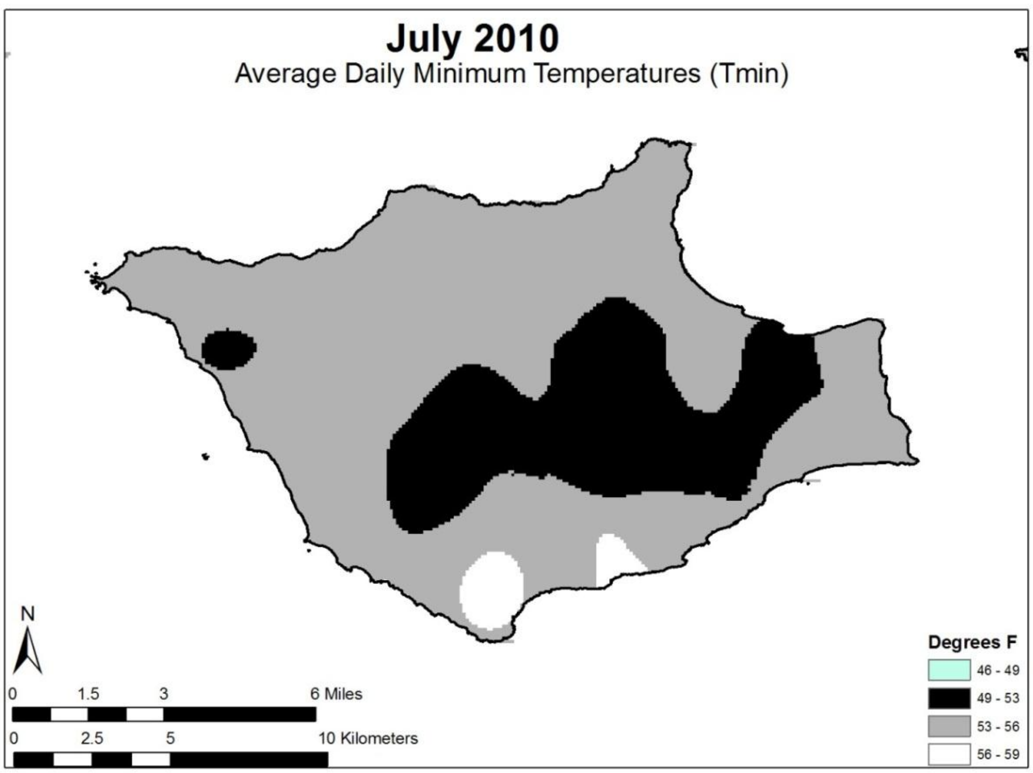
June 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
66 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 92
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers



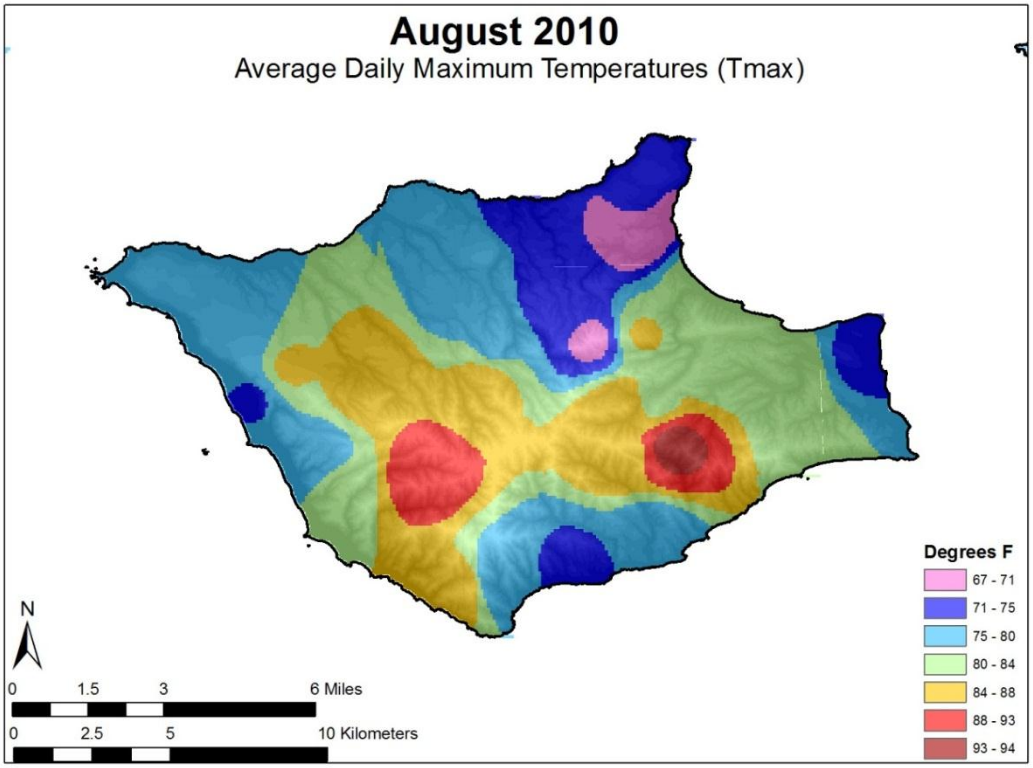
June 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers



July 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
93 - 95
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers



July 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
46 - 49
49 - 53
53 - 56
56 - 59
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers


August 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
93 - 94
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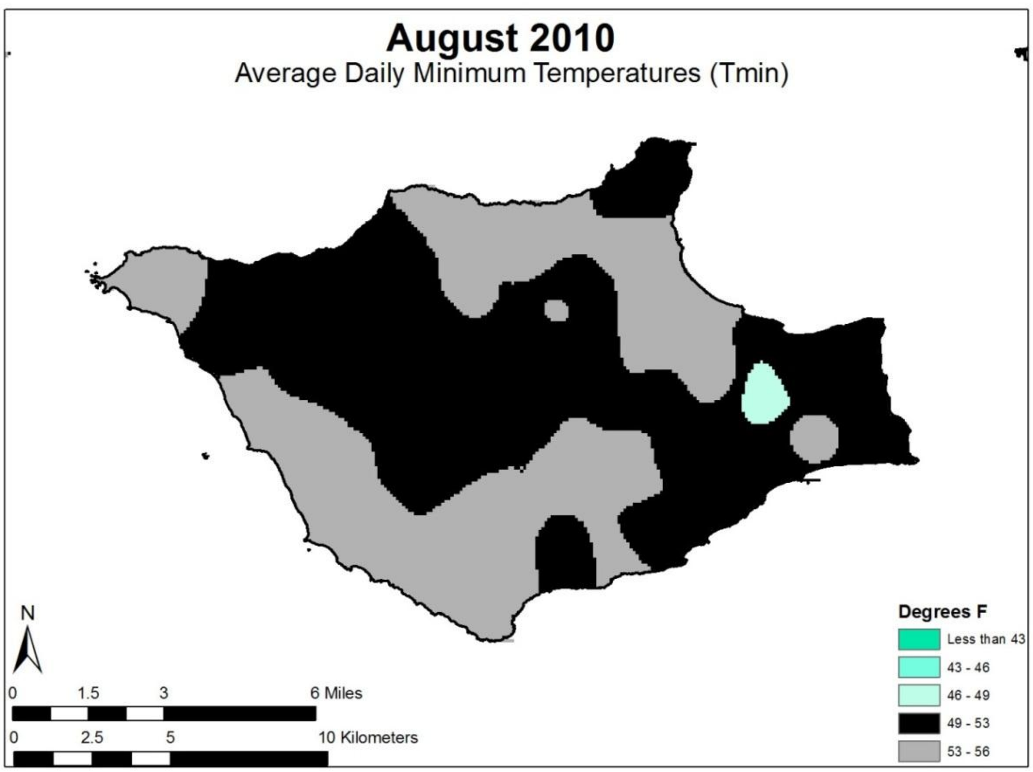
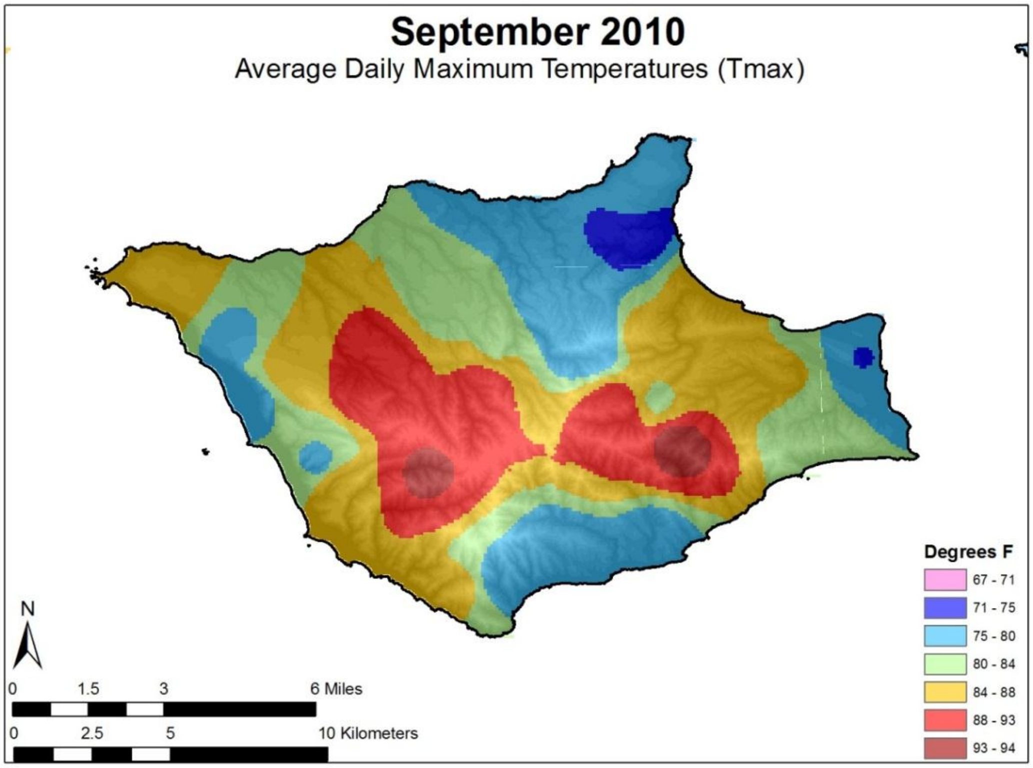
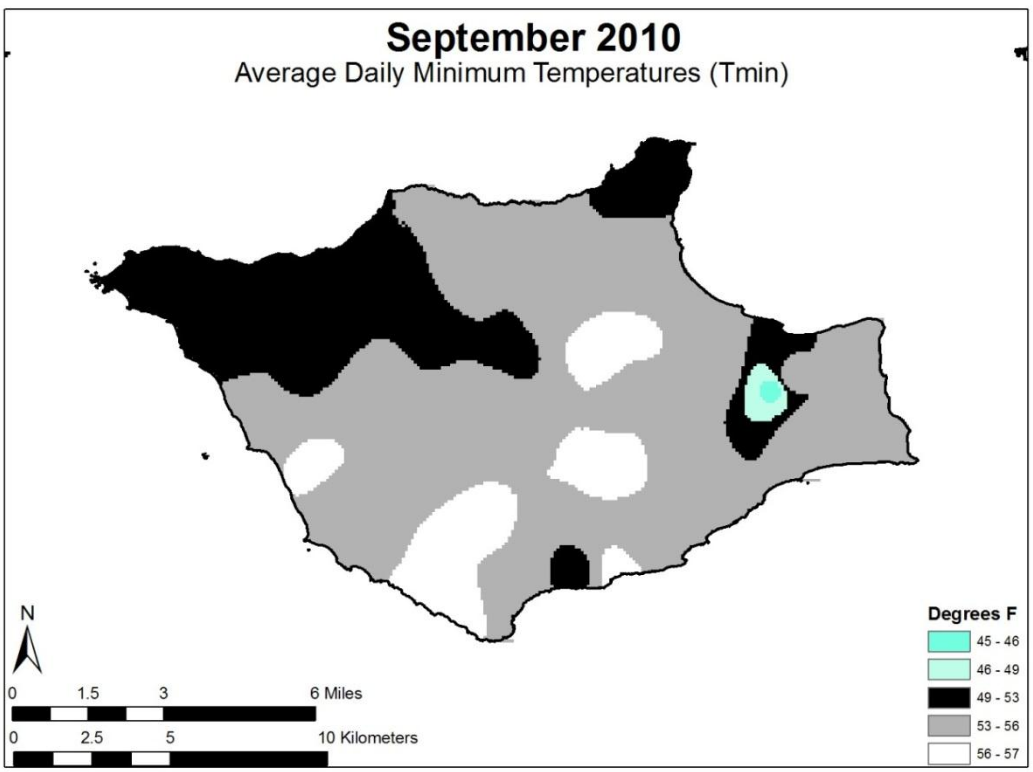
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

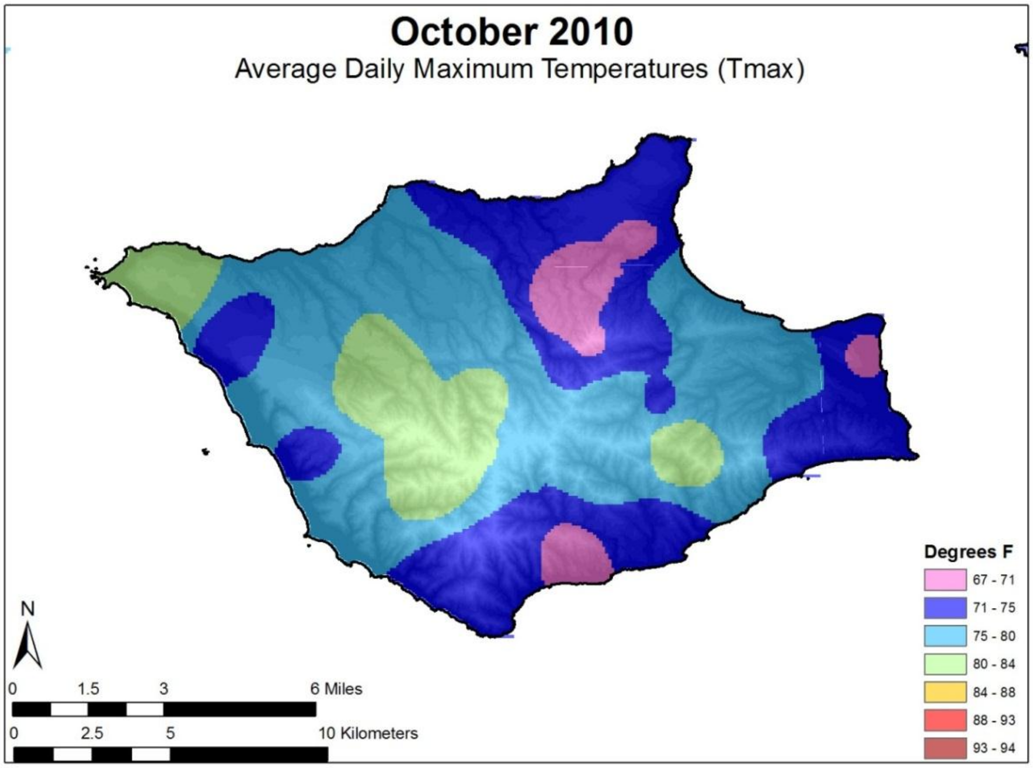

August 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

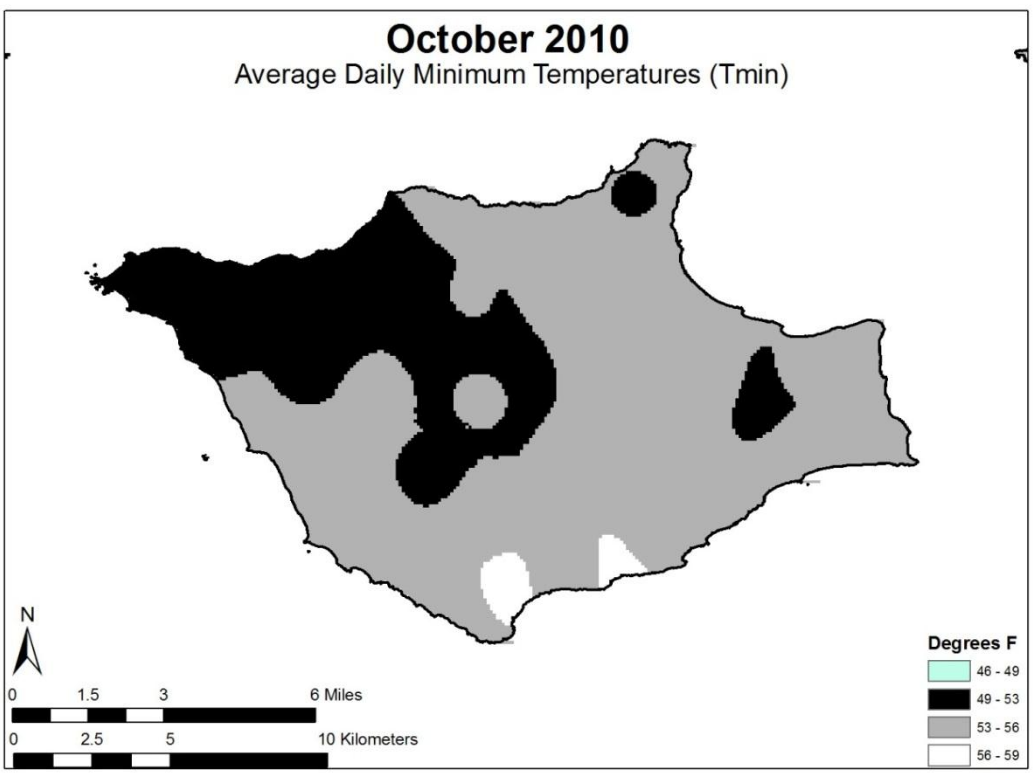


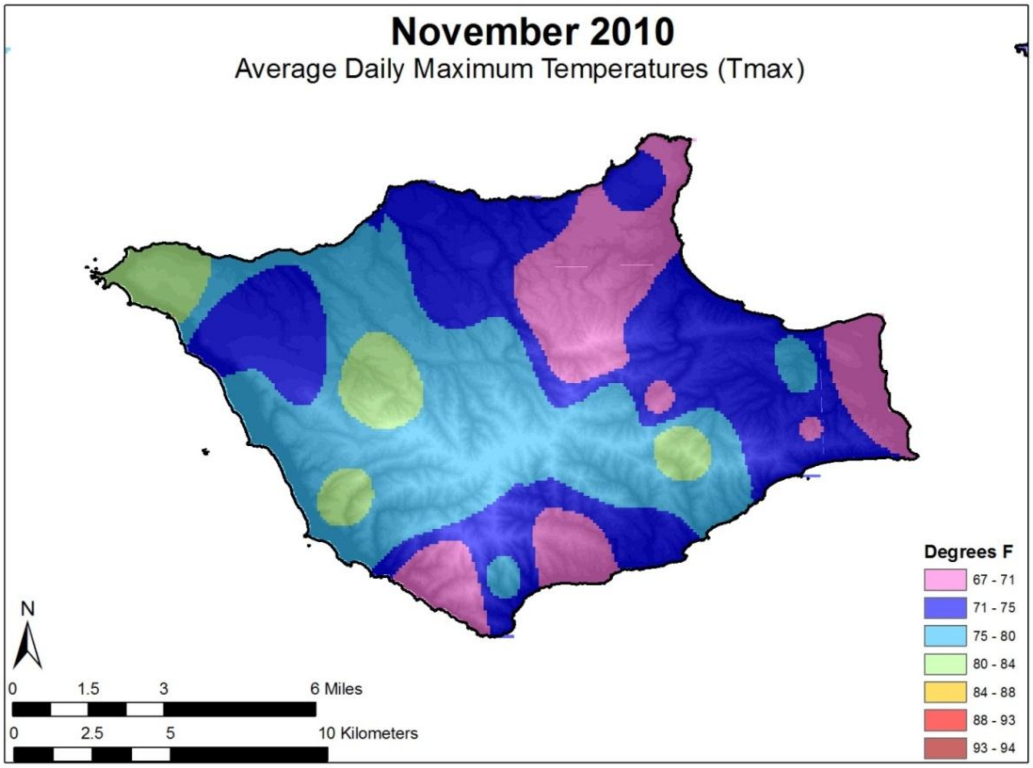
September 2010
Average Daily Maximum Temperatures (Tmax)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
93 - 94

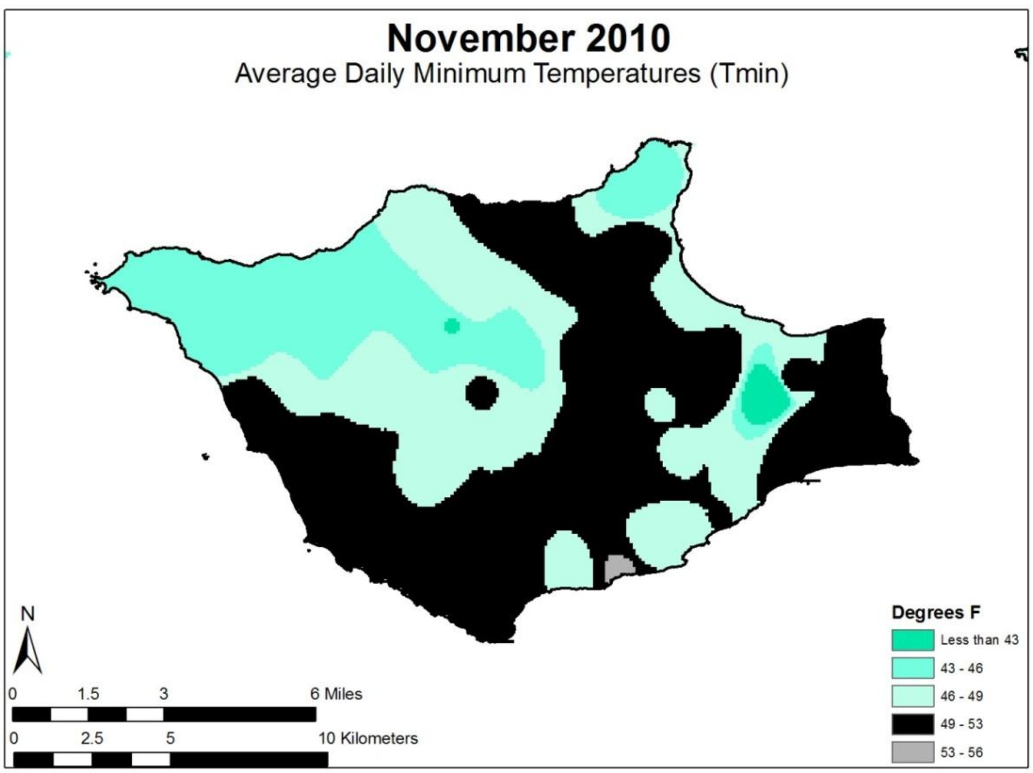


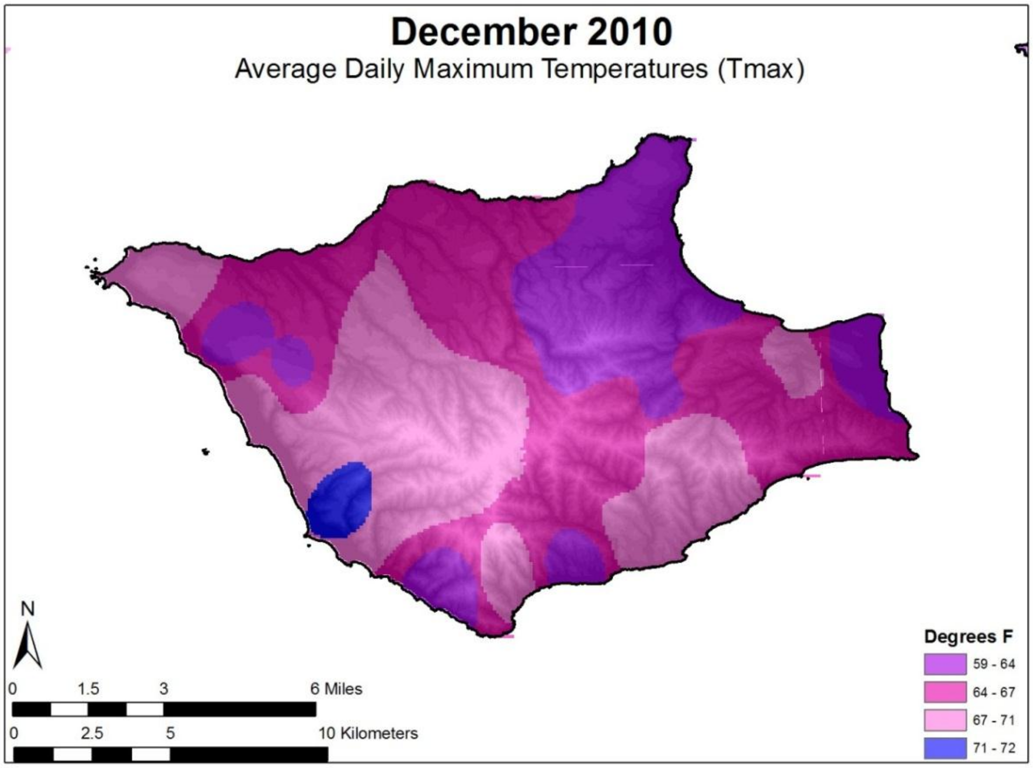
September 2010
Average Daily Minimum Temperatures (Tmin)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
45 - 46
46 - 49
49 - 53
53 - 56
56 - 57


