

**AN ANALYSIS OF THE INFLUENCE OF THERMAL HETEROGENEITY WITHIN
MOUNTAIN ENVIRONMENTS ON THE SPATIAL DISTRIBUTION AND THERMAL
BIOLOGICAL CHARACTERISTICS OF SURFACE-DWELLING ARTHROPODS**

NICHOLAS JACOB HASSINK
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NICHOLAS HASSINK

Date of Defense: May 26th, 2022

Dr. P. Bonnaventure	Associate Professor	PhD.
Dr. D. Johnson	Professor	PhD.
Thesis Co-Supervisors		
Dr. J. Lee-Yaw	Assistant Professor	PhD.
Thesis Examination Committee Member		
Dr. S. Kienzle	Professor	PhD.
Thesis Examination Committee Member		
Dr. C. Coburn	Professor	PhD.
Defense Chair		

Dedication

To my family, friends, and colleagues who supported me throughout the course of my degree. None of this would have been possible without the love, encouragement, and backing that I received from those around me. In particular, I'd like to thank my field staff who selflessly donated months of their time so I could pursue my passion. I also dedicate this document to my loving girlfriend Trinity who selflessly helped support me financially through these years while simultaneously serving as my greatest source of encouragement and inspiration. Finally, I'd also like to dedicate this document to the loving memory of Dexter Johnson, gone but not forgotten.

Abstract

Preliminary findings from previous research into the thermal biological characteristics of mountain arthropods have determined that temperature plays a critical role in the emergence timing, growth and development rates, dispersal, fecundity, and mortality of these taxa. However, a disconnect currently exist with regards to the application of this lab derived data to real world environments as current meteorological models lack the sophistication and resolution to describe the thermal conditions experienced by surface-dwelling arthropods. The aim of this thesis is to investigate thermal distribution across a temperate mountain landscape in southern Alberta with the goal of contextualizing this information in a manner which was relevant to these taxa. As a result, average air and surface temperature models were created on annual and monthly time scales using in-situ measurements as input data for a variety of interpolation methods employed in Arc GIS Pro (version 2.9.1). Temperature models were then used to delineate thermally defined ecosystems in which overwintering suitability was determined as a by-product of the severity, duration, and frequency of cold exposure events while summer suitability was determined by the number of net growing days experienced under threshold temperatures of 5 °C, 8 °C, and 10 °C. In this environment, surface temperatures ranged from -21.17 °C to 51.18 °C, sub zero temperatures persisted for as many as 214 consecutive days, as many as 45 freeze-thaw cycles occurred within a single calendar year and a range of 107 to 172 average net growing days over 5 °C were recorded. To compliment this meteorological investigation, this document also serves as a first-hand account of the composition, abundance, and distribution of 35 families of surface-dwelling arthropods present within Castle Provincial Park. Several rare and endemic species belonging to these families such as *Cyphoderris monstrosa* and *Grylloblatta Camodeiformis* were also documented. Finally, inferences as to the thermal biological characteristics of these taxa are made based on the locations where they were

collected, and estimations are made as to how the distribution of thermally suitable habitat for these creatures may change in accordance with future climate projections.

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List of Abbreviations

ACIS	Alberta Climate Information Service
asl.	Above Sea Level
BTS	Basal Temperature of Snow
DEM	Digital Elevation Model
IDW	Inverse Distance Weighting
LEG	Low Elevation Grassland
LEW	Lower Elevation Woodland
RMSE	Root-Mean Squared Error
SLRs	Surface Lapse Rates
SSP	Shared Socioeconomic Pathway
TPI	Topographic Position index
UEAC	Upper Elevation Alpine Cold
UEAW	Upper Elevation Alpine Warm
UEFC	Upper Elevation Forested Cold
UEFW	Upper Elevation Forested Warm
WS	Weather Station

Chapter 1 – Background

1.1 Introduction

The southwest portion of Alberta, Canada, is home to the eastern slopes of the Canadian Rockies. This area represents highly protected natural mountain environments, including several national and provincial parks. These pristine natural areas serve as habitat for a wide variety of different flora and fauna (Alberta Parks, 2020; Beaver, 2017). Currently in Alberta, the conservation status of more than half of the described species of arthropods is unknown (Alberta Government, 2017; CESCC, 2015). Consequently, the distribution of these species is also unknown (Alberta Government, 2017; CESCC, 2015). This is an issue because arthropods of southwestern Alberta provide essential ecological and economic services including but not limited to pollination, decomposition, and serving as important food sources for other animals (Forrest & Thompson, 2011; González et al., 2003; Maucieri & Barclay, 2021). Additionally, there are several key pest species and invasive species that exist within the province who have the potential to cause serious ecological damage (Cullingham et al., 2011; Meng et al., 2015).