October 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
93 - 94
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

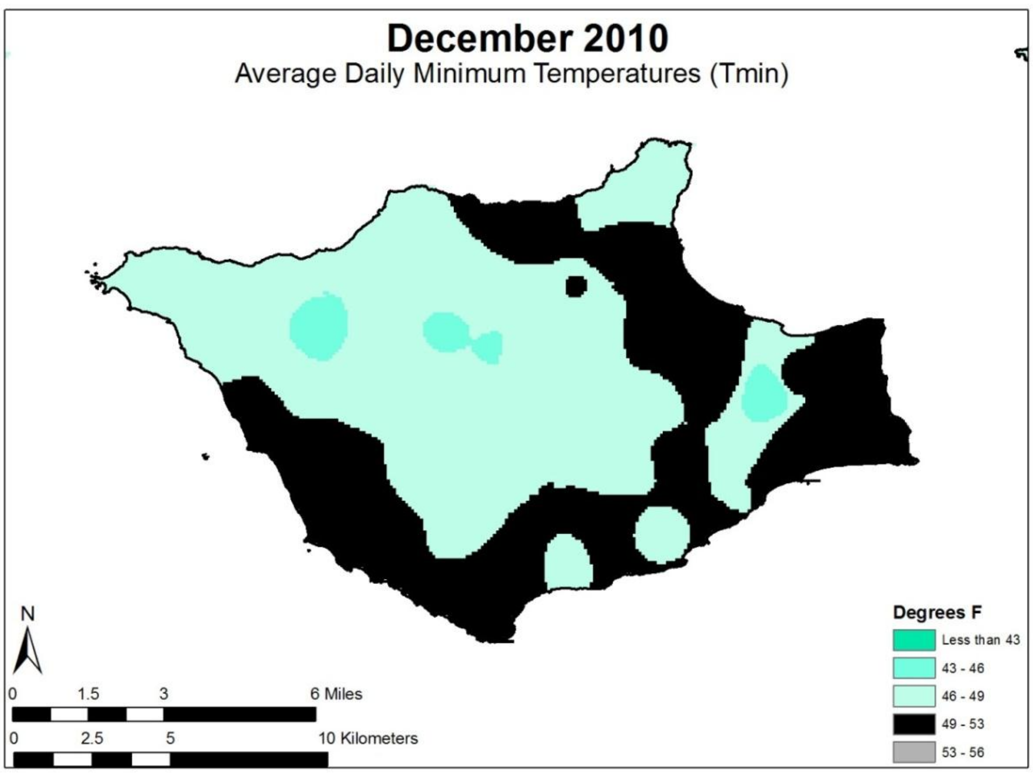

October 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
46 - 49
49 - 53
53 - 56
56 - 59
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers


November 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
93 - 94
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

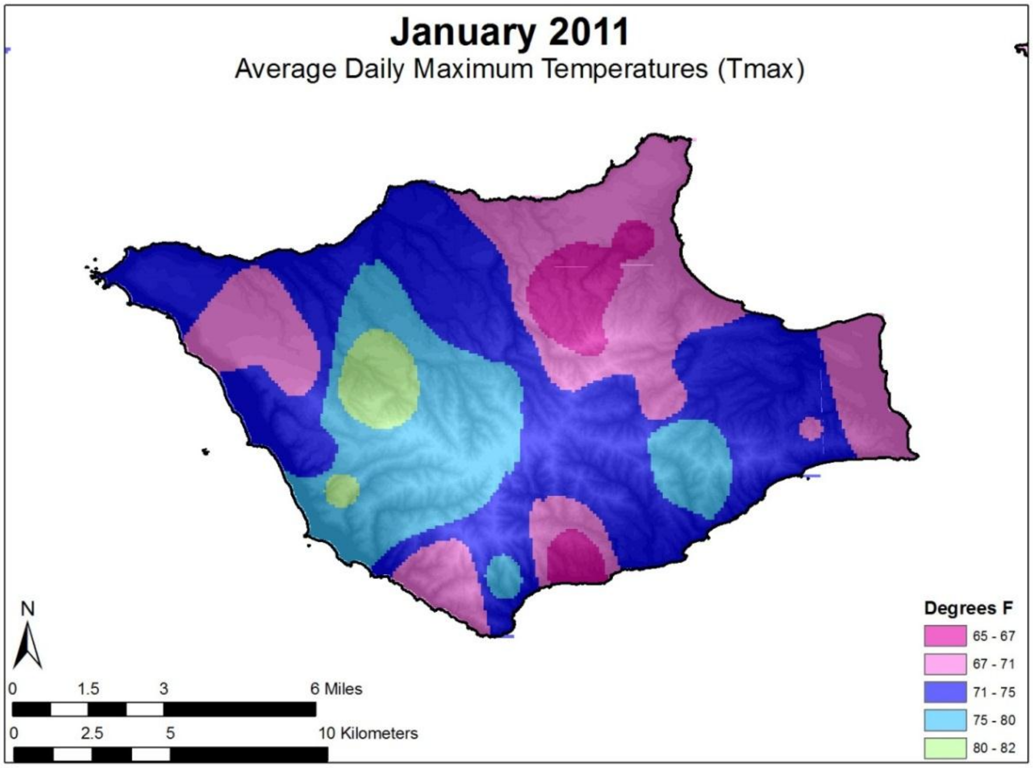

November 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

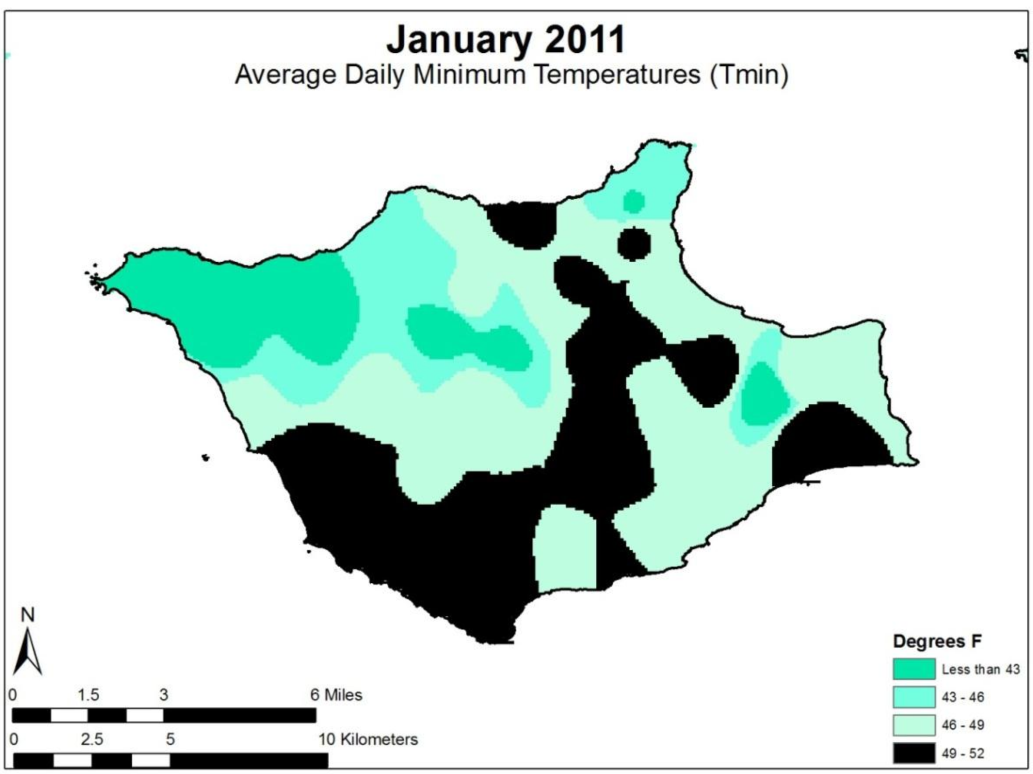


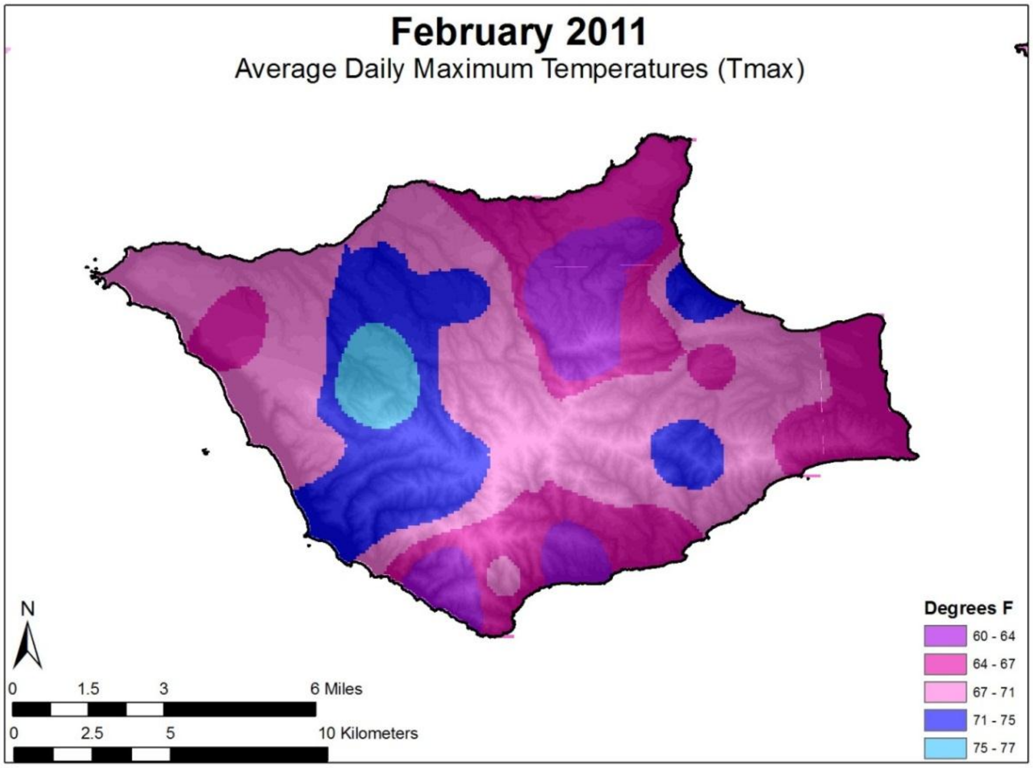
December 2010
Average Daily Maximum Temperatures (Tmax)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
59 - 64
64 - 67
67 - 71
71 - 72

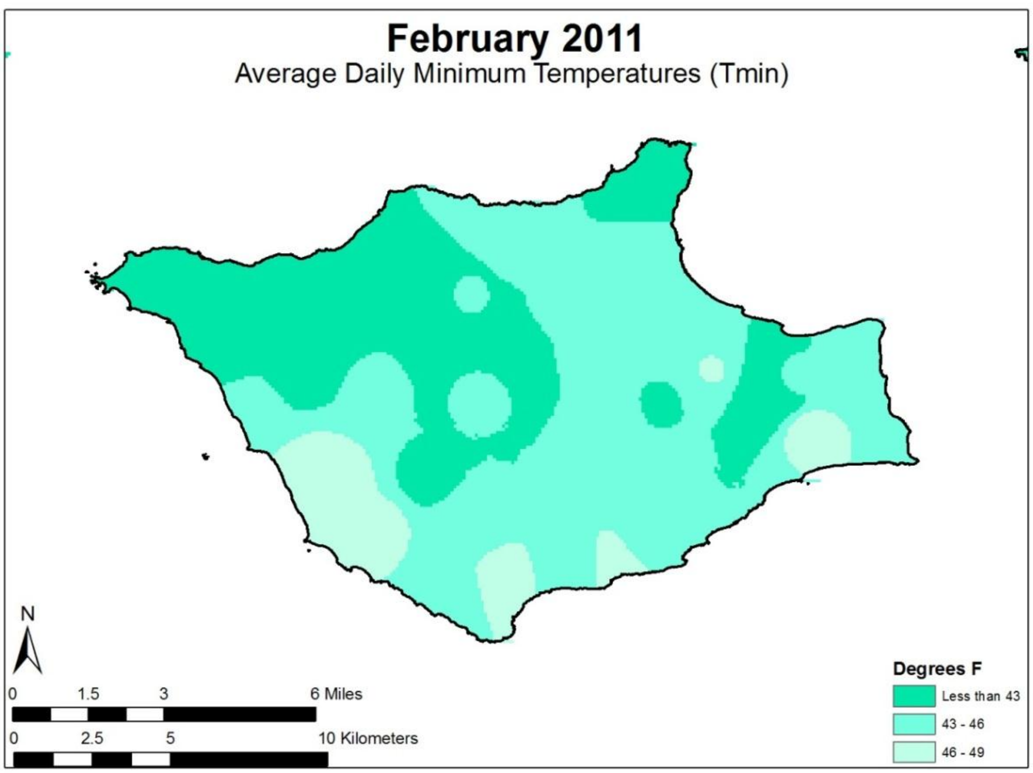


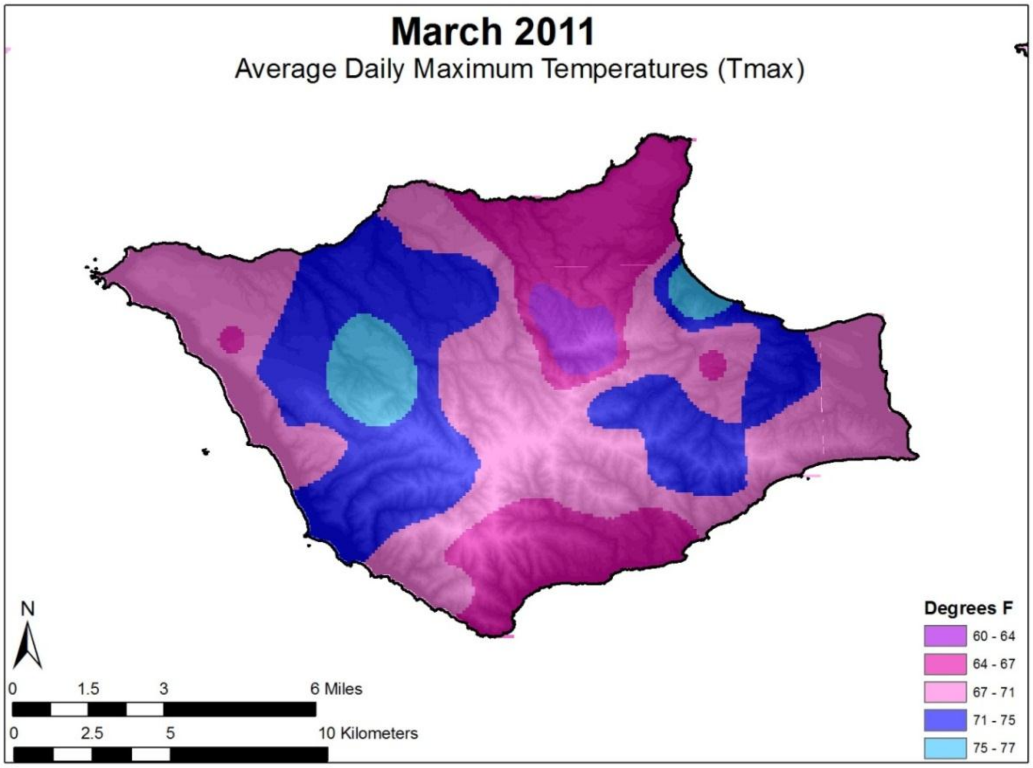
December 2010
Average Daily Minimum Temperatures (Tmin)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56

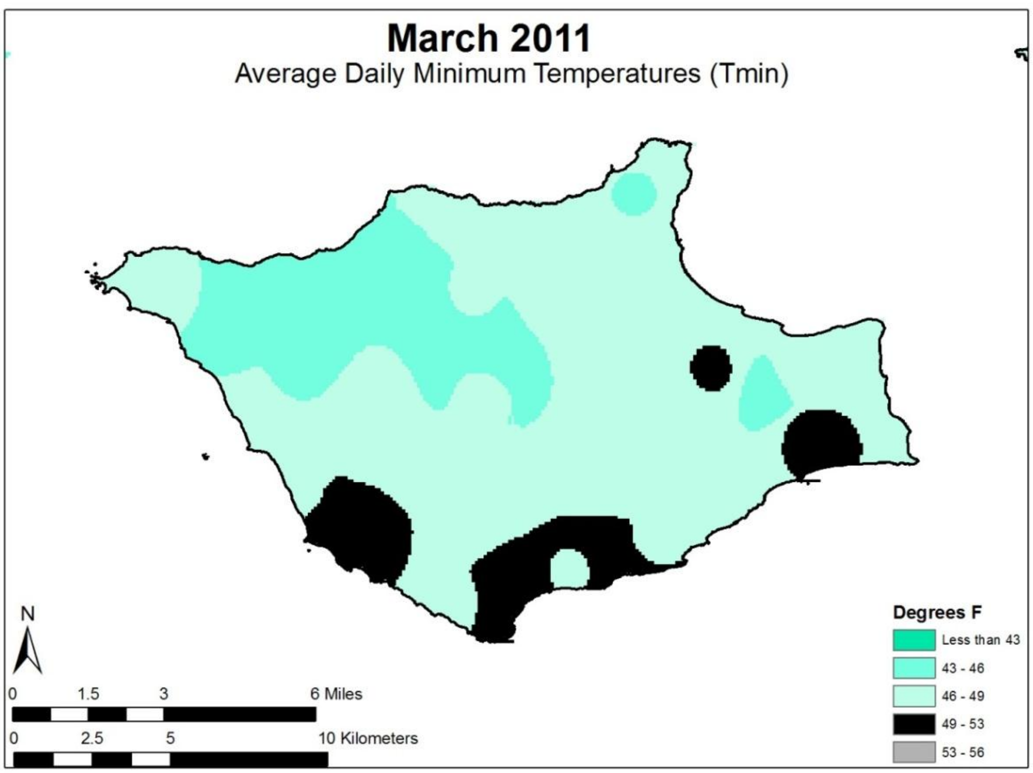

January 2011
Average Daily Maximum Temperatures (Tmax)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
65 - 67
67 - 71
71 - 75
75 - 80
80 - 82

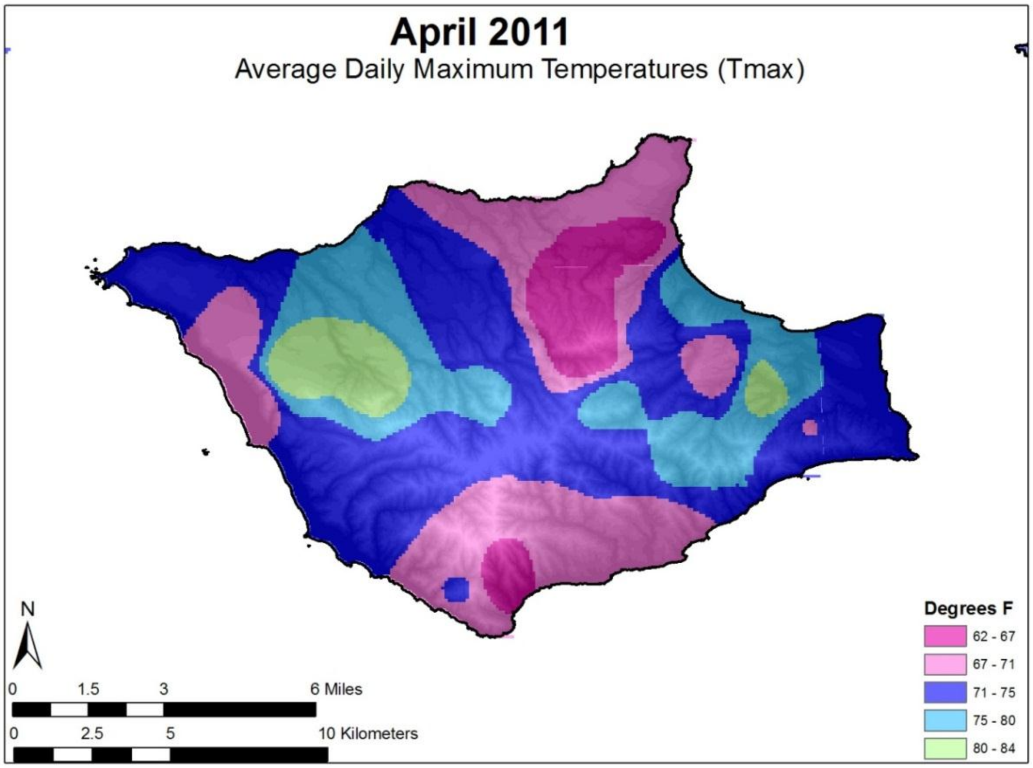

January 2011
Average Daily Minimum Temperatures (Tmin)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 52

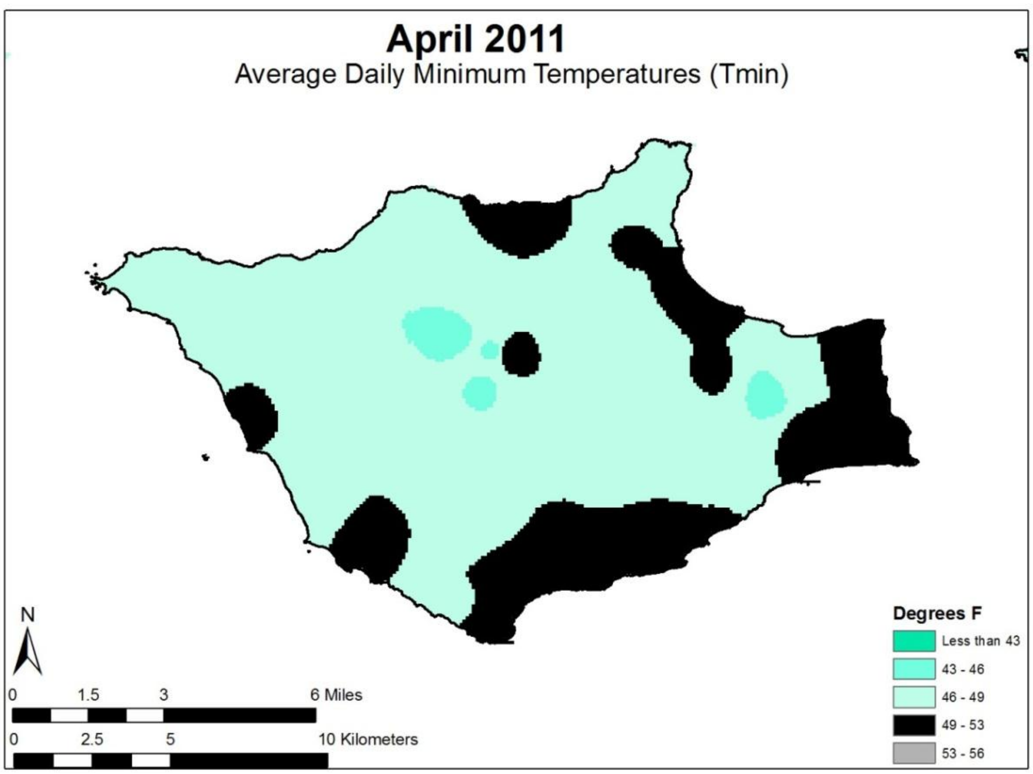

February 2011
Average Daily Maximum Temperatures (Tmax)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
60 - 64
64 - 67
67 - 71
71 - 75
75 - 77

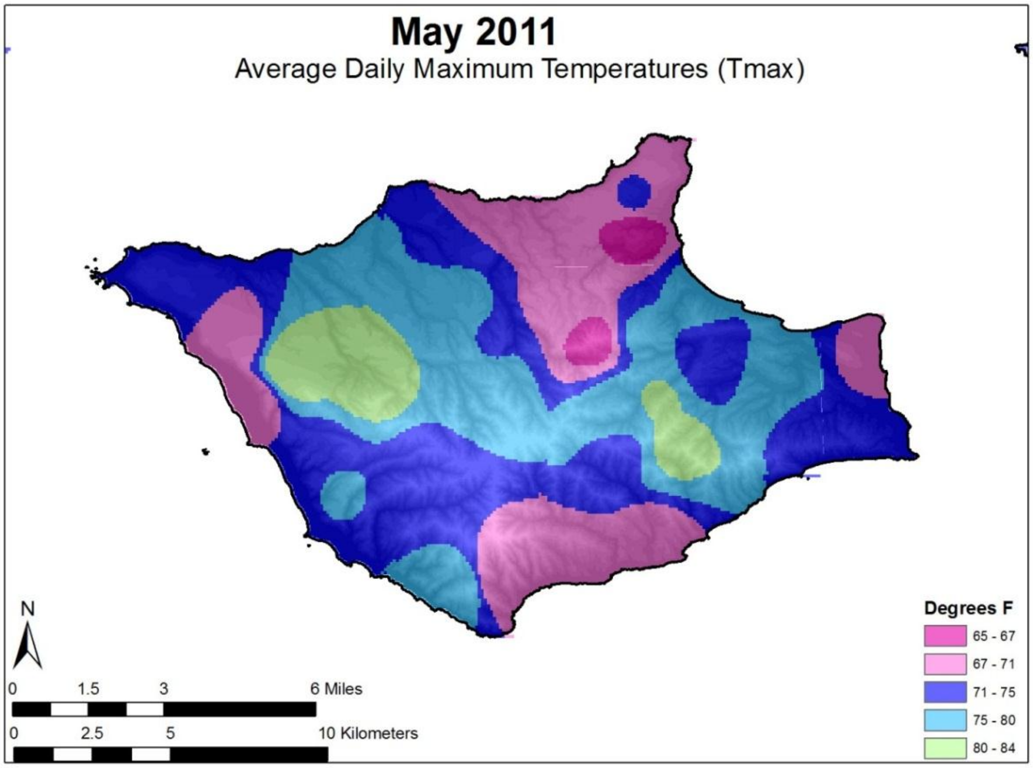

February 2011
Average Daily Minimum Temperatures (Tmin)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49

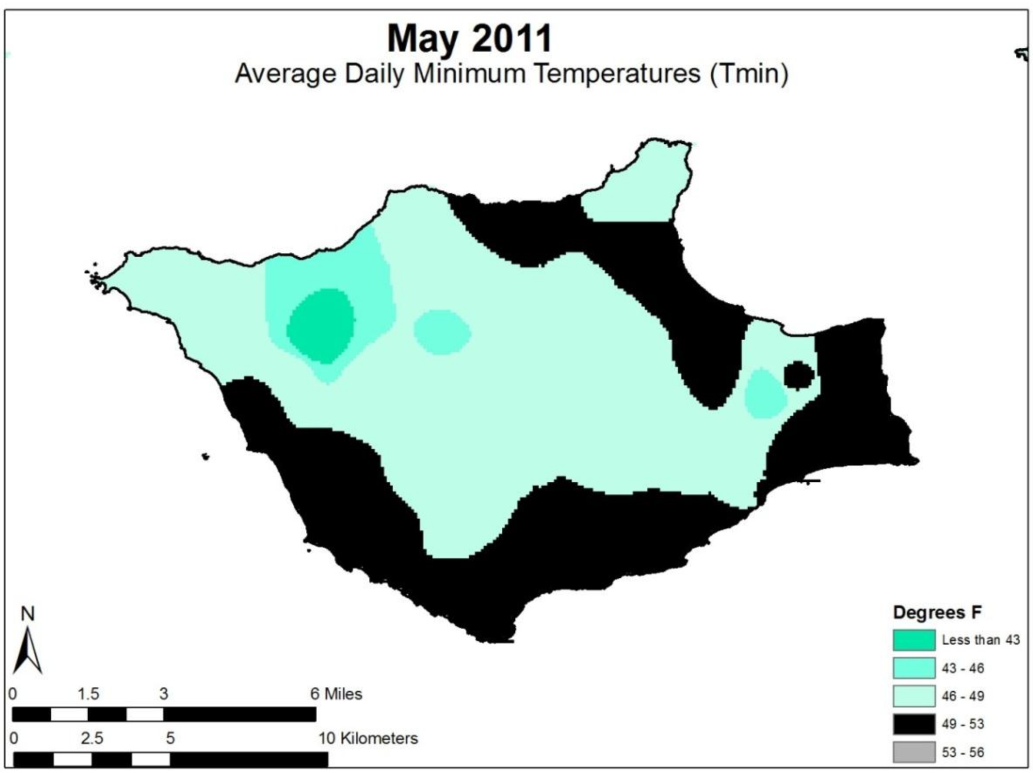

March 2011
Average Daily Maximum Temperatures (Tmax)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
60 - 64
64 - 67
67 - 71
71 - 75
75 - 77

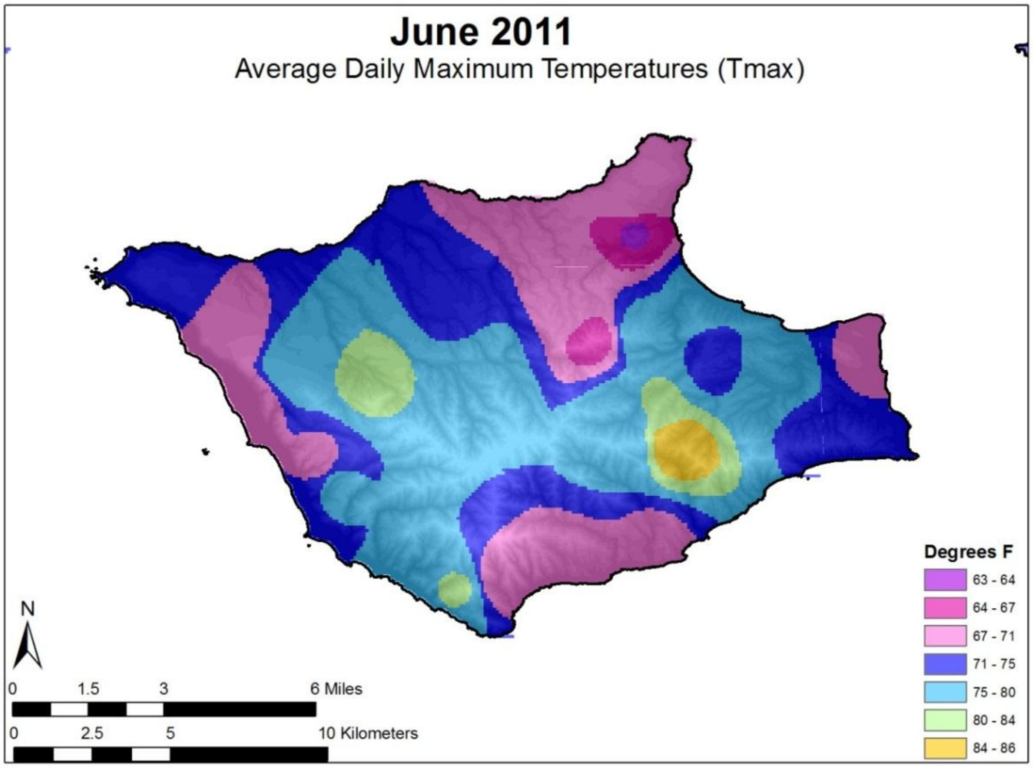

March 2011
Average Daily Minimum Temperatures (Tmin)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56

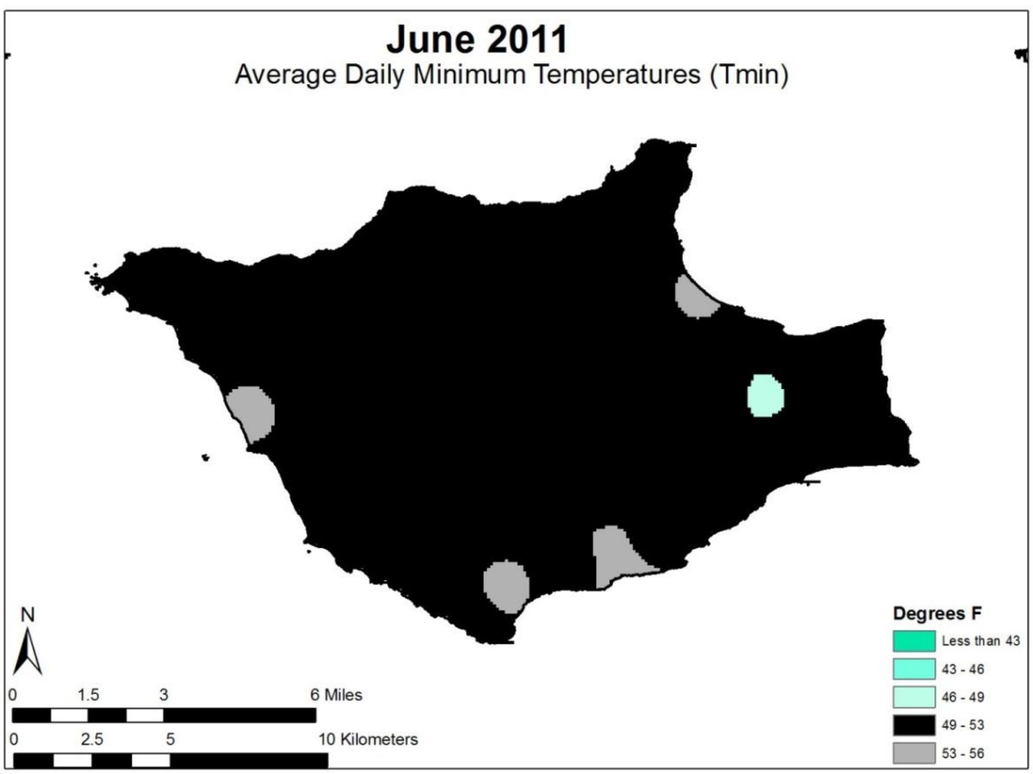

April 2011
Average Daily Maximum Temperatures (Tmax)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
62 - 67
67 - 71
71 - 75
75 - 80
80 - 84

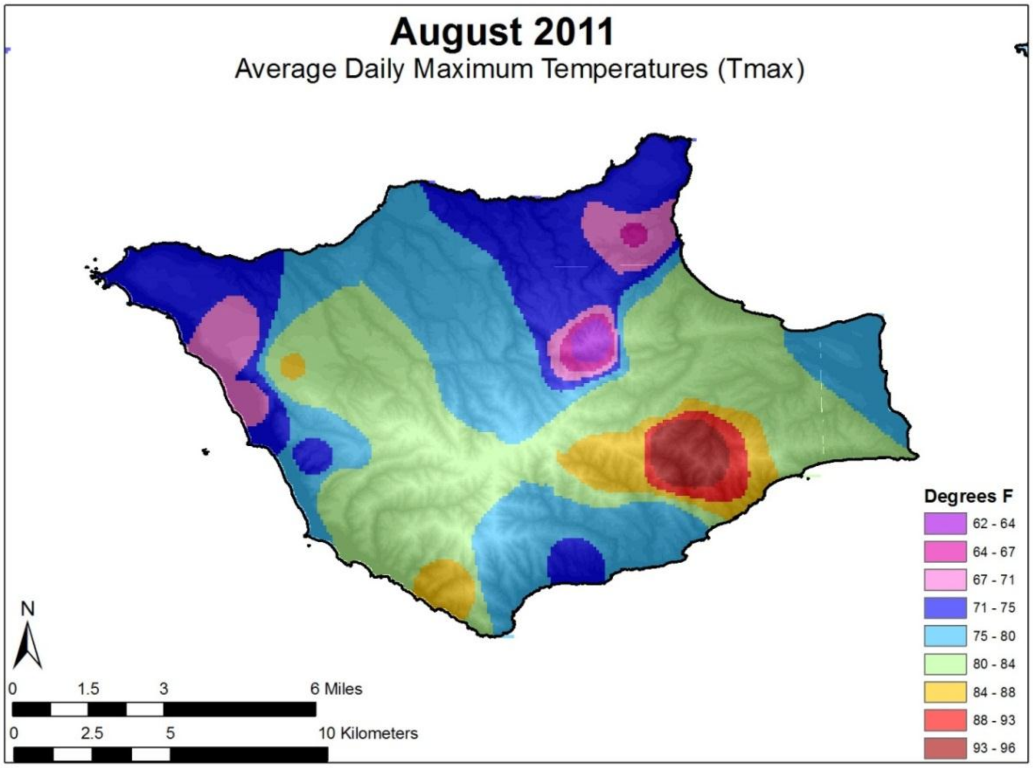

April 2011
Average Daily Minimum Temperatures (Tmin)
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56

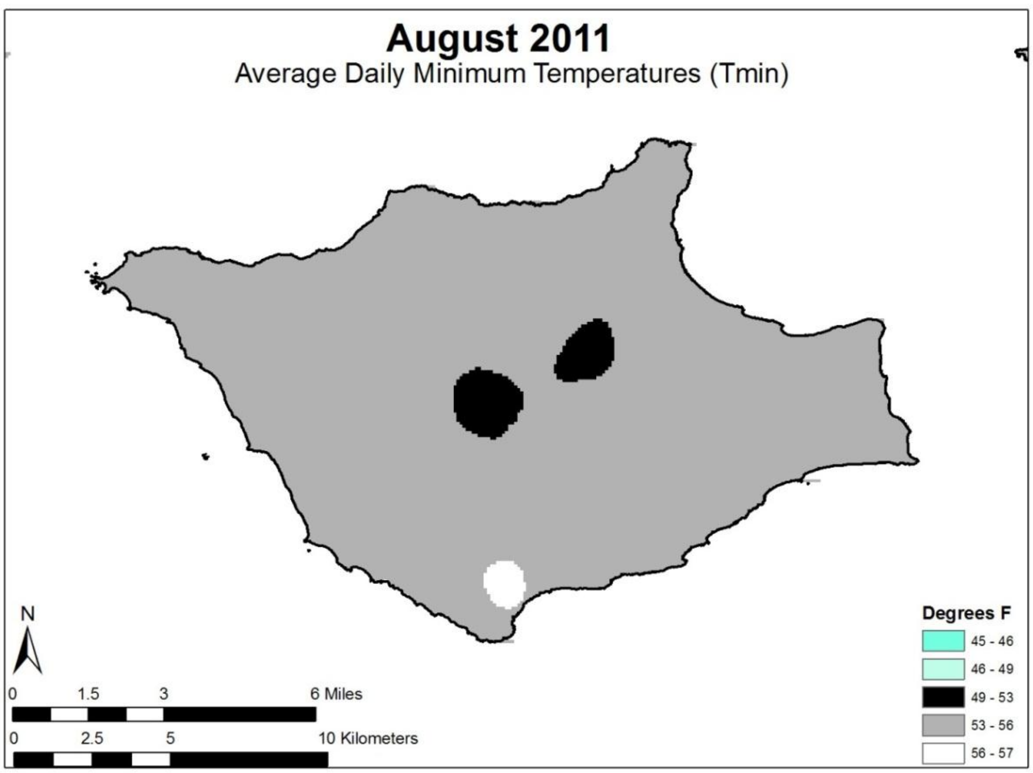

May 2011
Average Daily Maximum Temperatures (Tmax)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
65 - 67
67 - 71
71 - 75
75 - 80
80 - 84


May 2011
Average Daily Minimum Temperatures (Tmin)
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56

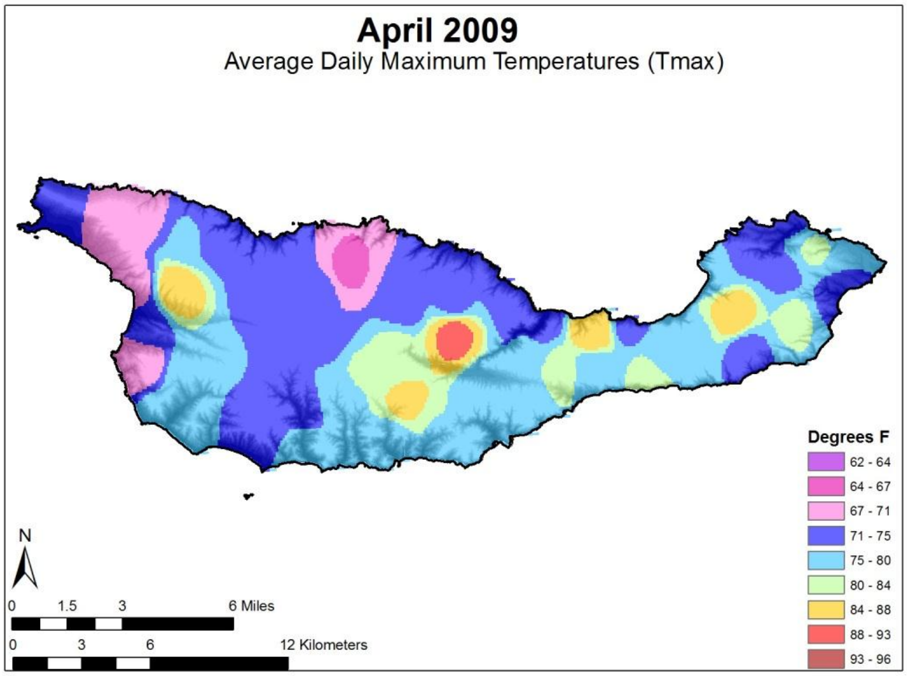

June 2011
Average Daily Maximum Temperatures (Tmax)
Degrees F
63 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 86
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers

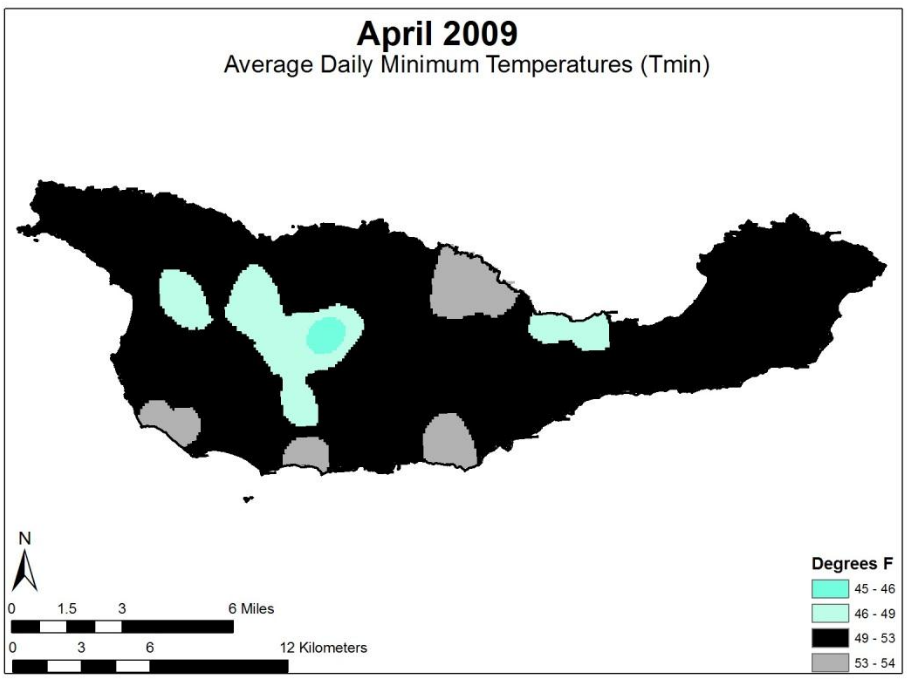

June 2011
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0
1.5
3
6 Miles
0
2.5
5
10 Kilometers