Principally, the focus of this document is on the small-scale (10m x 10m) composition of surface-level thermal regimes that exist within mountainous terrain and the impact that localized microclimates have on the thermal biology of arthropods that live there. This research was completed in the aims of developing an empirical statistical model that can illustrate the composition and distribution of surface-level temperatures within an 87 km² study area located situated in Castle Provincial Park. The development of such a model will aid in estimating the emergence timing, growth and development rates, dispersal, fecundity, and mortality rates for species of interest, serving as a medium for the application of lab determined biological

characteristics to real world environments. In addition to the environmental modelling outlined in this document, this publication also serves as a firsthand empirical account of the diversity, abundance, and distribution of the surface-dwelling arthropods that exist within the West Castle region of Castle Provincial Park.

1.2 Objectives

The primary goal of this research was to model the distribution and persistence of ecologically significant surface-level temperatures (in the context of the development and survival of surface-dwelling arthropods) across an 87 km² section of Castle Provincial Park, Alberta, Canada. The research objectives underlying this goal are as follows:

1. Describe the spatial distribution of surface-level temperatures across a heterogeneous mountain landscape via the development of high-resolution, computer-generated surfaces.
2. Document the diversity, distribution, and abundance of prominent surface-dwelling arthropods across thermally distinct microhabitat types that exist within Castle Provincial Park.
3. Describe the relationship between the severity, duration, and frequency of surface-level thermal events and the impact of these events on the thermal biology of these surface-dwelling inhabitants.
4. Describe how the distribution of thermal conditions throughout this region may change in accordance with future climate projections.

Chapter 2 - Literature Review

2.1. Overwintering Adaptations of Arthropods

As poikilothermic taxa, surface-dwelling arthropods lack the ability to regulate their internal body temperature, independent of their external environment (Bale, 1991, 1993, 1996). Due to this, arthropods utilizing upper latitude or upper elevation habitat are at an increased risk of injury or death due to exposure (Sømme & Zachariassen, 1981). However, despite being poikilothermic, a wide range of arthropods take advantage of polar and alpine terrain, suggesting that these taxa have developed other strategies for surviving in these extreme climates (Gillespie et al., 2019). The primary cold-survival tactics that have evolved amongst freeze-tolerant and freeze-avoidant species include supercooling, the utilization of ice nucleating agents (INA's), and behavioural modifications (Bale, 1996; Lactin & Johnson, 1996).

2.1.1 Supercooling

Winter mortality is a primary limiting factor which regulates populations of arthropods inhabiting temperate climates (Sinclair et al., 2003). Injuries and subsequent mortality rates incurred by arthropods because of cold exposure are the by-product of the intracellular freezing of water (Bale, 1993; 1996). Whereby, once a certain critical lower temperature threshold is reached, intracellular water spontaneously freezes, causing the cells to burst (Bale, 1996). Entomologists have commonly referred to this point of spontaneous intracellular freezing as the supercooling point (SCP) (Ohyama & Asahina, 1972; Sømme, 1982). Supercooling is a phenomenon observed in freeze-avoidant arthropods by which intracellular liquid water cools below 0 °C without a phase change. Supercooling is accomplished via the removal of possible intracellular nucleation sources and the production of cryoprotectant compounds (Sømme, 1982). The supercooling point for an arthropod is determined as the point when the rate of internal body

temperature cooling is reversed as the spontaneous freezing of intracellular water releases latent heat due to a phase change (Ohyama & Asahina, 1972). This release of latent heat is detectable if a thermistor is attached to the arthropod.