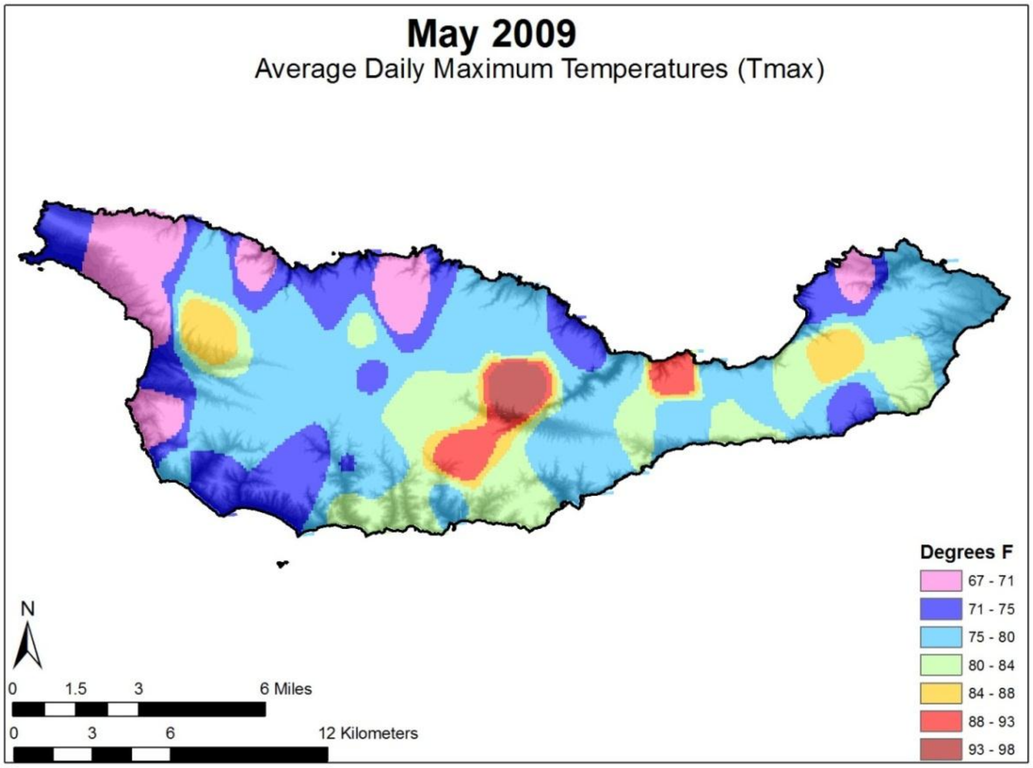

August 2011
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
93 - 96
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

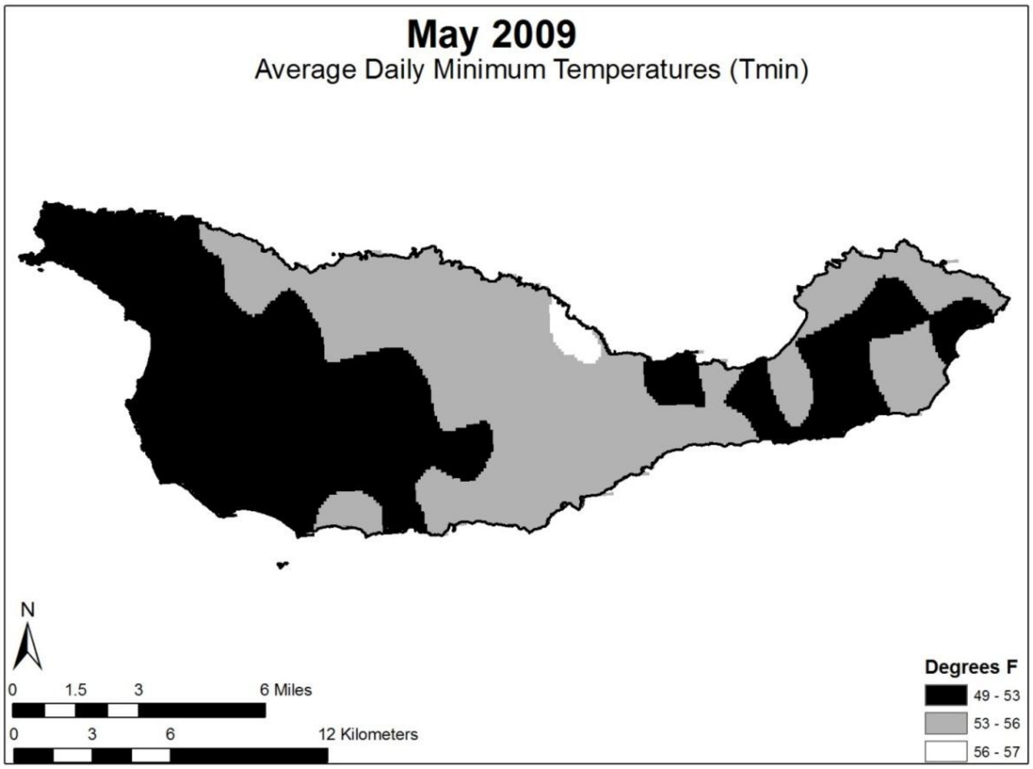

August 2011
Average Daily Minimum Temperatures (Tmin)
Degrees F
45 - 46
46 - 49
49 - 53
53 - 56
56 - 57
N
0 1.5 3 6 Miles
0 2.5 5 10 Kilometers

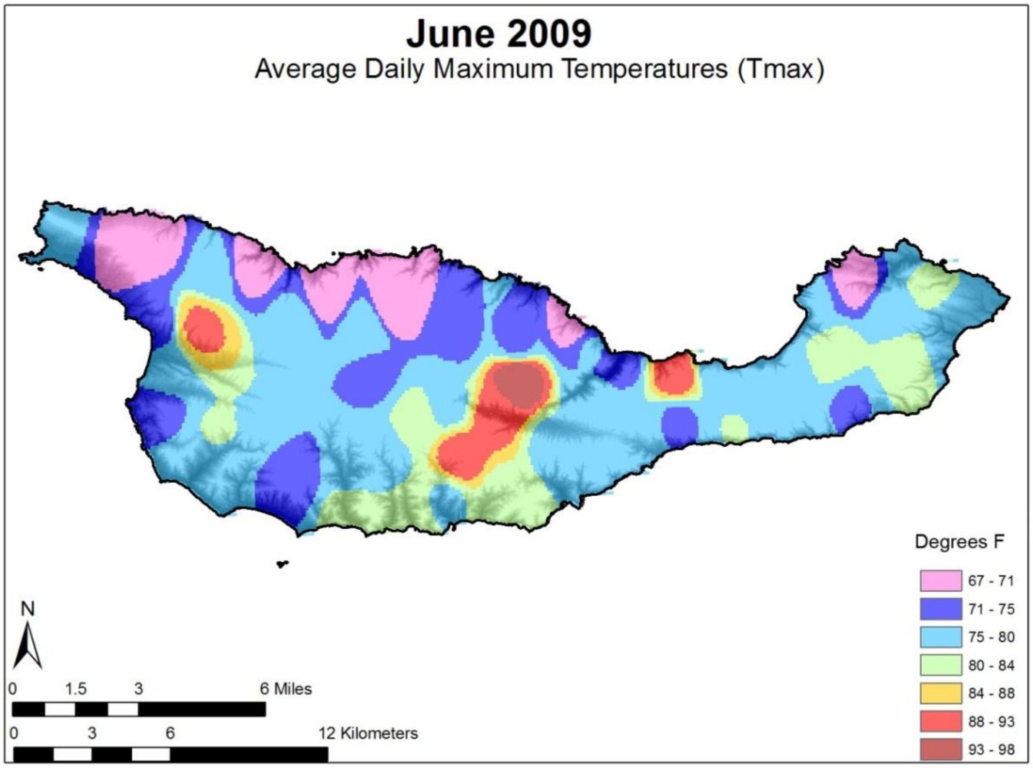
Santa Cruz Island

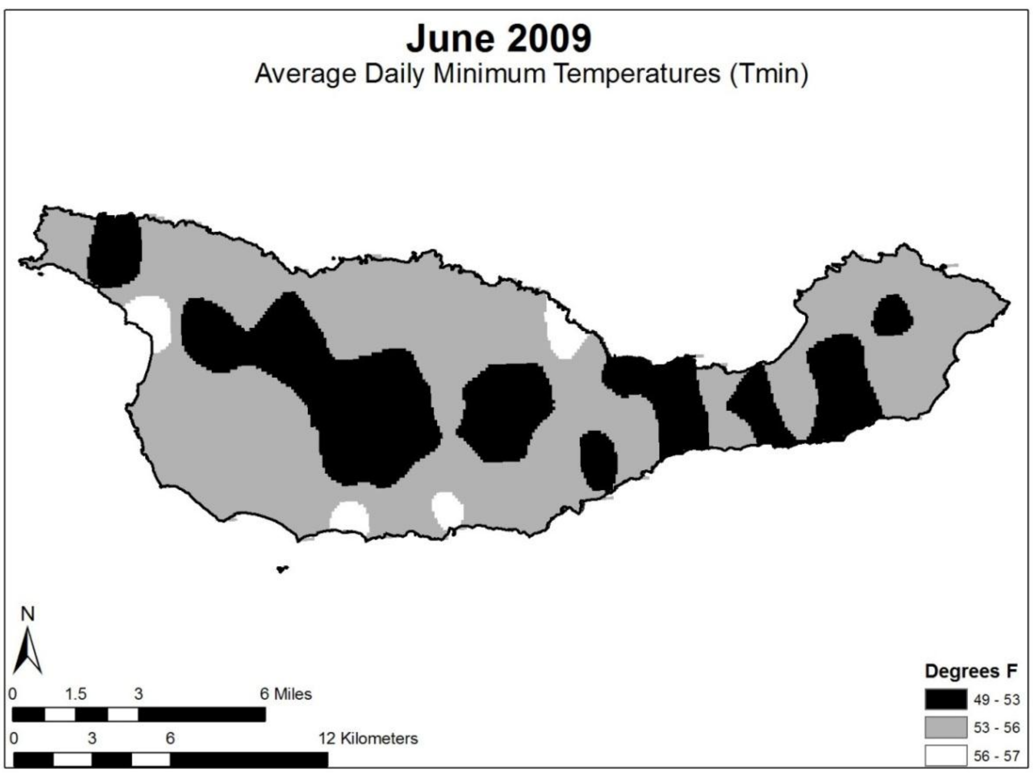


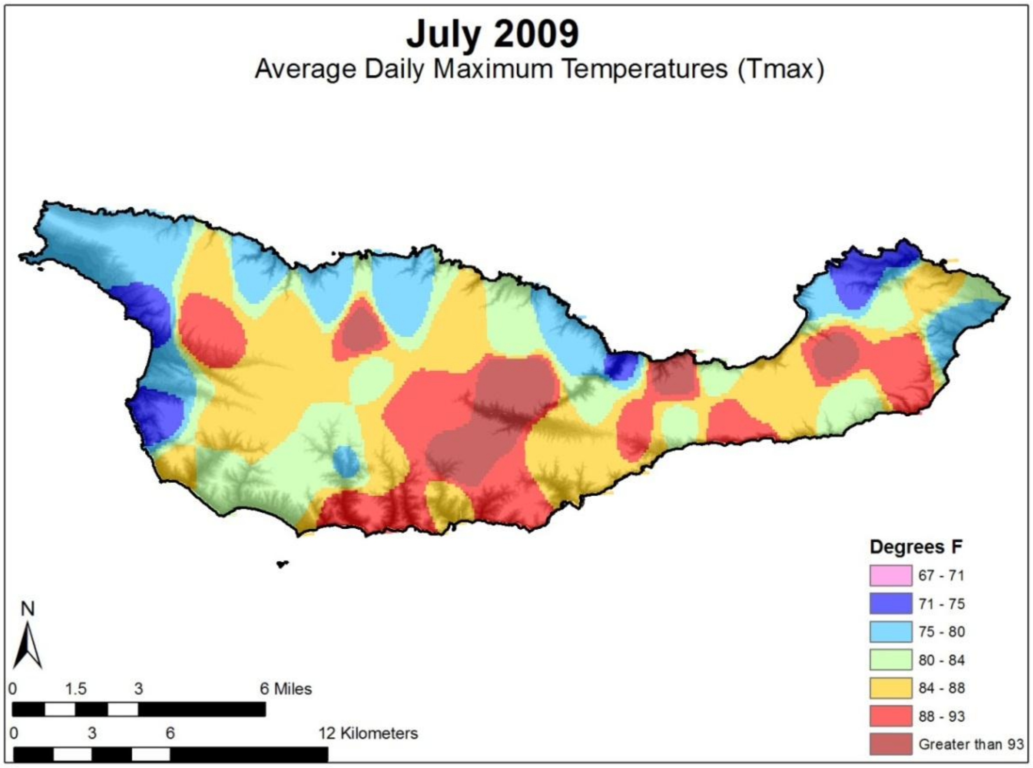


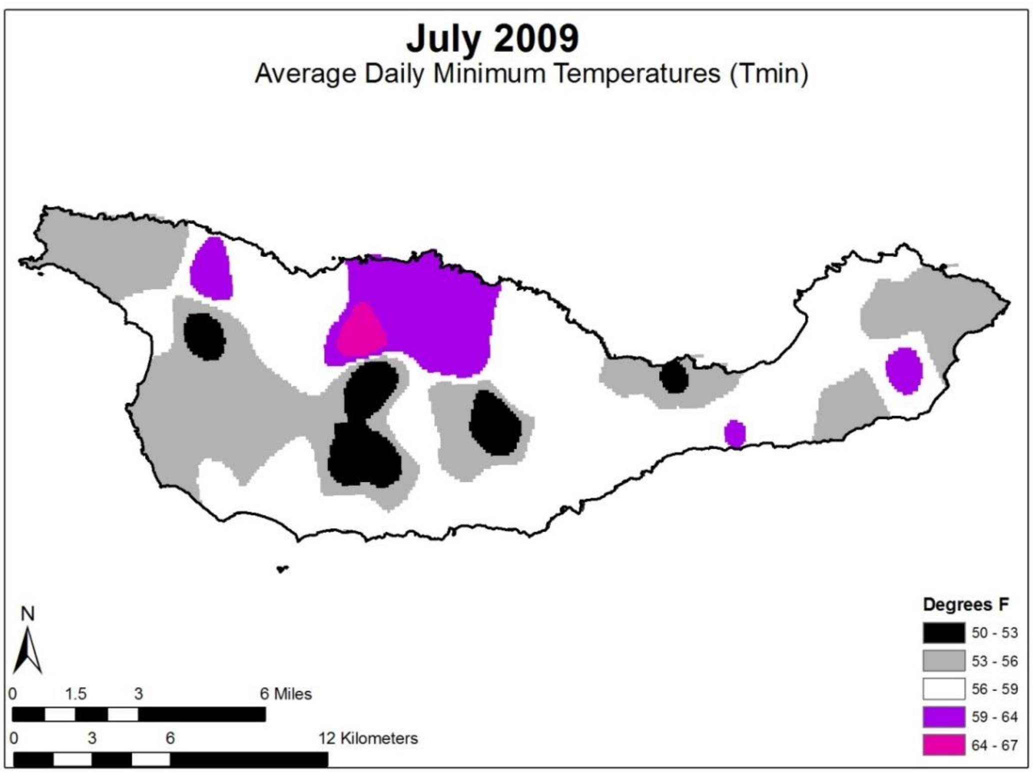

May 2009
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
93 - 98
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

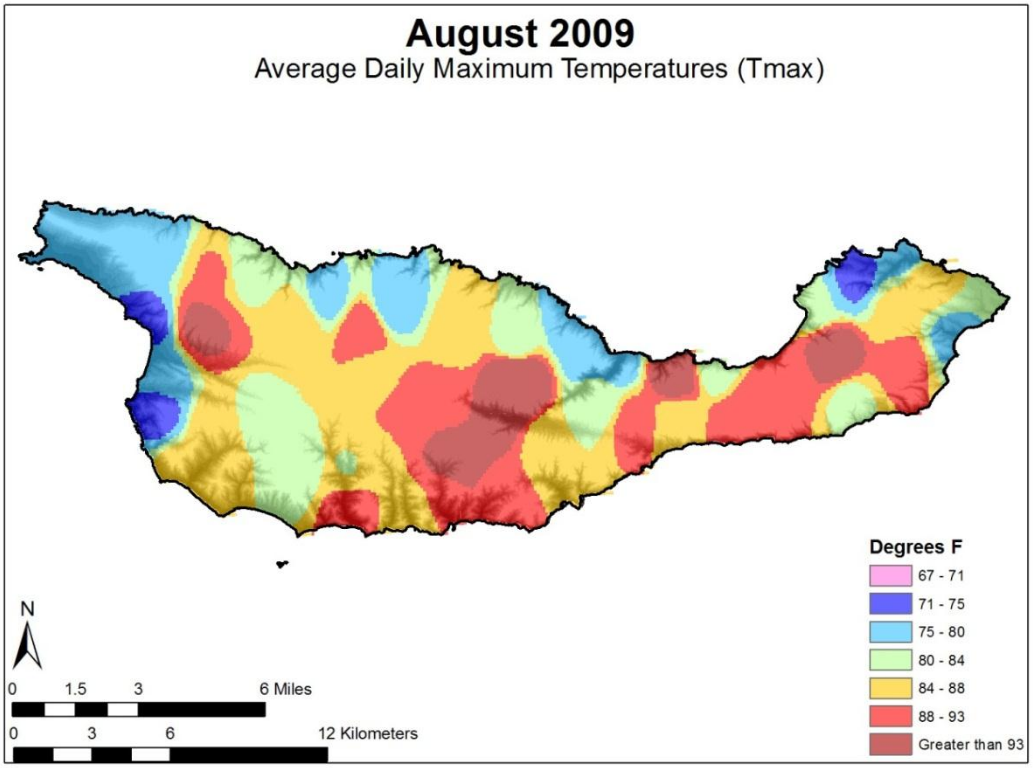

May 2009
Average Daily Minimum Temperatures (Tmin)
Degrees F
49 - 53
53 - 56
56 - 57
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

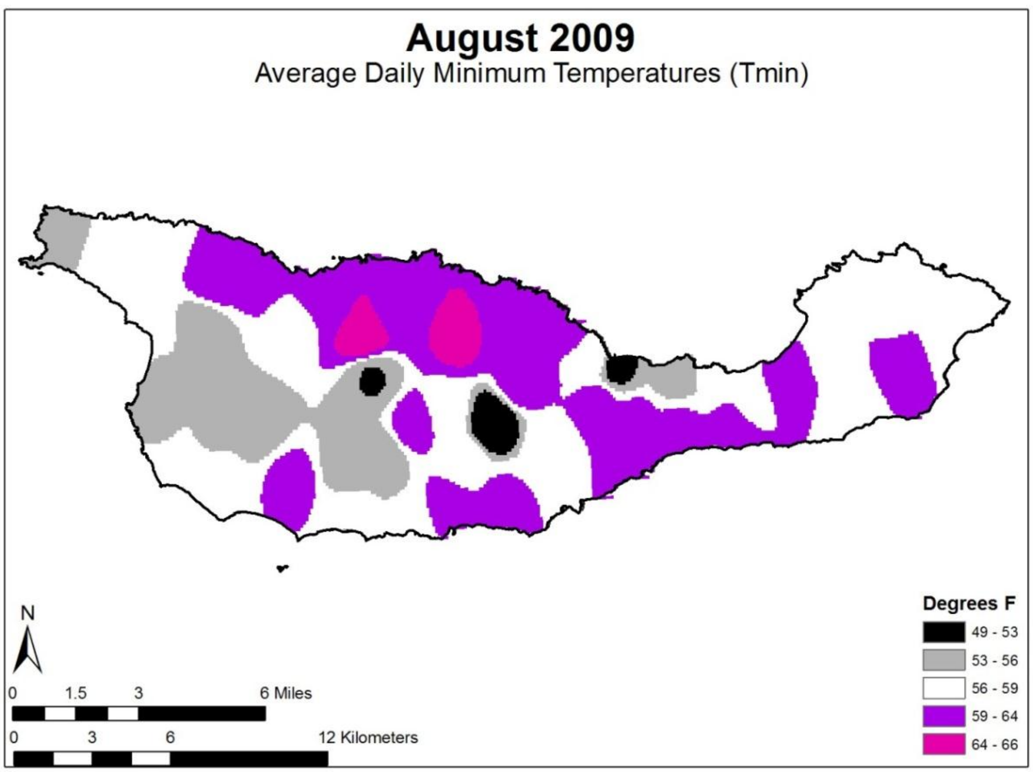

June 2009
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
93 - 98
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

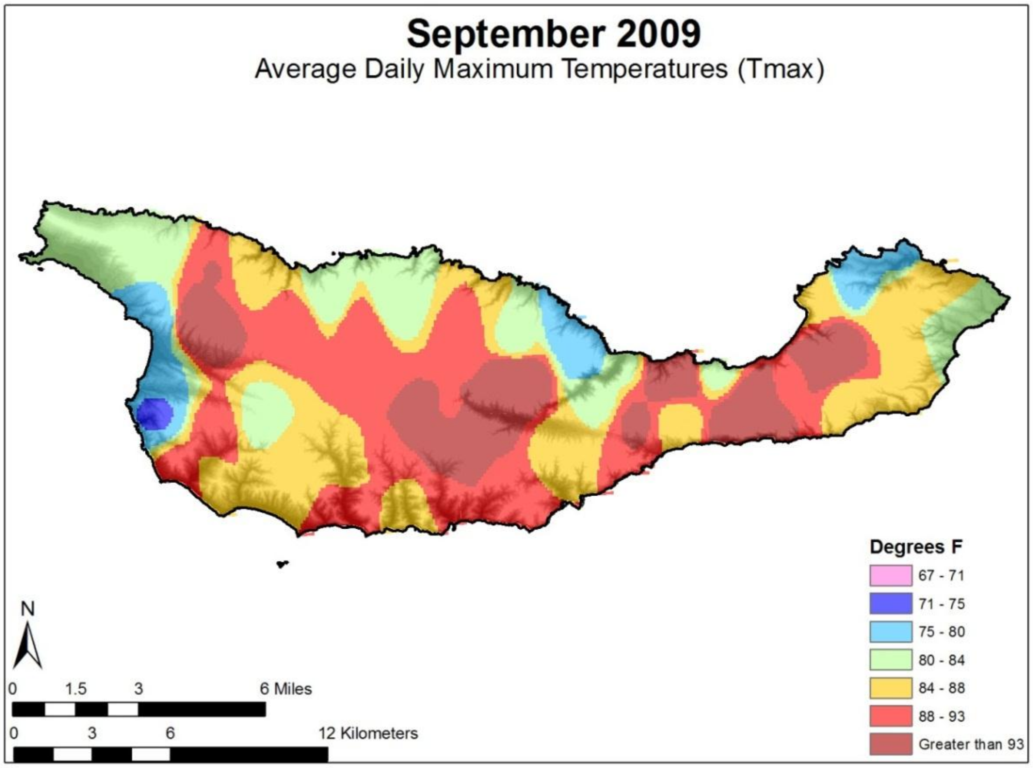

June 2009
Average Daily Minimum Temperatures (Tmin)
Degrees F
49 - 53
53 - 56
56 - 57
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

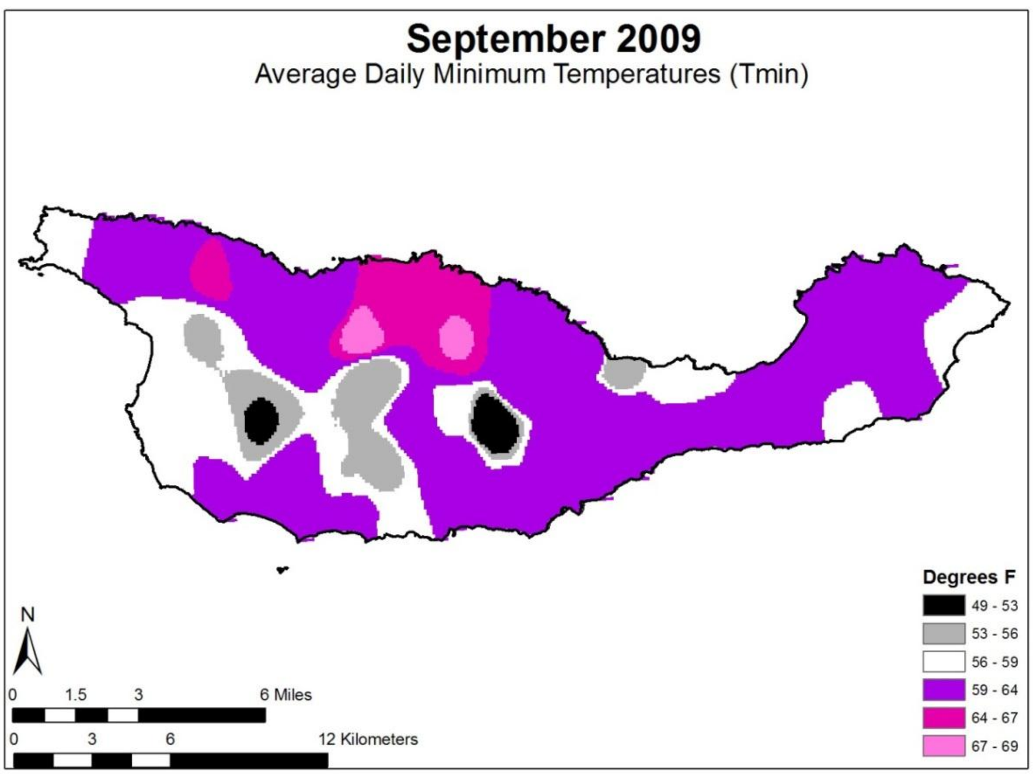

July 2009
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

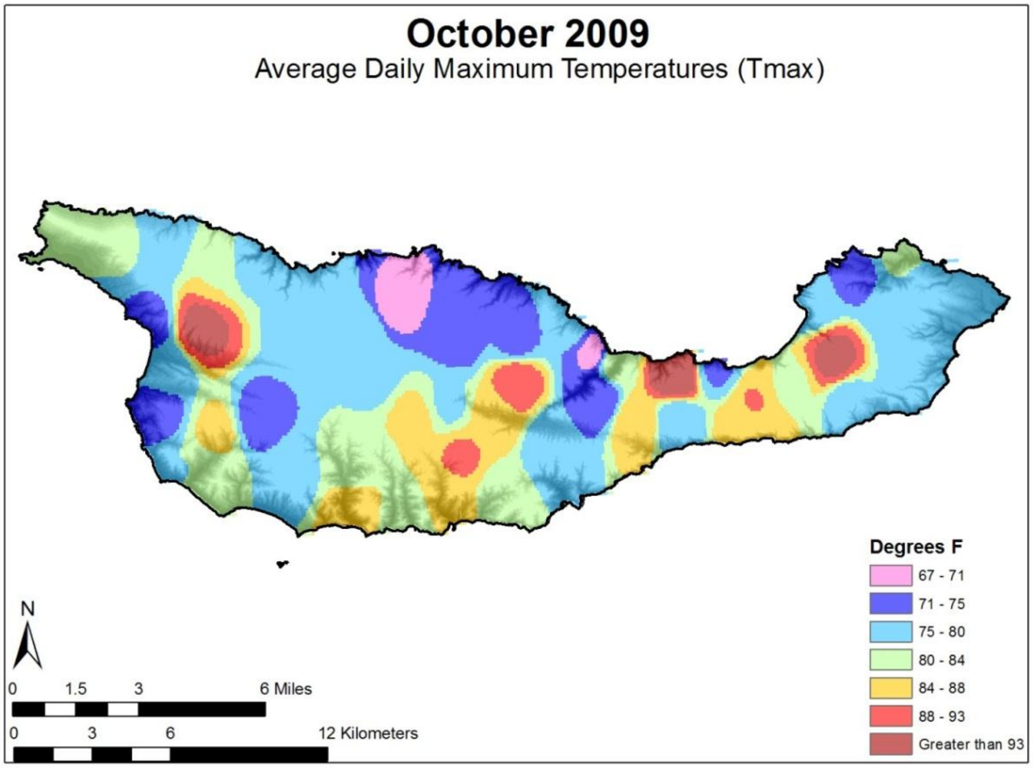

July 2009
Average Daily Minimum Temperatures (Tmin)
Degrees F
50 - 53
53 - 56
56 - 59
59 - 64
64 - 67
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

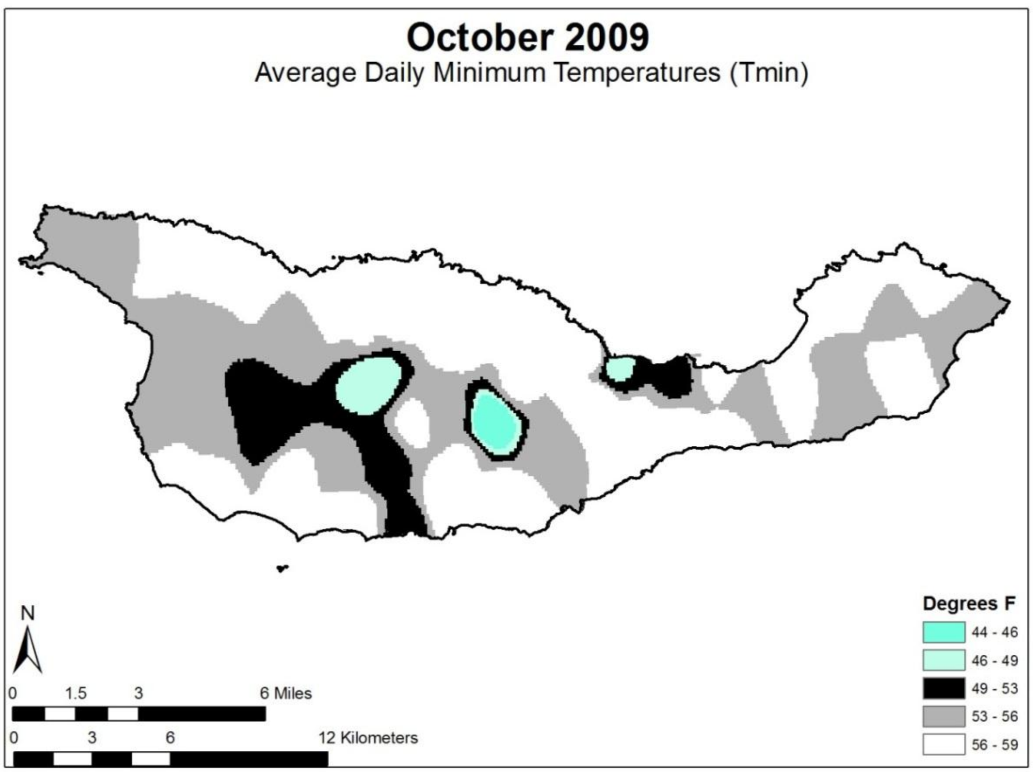

August 2009
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

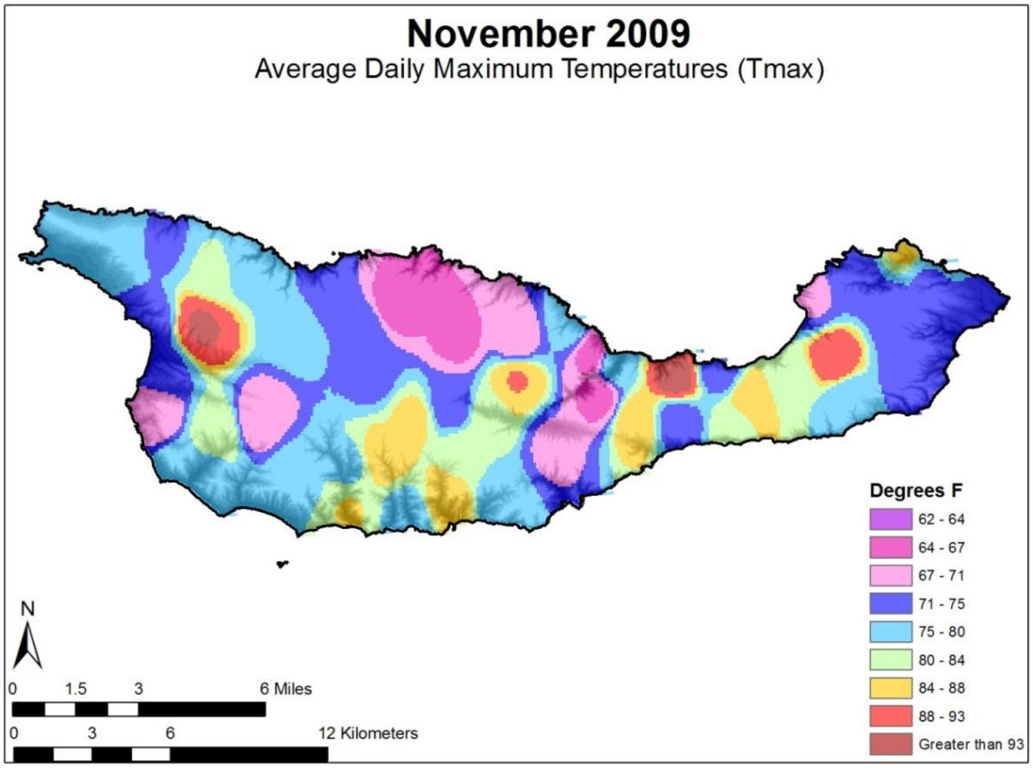

August 2009
Average Daily Minimum Temperatures (Tmin)
Degrees F
49 - 53
53 - 56
56 - 59
59 - 64
64 - 66
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

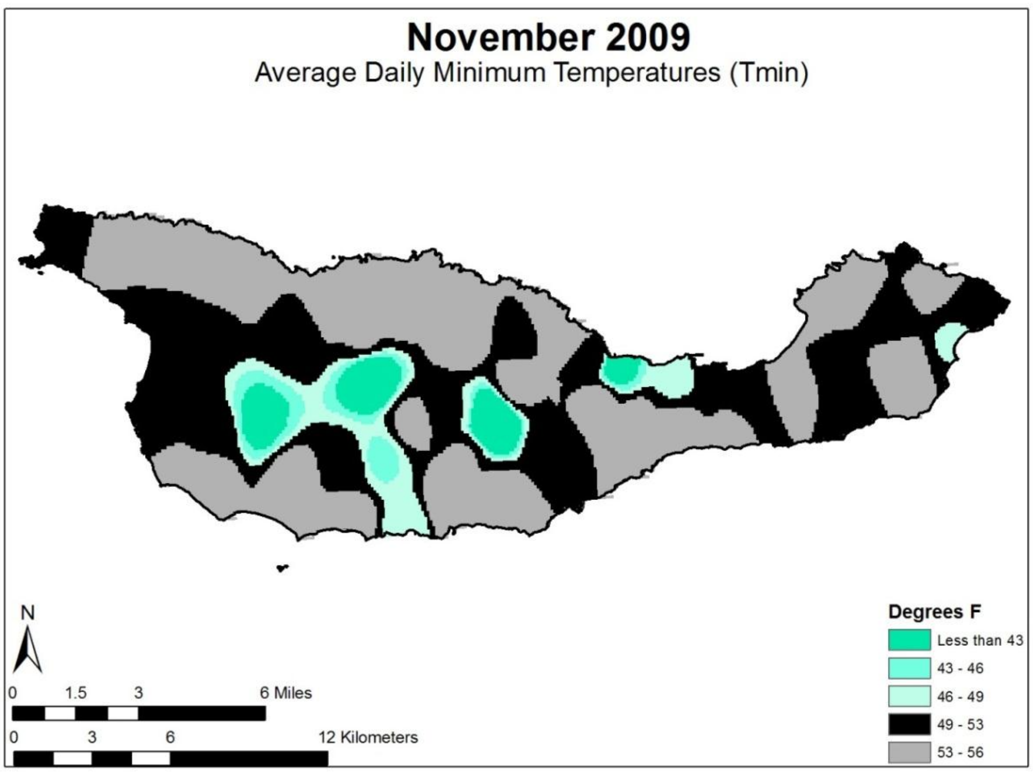

September 2009
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

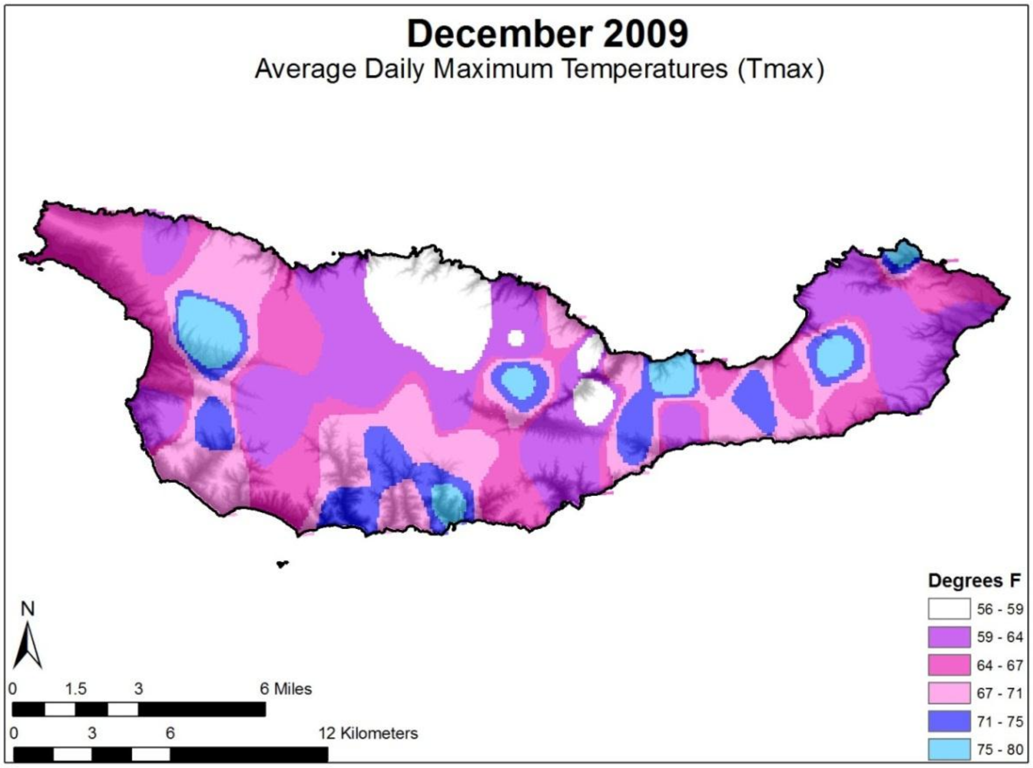

September 2009
Average Daily Minimum Temperatures (Tmin)
Degrees F
49 - 53
53 - 56
56 - 59
59 - 64
64 - 67
67 - 69
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

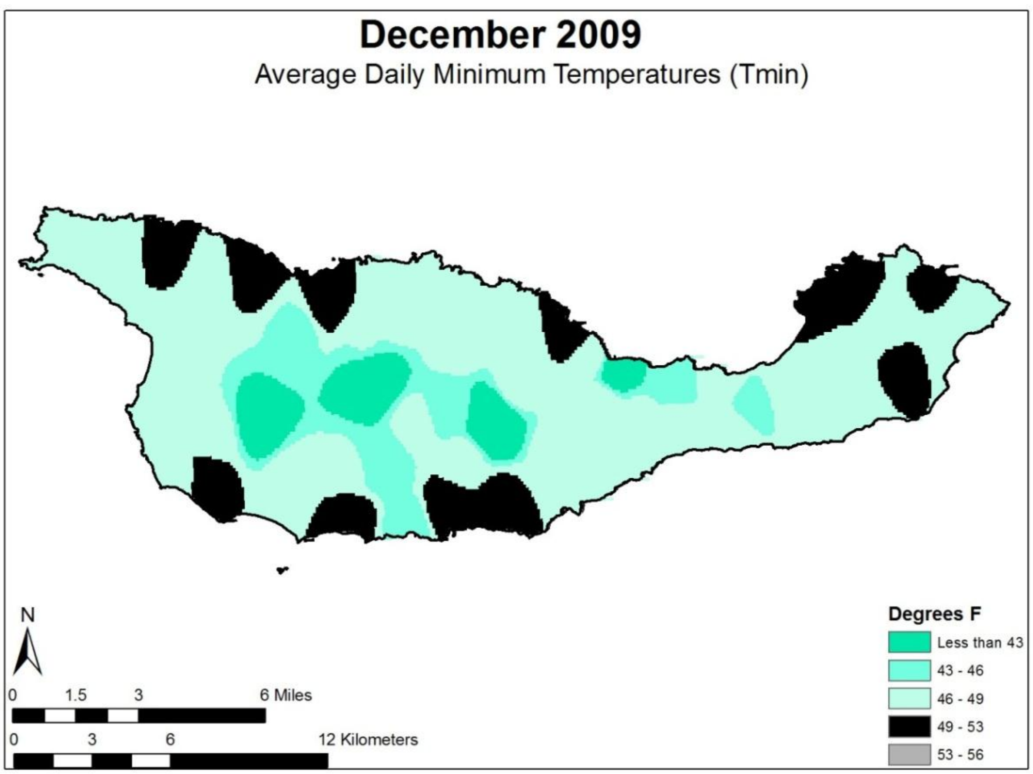

October 2009
Average Daily Maximum Temperatures (Tmax)
Degrees F
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

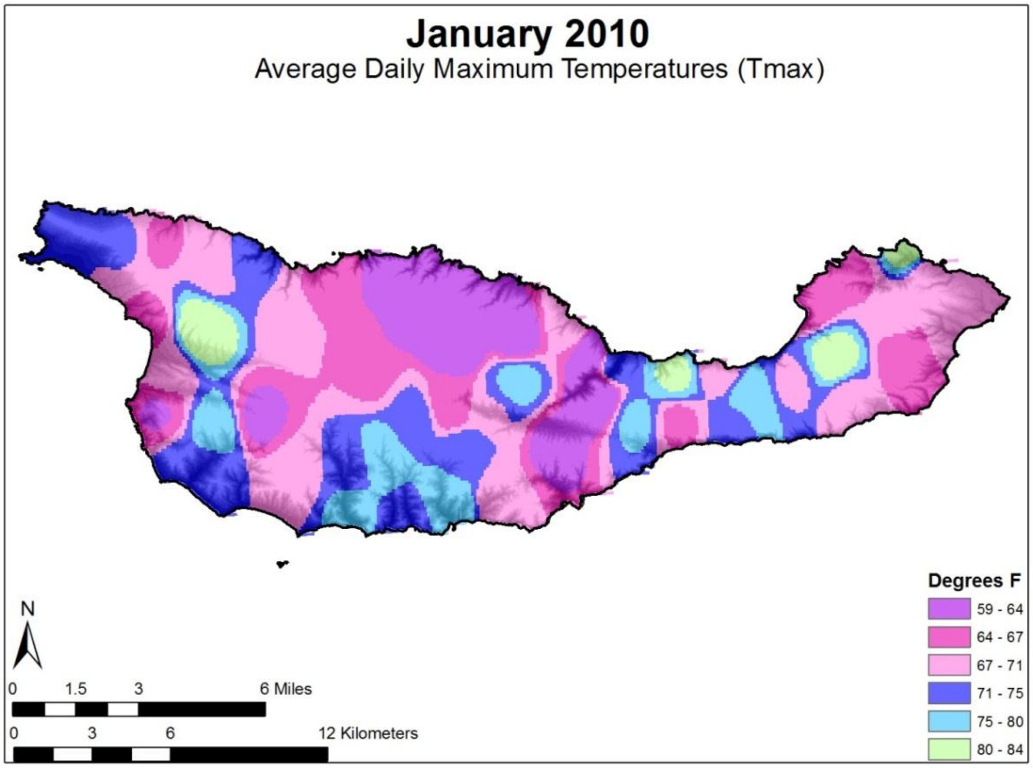

October 2009
Average Daily Minimum Temperatures (Tmin)
Degrees F
44 - 46
46 - 49
49 - 53
53 - 56
56 - 59
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

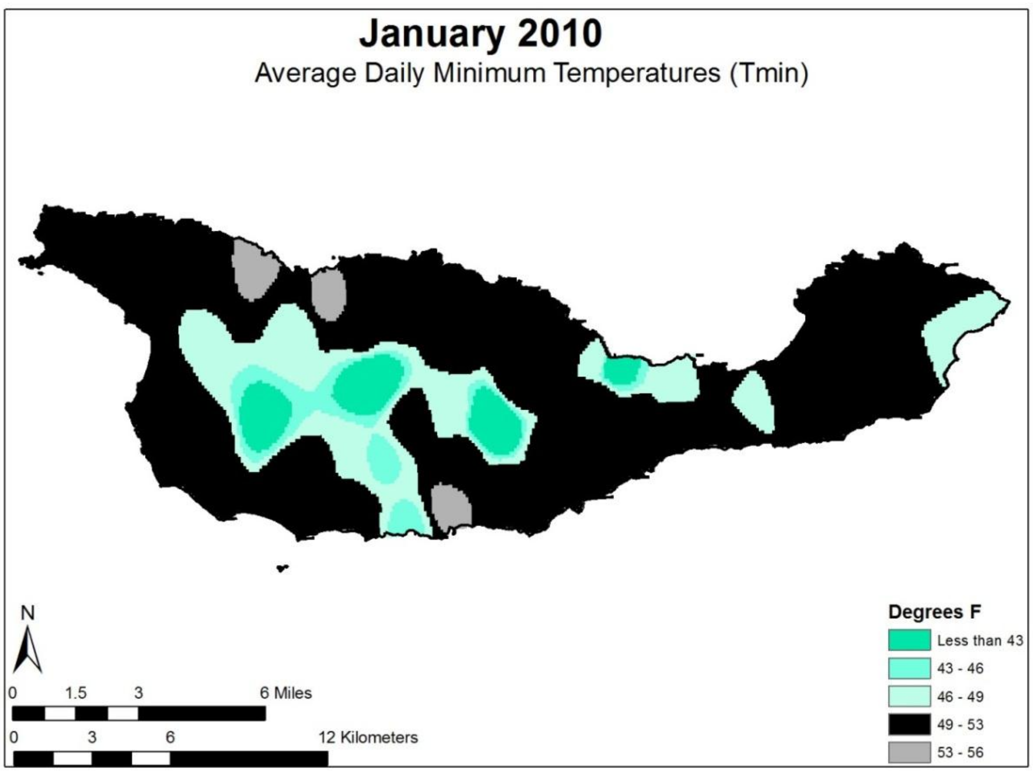

November 2009
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

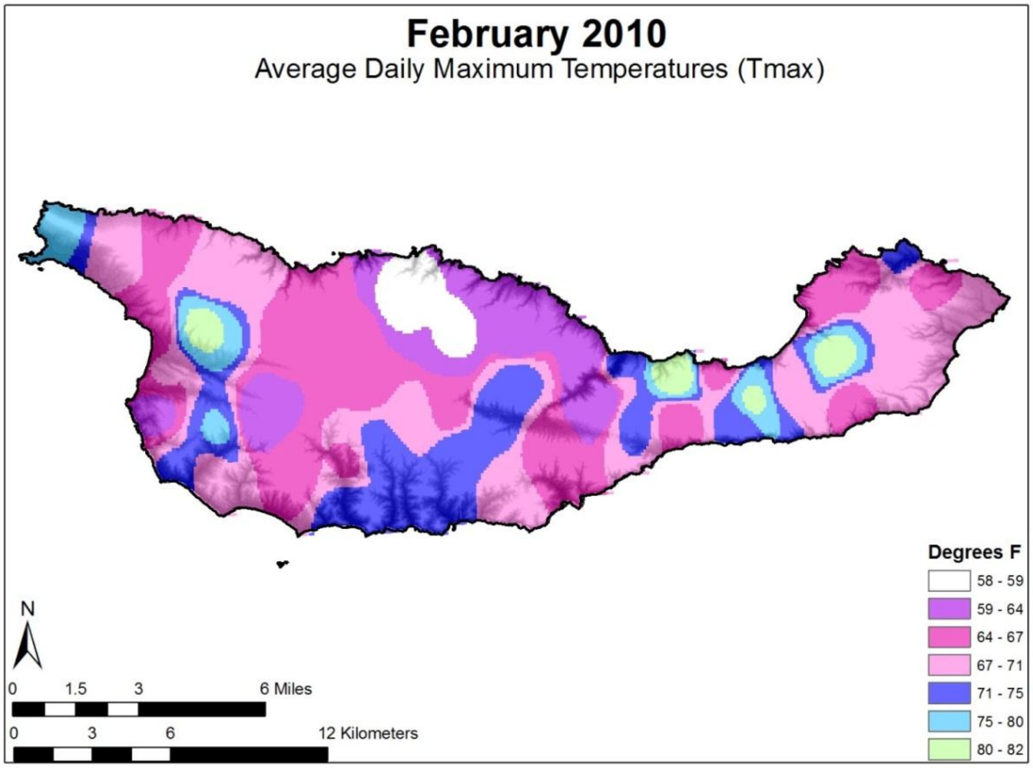

November 2009
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

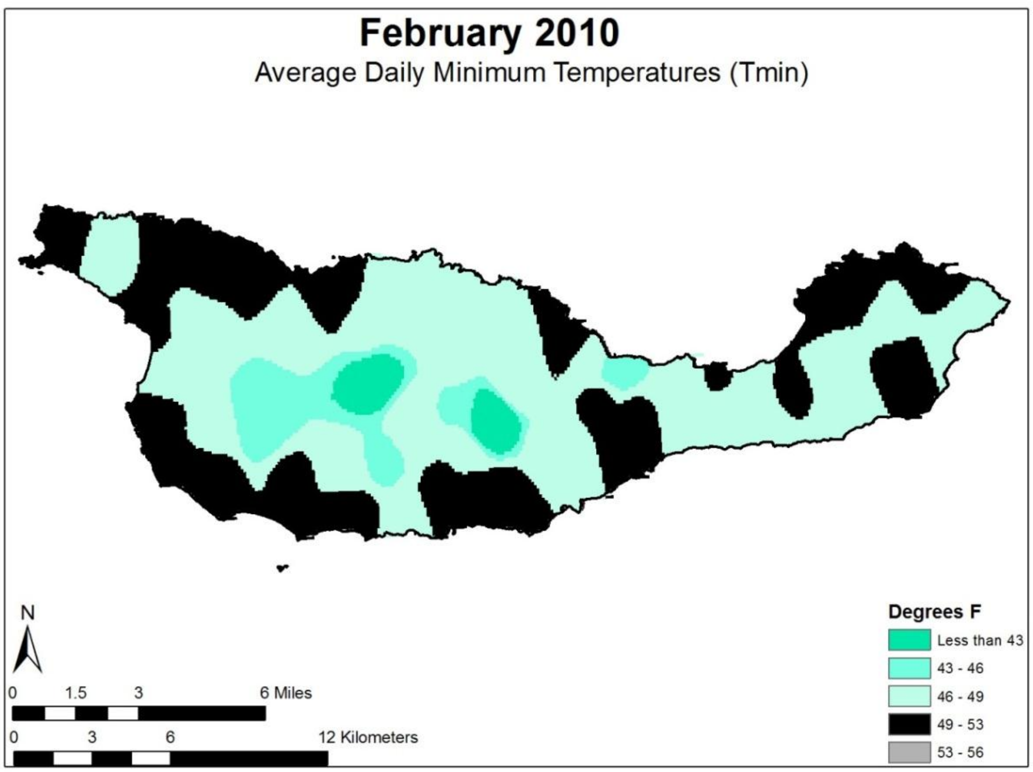

December 2009
Average Daily Maximum Temperatures (Tmax)
Degrees F
56 - 59
59 - 64
64 - 67
67 - 71
71 - 75
75 - 80
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

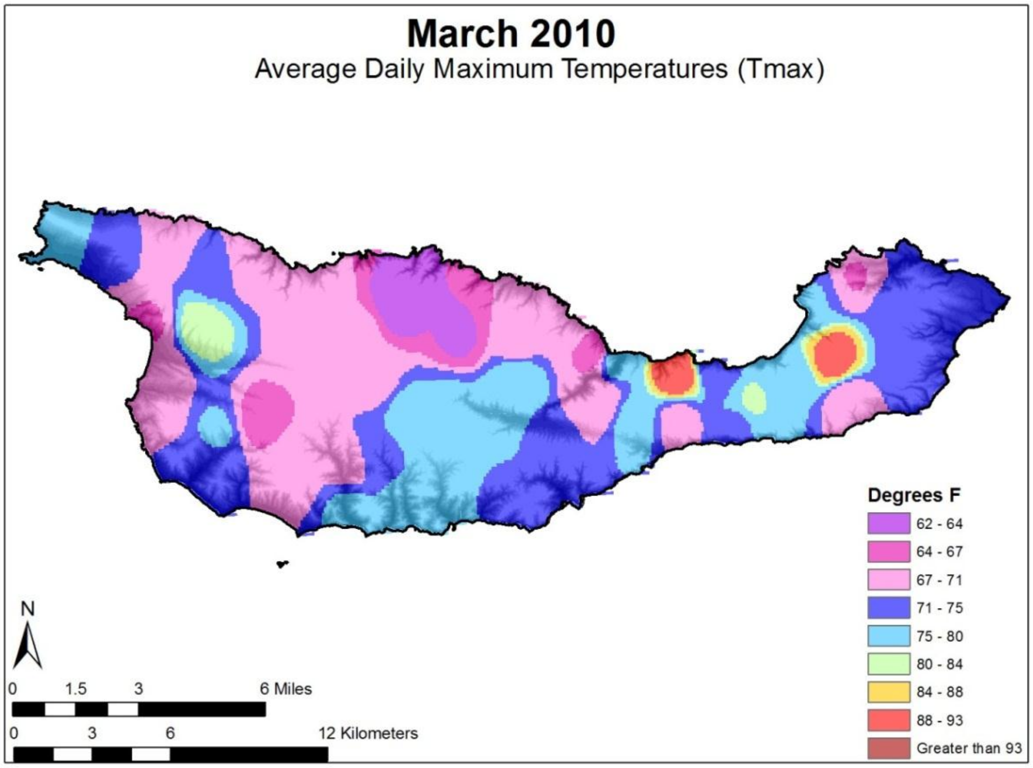

December 2009
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

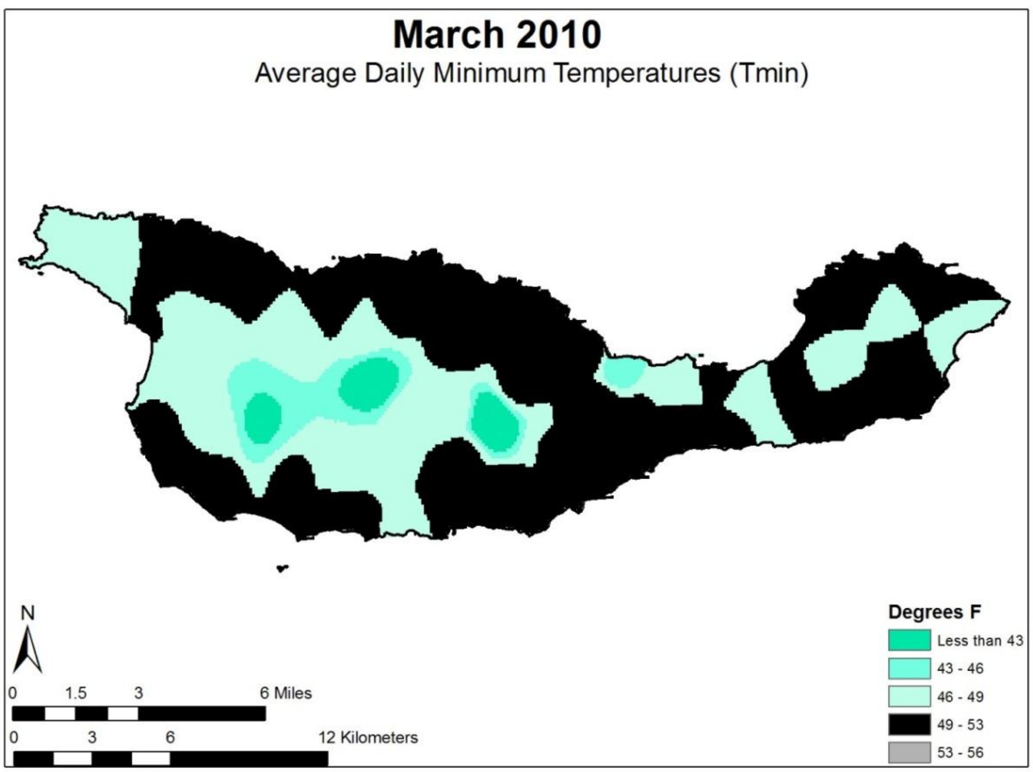

January 2010
Average Daily Maximum Temperatures (Tmax)
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers
Degrees F
59 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84

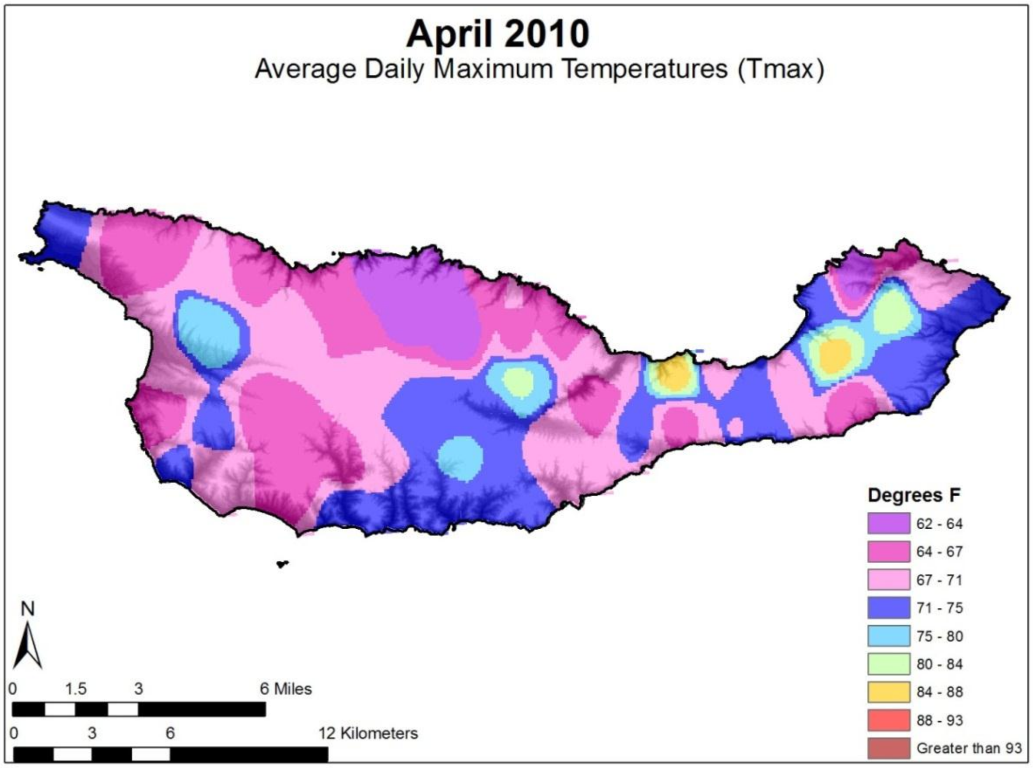

January 2010
Average Daily Minimum Temperatures (Tmin)
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56

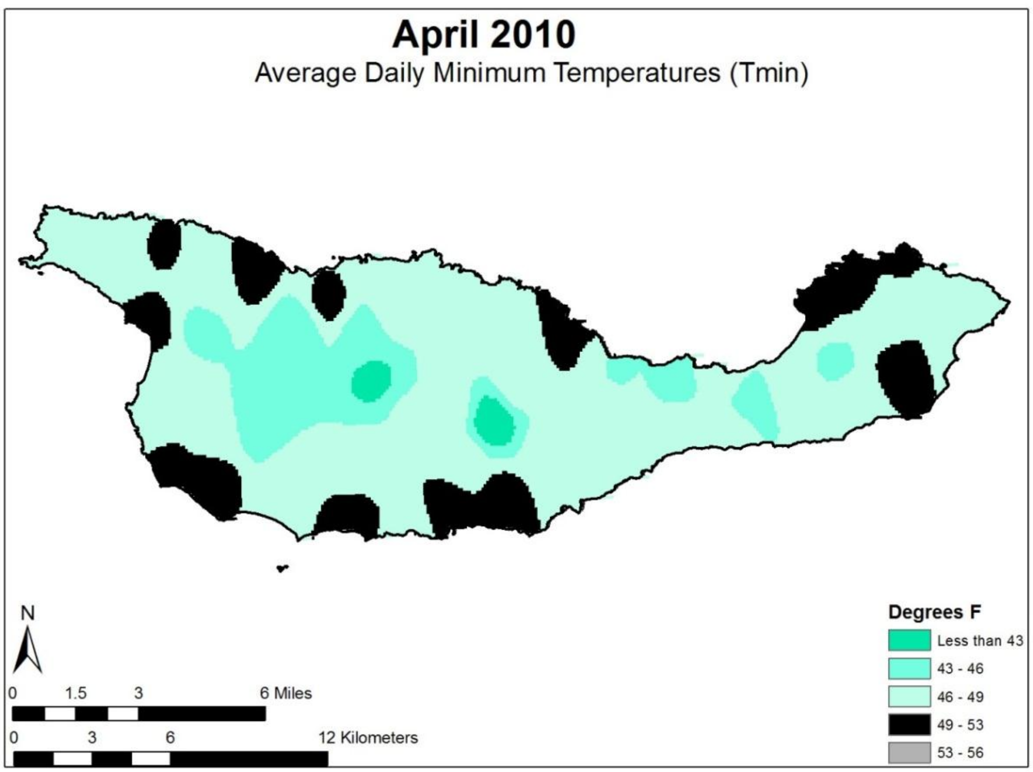

February 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
58 - 59
59 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 82
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers


February 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

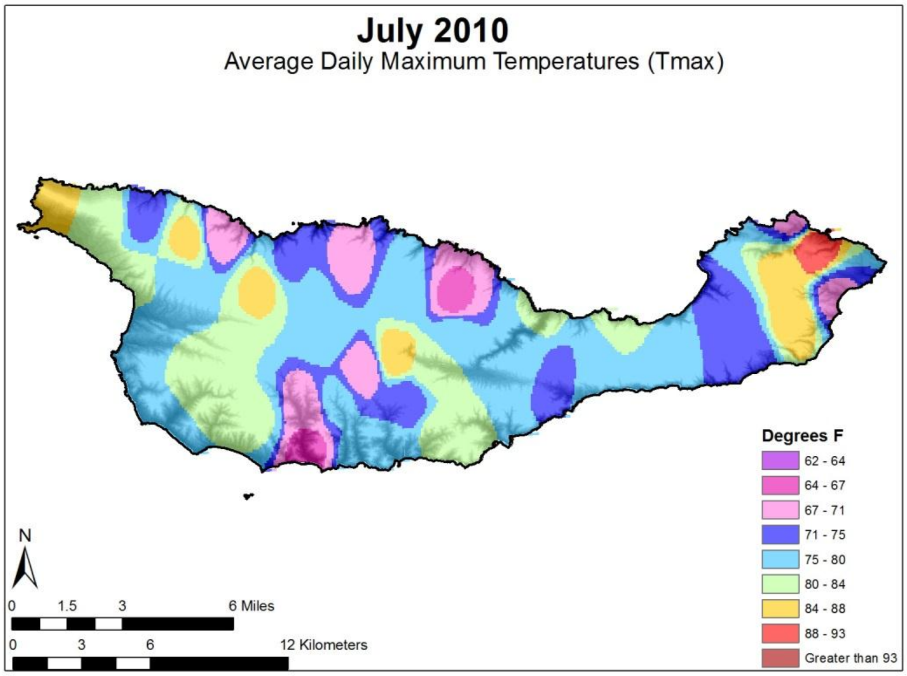

March 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

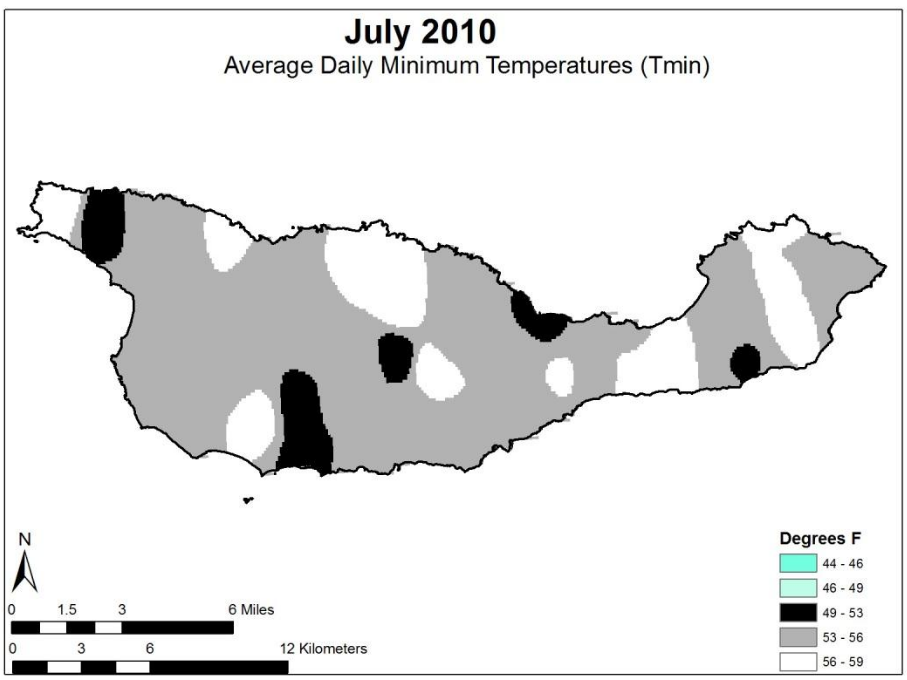

March 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

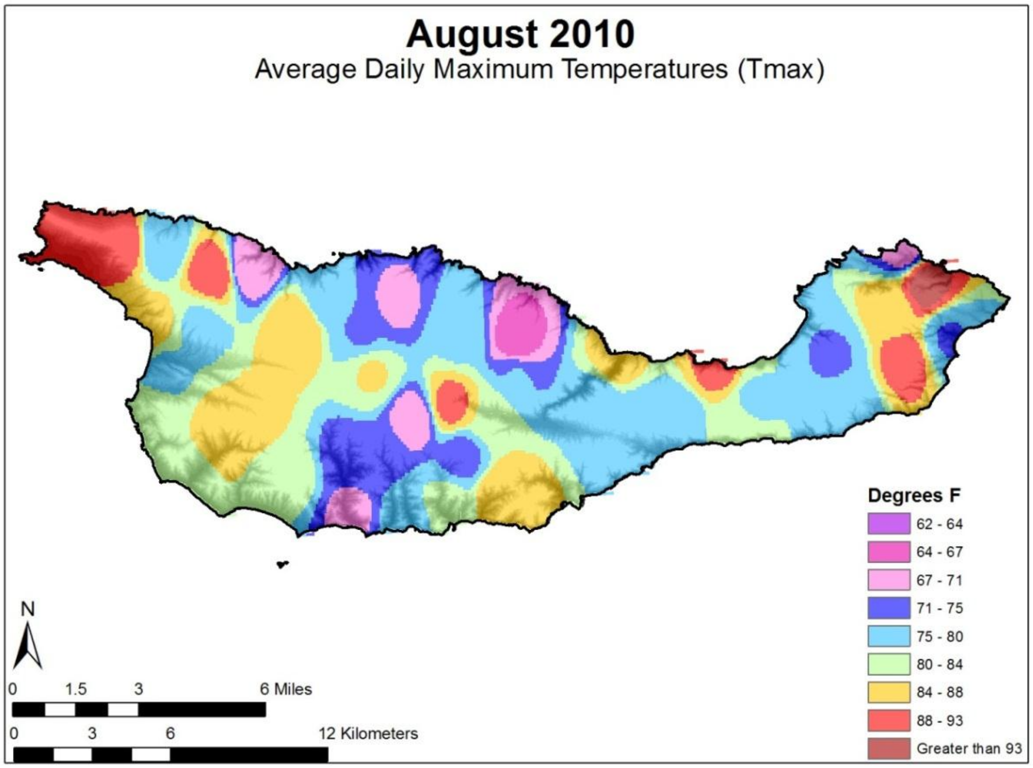

April 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

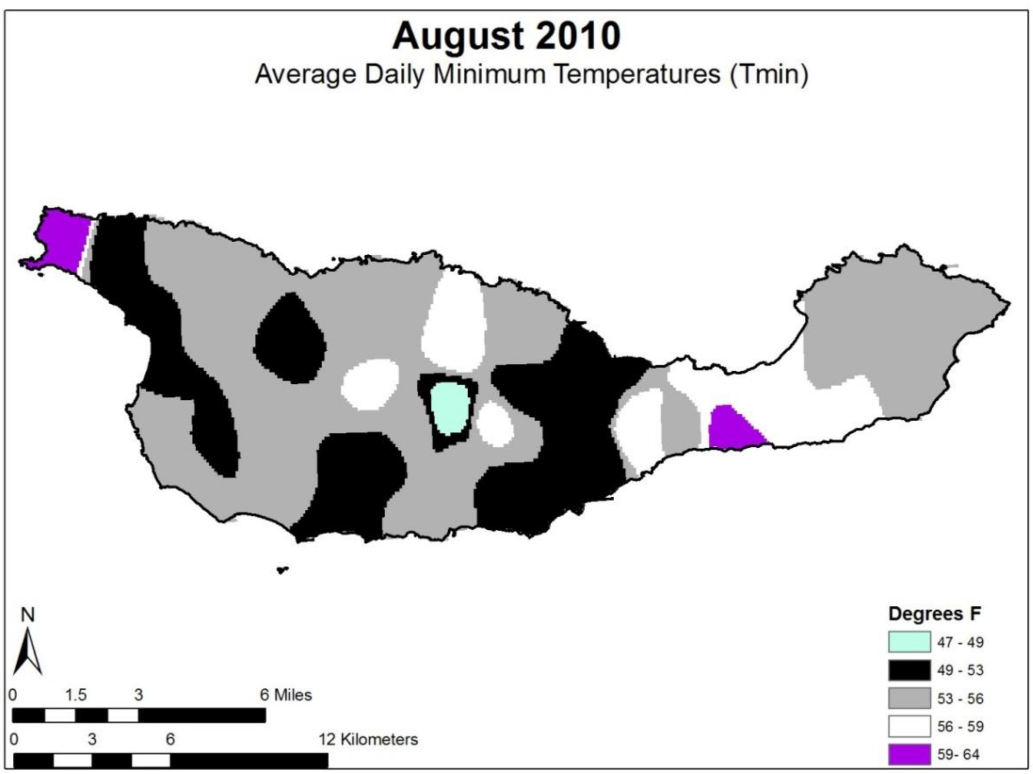

April 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

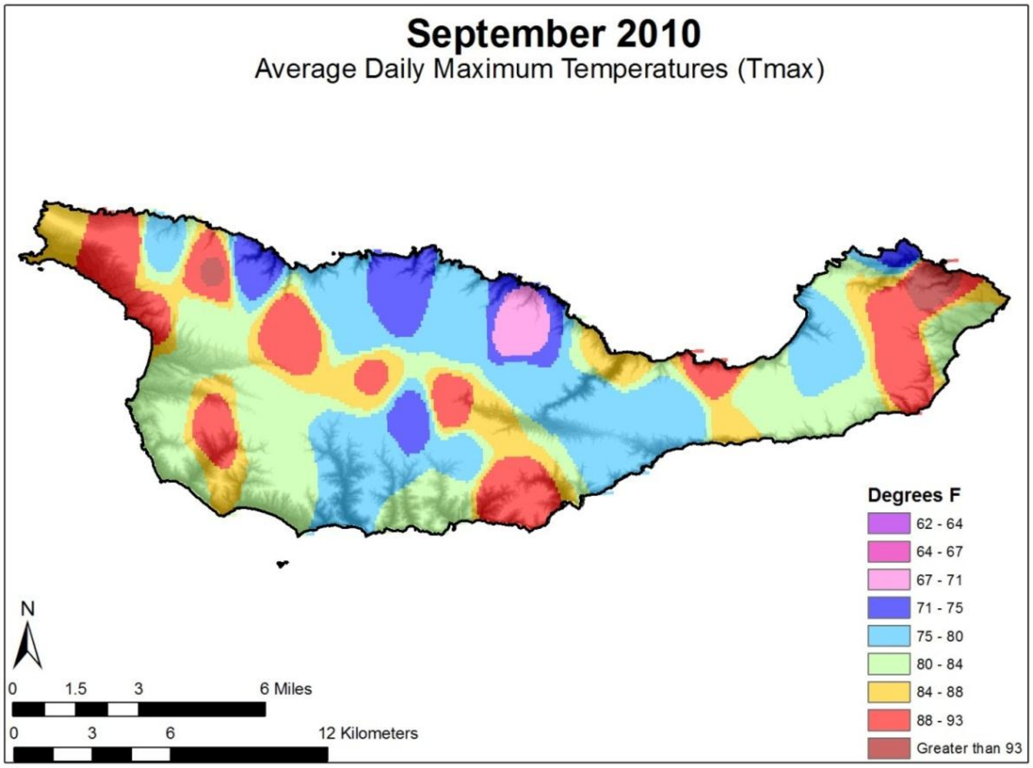
{NO DATA FOR MAY AND JUNE 2010}

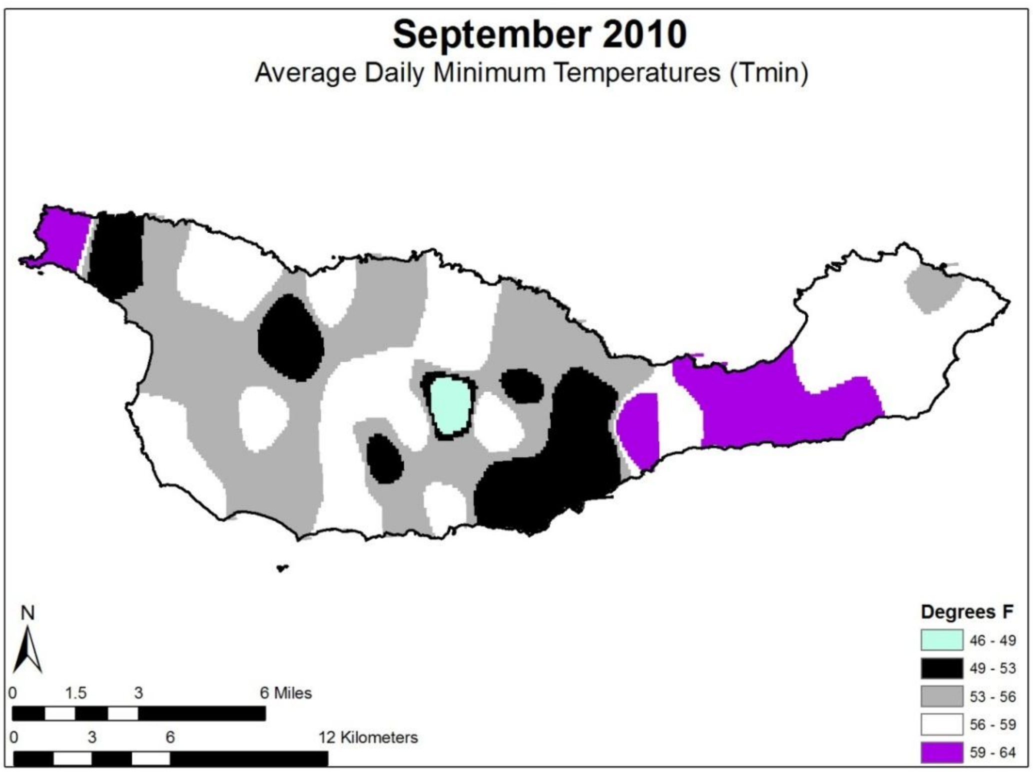


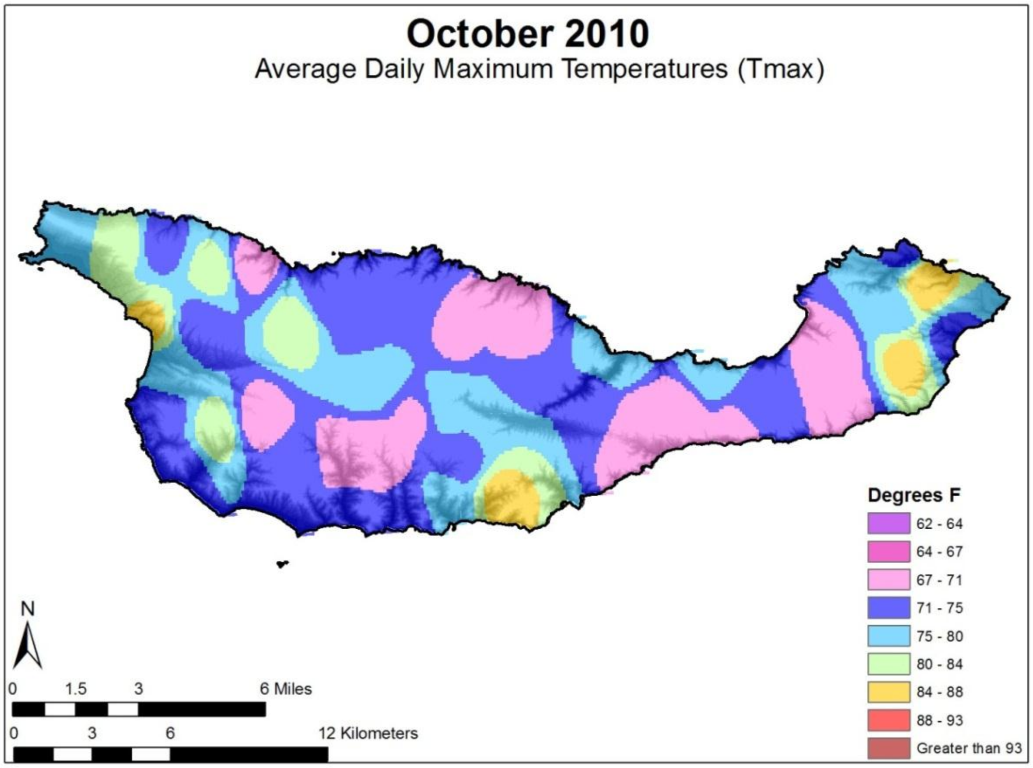


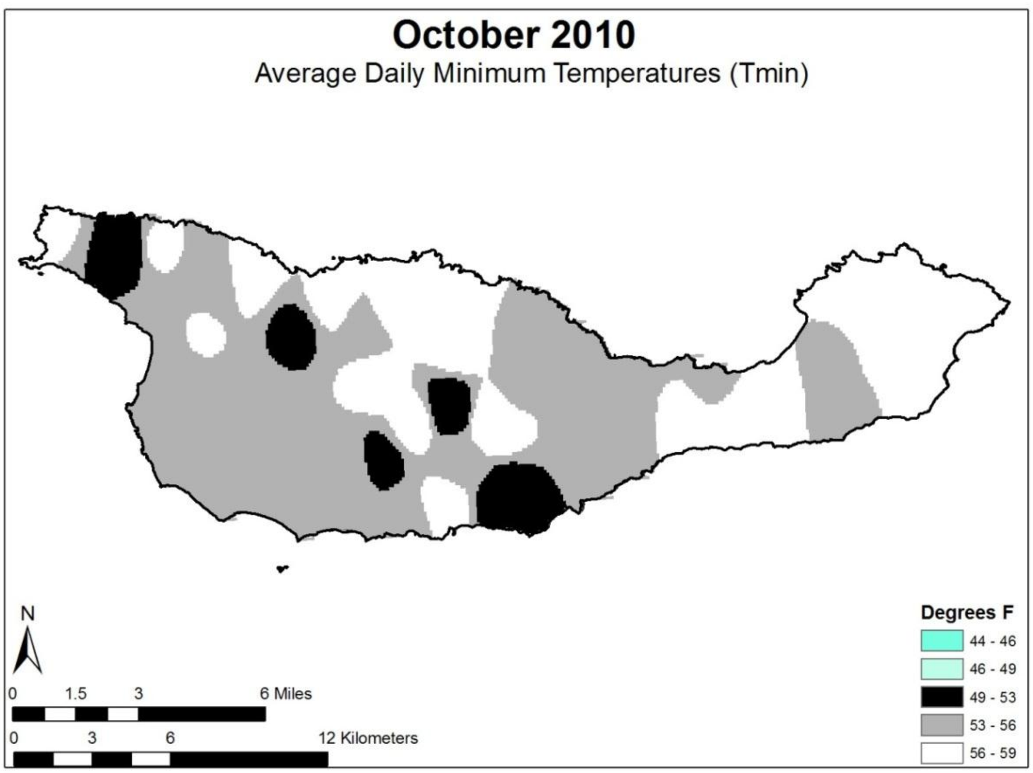

August 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

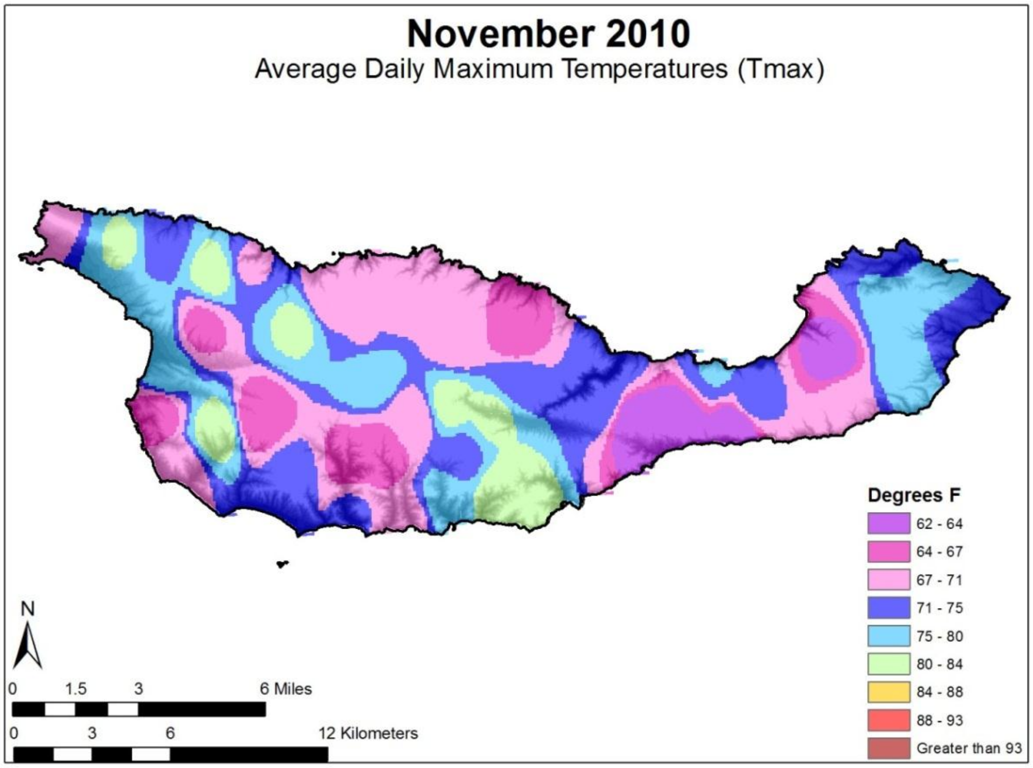

August 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
47 - 49
49 - 53
53 - 56
56 - 59
59- 64
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

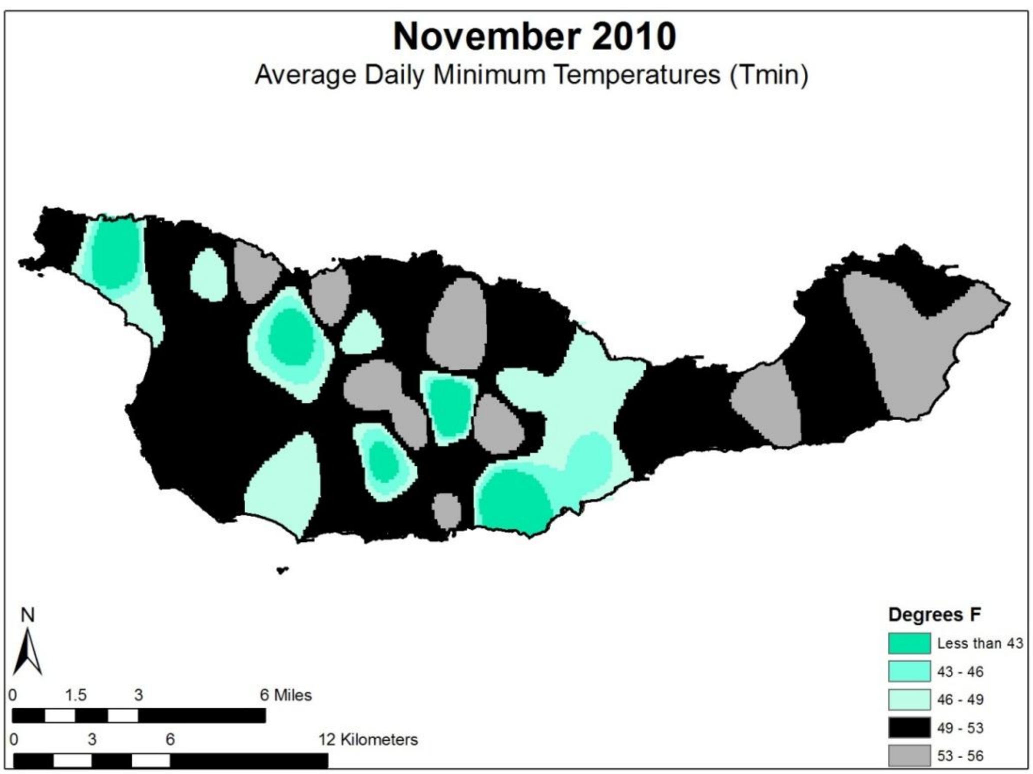

September 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

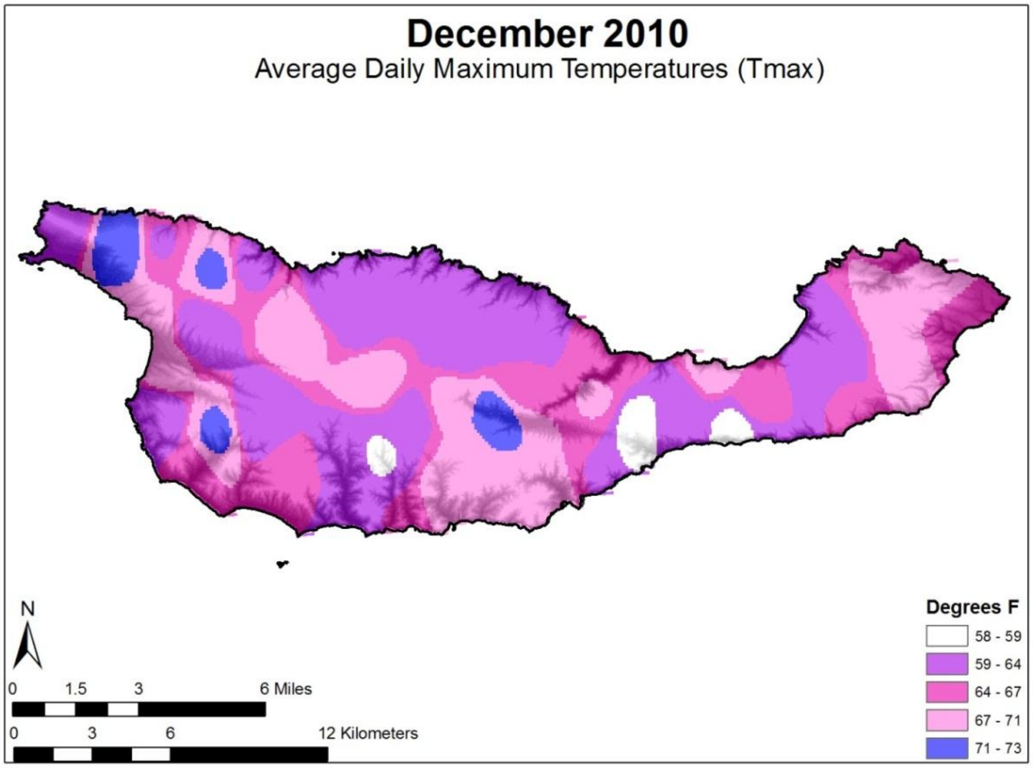

September 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
46 - 49
49 - 53
53 - 56
56 - 59
59 - 64
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers


October 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0
1.5
3
6 Miles
0
3
6
12 Kilometers

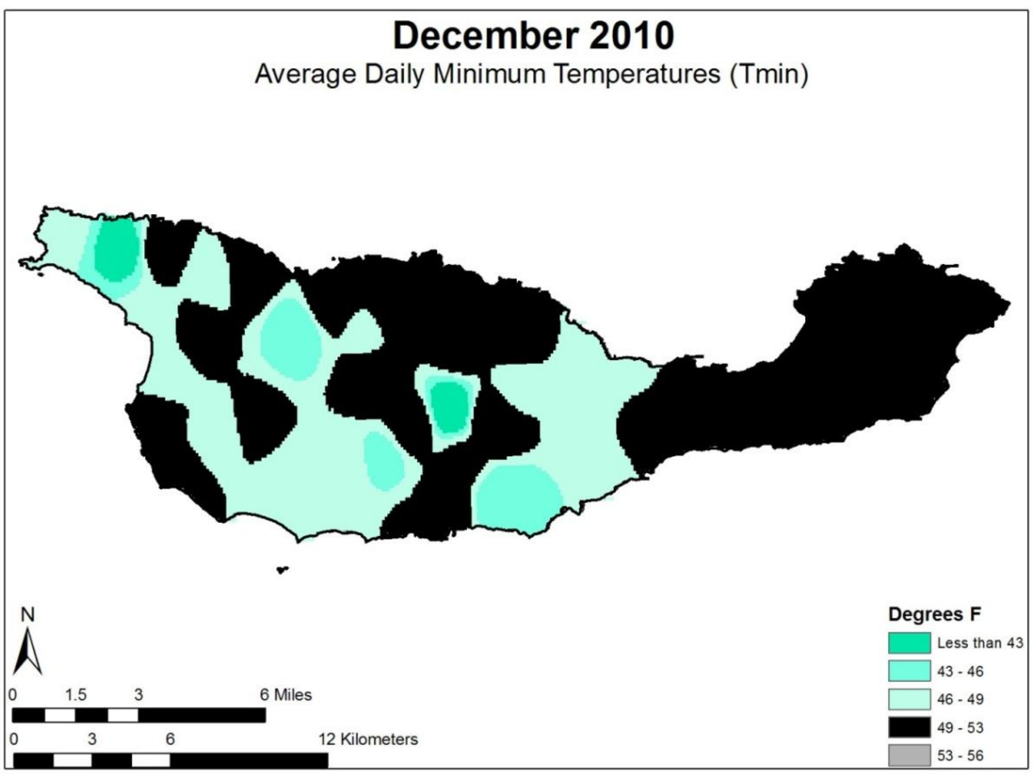

October 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
44 - 46
46 - 49
49 - 53
53 - 56
56 - 59
N
0
1.5
3
6 Miles
0
3
6
12 Kilometers


November 2010
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

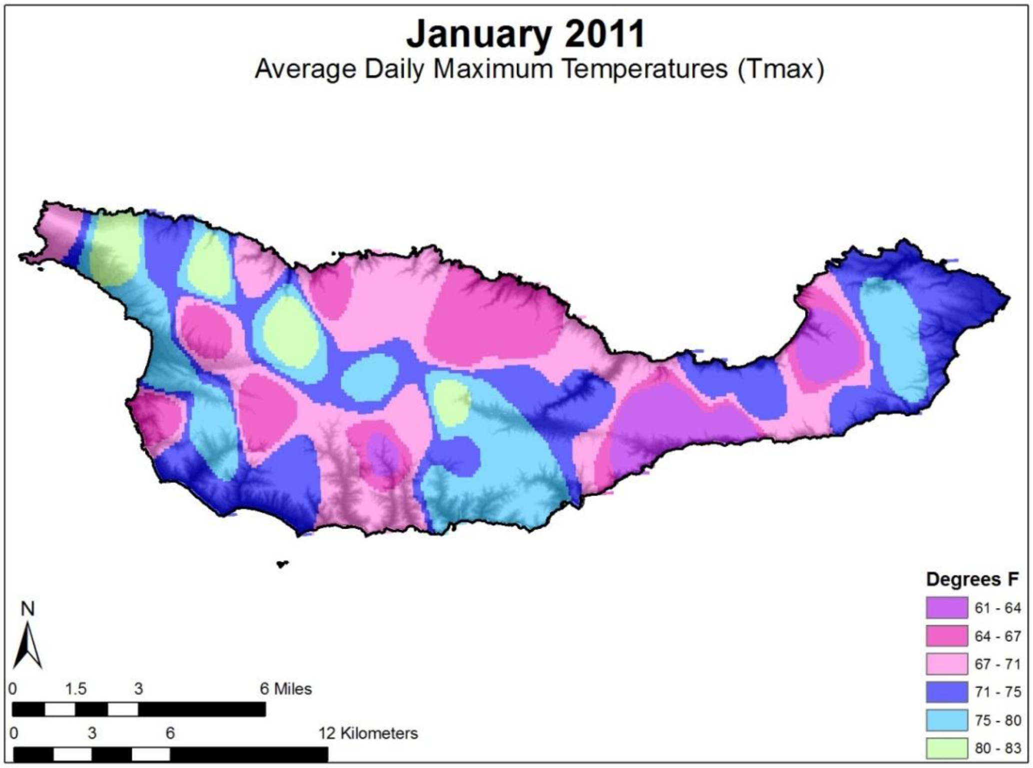

November 2010
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

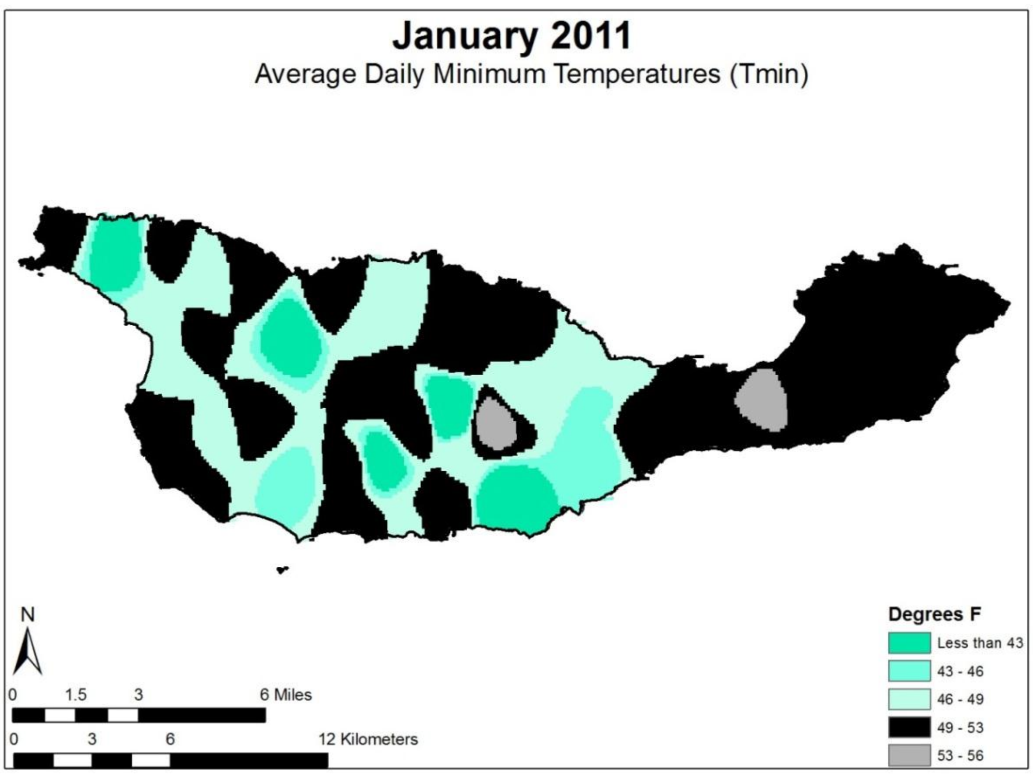


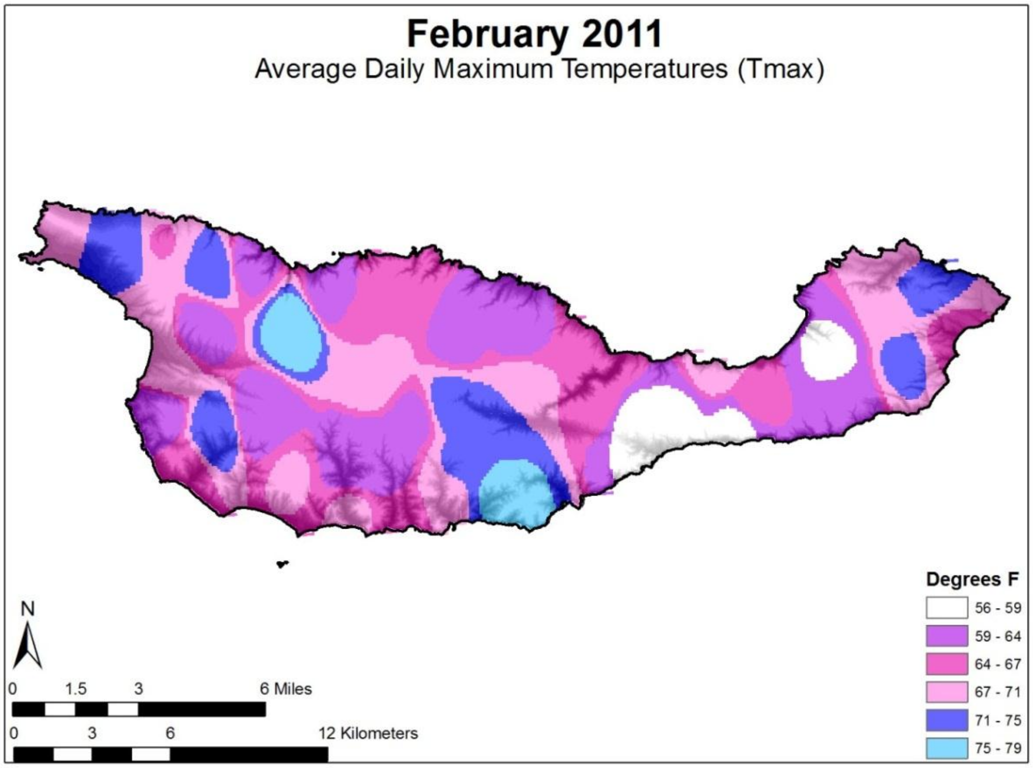
December 2010
Average Daily Maximum Temperatures (Tmax)
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers
Degrees F
58 - 59
59 - 64
64 - 67
67 - 71
71 - 73

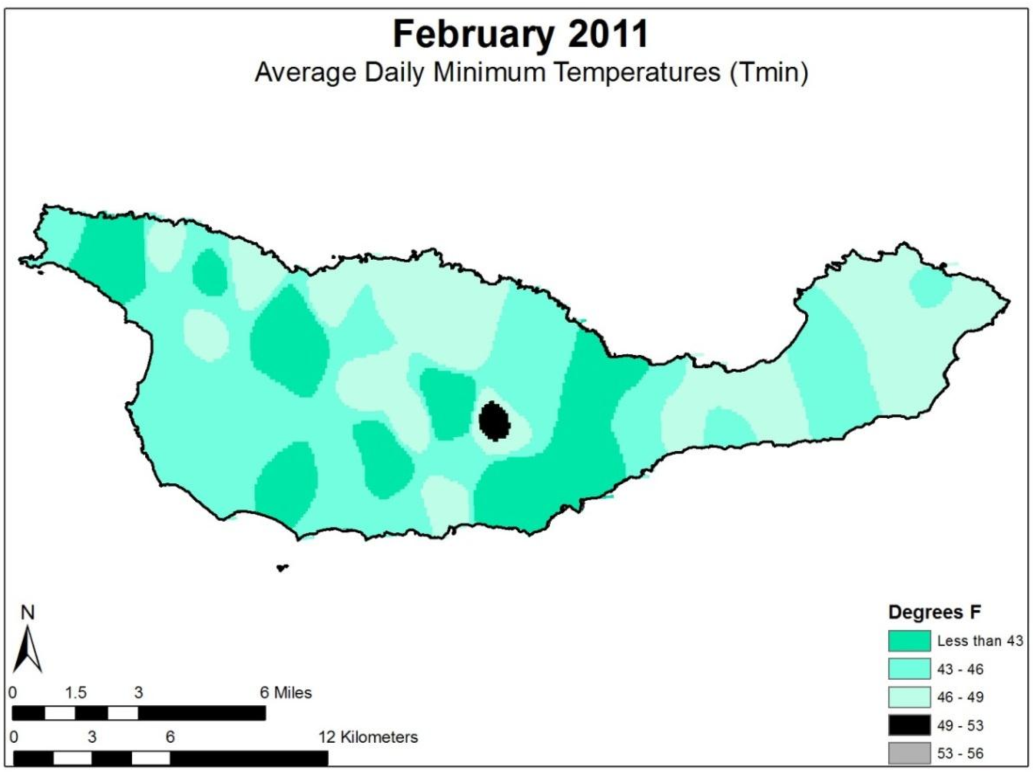


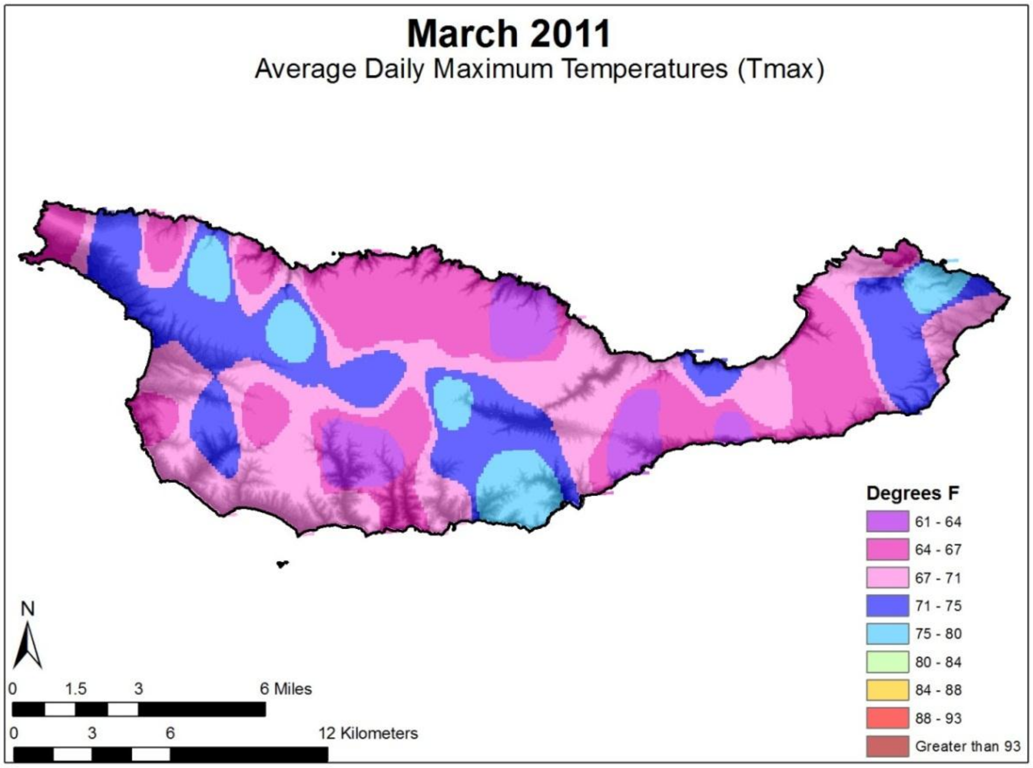
December 2010
Average Daily Minimum Temperatures (Tmin)
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56


January 2011
Average Daily Maximum Temperatures (Tmax)
Degrees F
61 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 83
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

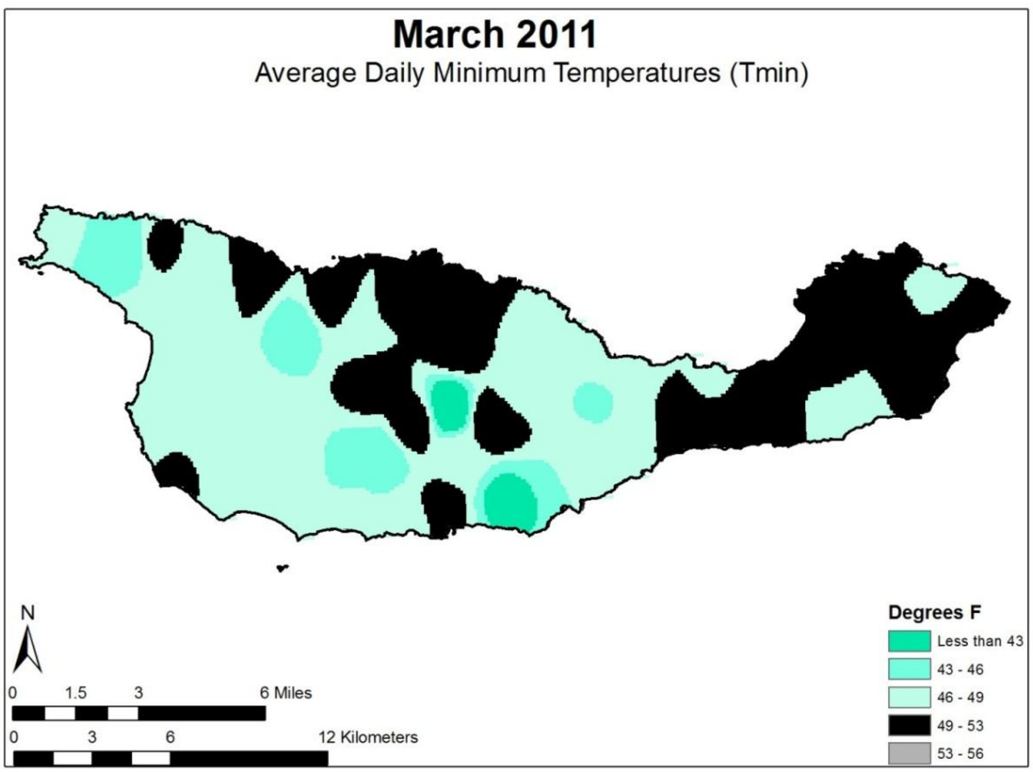

January 2011
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers


February 2011
Average Daily Maximum Temperatures (Tmax)
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers
Degrees F
56 - 59
59 - 64
64 - 67
67 - 71
71 - 75
75 - 79

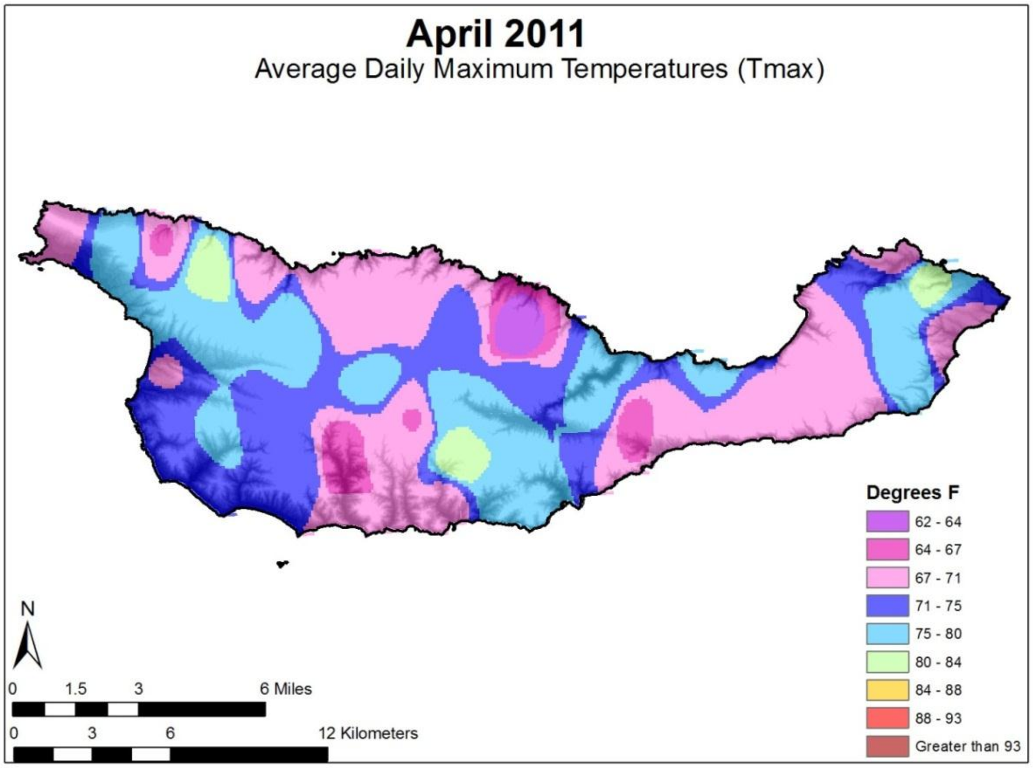

February 2011
Average Daily Minimum Temperatures (Tmin)
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56

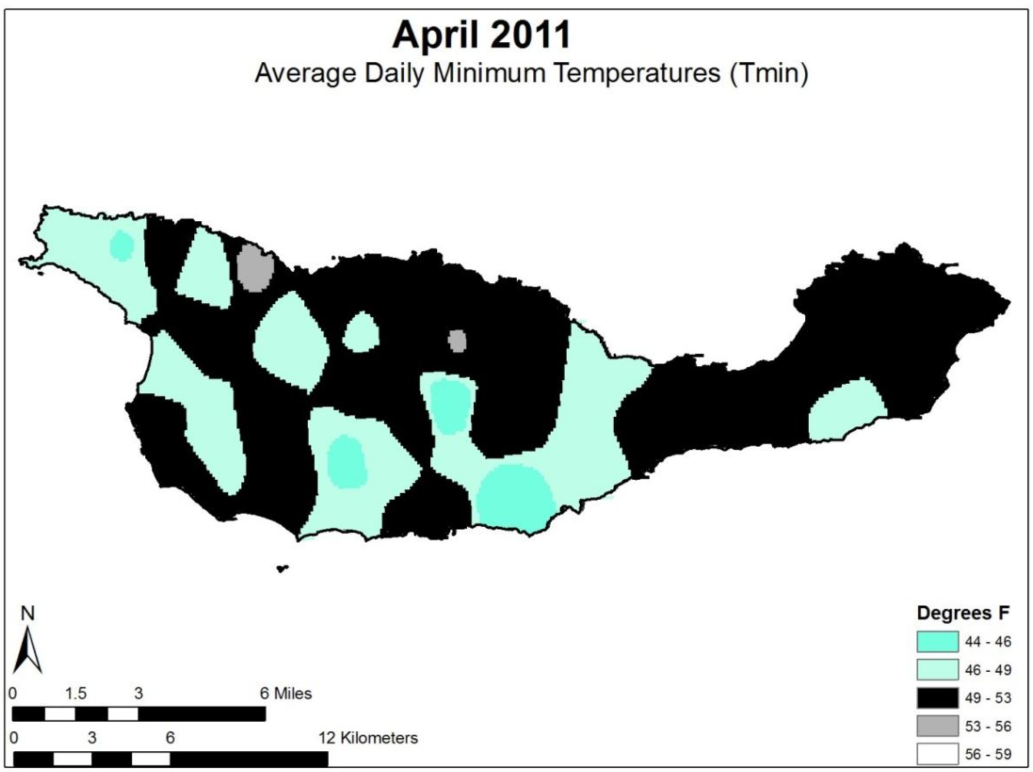


March 2011
Average Daily Maximum Temperatures (Tmax)
Degrees F
61 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers



March 2011
Average Daily Minimum Temperatures (Tmin)
Degrees F
Less than 43
43 - 46
46 - 49
49 - 53
53 - 56
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers


April 2011
Average Daily Maximum Temperatures (Tmax)
Degrees F
62 - 64
64 - 67
67 - 71
71 - 75
75 - 80
80 - 84
84 - 88
88 - 93
Greater than 93
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers


April 2011
Average Daily Minimum Temperatures (Tmin)
Degrees F
44 - 46
46 - 49
49 - 53
53 - 56
56 - 59
N
0 1.5 3 6 Miles
0 3 6 12 Kilometers

Appendix 2 – R code for performing linear regressions of monthly temperature data from dataloggers.

Purpose: The code provided here will produce the plots and regressions in Figure 9 of this report. The user needs to understand linear regressions and other basic statistics. In particular, it is important to evaluate the quality and strength of any models before you use them for practical applications.

Data source: The code provided below can be run on a comma delimited (csv) file. To obtain the appropriate data, download the monthly data from the links provided in the results section of this report, open it in Microsoft Excel and "Save as" a .csv file. You can also download this example file or this one.

Obtaining the R statistical platform: R is a set of free statistics packages and a programming language. You can download it from: http://www.r-project.org/

Instructions for using the code provided below:
1. Run R
2. Paste the commands below into the R command line prompt one at a time.

Program Code: Code is printed below in the `Courier New Font` to distinguish it from the rest of the text in this appendix.

```
# R code for performing a linear regression on monthly average
temperature data.


# The following line will allow you to choose the data file with
your file browser.

data<-read.table(file.choose(),header=T,sep=",")
```

```
# Make subsets of the data based on aspect
north_slopes <- subset(data, face == "N")
south_slopes <- subset(data, face == "S")
east_slopes <- subset(data, face == "E")
west_slopes <- subset(data, face == "W")

# Use the following line when you want to analyze data from
#north-facing slopes

attach(north_slopes)

# When you are done with north facing slopes use
#detach(north_slopes) and then attach(south_slopes), #etc.

#The next section will do a regression of February 2010 data
#against elevation. Edit it for other months as necessary by
#changing the variable names to, for example, X2010_3. For each
#new variable analyzed, make changes as needed throughout.

regr1 = lm(north_slopes$X2010_2 ~ Elev..m.)

summary(regr1)

# Take a look at the results after you enter the previous line.
#Is it significant?

# Further evaluate the regression with plots as #follows:

par(mfrow=c(2,2))

plot(regr1)

# If you have a good model, Make a plot with the next bit:
x<-.01:350
plot(north_slopes$Elev..m.,north_slopes$X2010_2,xlab="Elevation
(m)", ylab = "Avg. Tmin (F)",pch=19)
y<-predict(regr1,list(Elev..m.=x))
lines(x,y)
title(main="February 2010", col.main="red", font.main=4)
```

```
# If you want to label the points on the plot so you can tell
#which datalogger is which, use this:

library(calibrate)
textxy(Elev..m.,X2010_2,labs = logger)

#Labeling the points in your plots will help you compare them to
#maps, as shown in Figure 9. Remove points as necessary as shown
#in Figure 9 and re-run.
```