The ability for arthropods to supercool is primarily a function of the accumulation of cryoprotectants (Ohyama & Asahina, 1972; Sømme, 1982). The modification of summer diets to autumn diets allows arthropods to consume the necessary carbohydrates and proteins needed to produce cryoprotectant molecules which resist nucleation and therefore decrease the likelihood of intracellular ice formation (Sinclair, 2015; Sømme, 1964; Sømme, 1982). The most prominent and universal anti-freeze molecule in the arthropod world is glycerol which is produced from glycogen stores that are burned throughout the winter (Ohyama & Asahina, 1972; Sømme, 1964; Sømme, 1982). Glycerol is not utilised to the same extent by every terrestrial arthropod species; however, it is the most universally utilized compound and it is present at various concentrations in a wide range of freeze-tolerant and freeze-avoidant species (Bale, 1996; Sømme, 1964; Sømme, 1982). The concentration of glycerol and other cryoprotectant molecules fluctuates within arthropods as a response to seasonality, with the highest concentrations occurring during late winter to coincide with the lowest temperatures of the year. Ohyama & Asahina (1972) determined that this change in the concentration of glycerol content is strongly related to the SCP of the individual, suggesting that the lower lethal temperature for an individual arthropod changes throughout the year.

The links between glycerol content and the ability for arthropods to overwinter raises questions with regards to climatic instability. Increased climatic variability brought on by climate change has the capacity to create unseasonably cold temperatures in spring and autumn over short periods of time, contributing to temperature related mortality outside of the winter

months (Bale & Hayward, 2010; Marshall & Sinclair, 2015). Additionally, Marshall and Sinclair (2015) found that with regards to cold exposure, the frequency of cold exposure events can have a much greater impact on mortality than the duration or intensity of cold exposure. Since anti-freeze molecules need to be synthesized from glycogen stores, Marshall and Sinclair (2015) found that there is a significant energy expenditure associated with the repeated synthesis of glycerol, suggesting that variable autumn and spring temperatures may serve as an important source of mortality. However, more research is needed to completely understand the links between climatic variability, the production of glycerol, other winter energetic costs (e.g., metabolism), and overwintering success.

2.1.2 Ice Nucleating Agents

Freeze-tolerant arthropods are the most cold-hardy classification of arthropods which inhabit arctic, sub-arctic and high-elevation climates (Bale, 1996; Gillespie et al., 2019). Freeze-tolerant species can survive harsh winter conditions due to their capacity to promote the safe, extracellular freezing of water (Bale, 1996). Extracellular freezing of water is enabled via the production of ice-nucleating agents (INA's). INA's are synthesised in late autumn and early winter to serve as extracellular freezing sites which promote the safe extraction and freezing of intracellular water (Bale, 1996). In freeze-tolerant species, the extracellular freezing of water initially occurs when core body temperature is between -5 °C and -10 °C (Bale, 1996). Once frozen, freeze-tolerant individuals can survive short exposure to incredibly low temperatures between -40 °C and -80 °C, which is well below the supercooling point of any freeze-avoidant species (Bale, 1996).

Freeze-tolerant species are so successful in harsh winter climates because they utilise INA's in conjunction with other biochemical compounds such as glycerol to ensure their ability

to supercool before the INA's become fully active (Bale, 1996). This ensures that the individuals do not freeze to death in spring or fall in addition to being able to endure bitterly cold winters (Bale, 1996). However, the production of biochemical protectants and INA's comes at an energetic cost and in the context of unstable climatic conditions, the frequency of exposure to sub-zero temperatures has a negative impact on the ability for freeze-tolerant species to continually re-synthesize winter protectants at sufficient concentrations (Bale, 1996; Bale & Hayward, 2010; Marshall & Sinclair, 2015). In addition, climate change has contributed to more moderate winter conditions in upper latitude and high-elevation habitats which has allowed for the range expansion of less freeze-tolerant species into fringe habitat, causing increased levels of competition and other ecological issues (Gillespie et al., 2019). As a result, the distributional limits of freeze-tolerant species across various habitats are in a state of flux, the consequences of which are yet to be foreseen (Gillespie et al., 2019).

2.1.3 Behavioural Modifications

Behavioural responses by arthropods to extreme temperatures can include migration, basking, seeking shelter, modification of their life cycle, and the induction of diapause (Bale & Hayward, 2010; Lactin & Johnson, 1996; Sømme & Zachariassen, 1981; Tauber et al., 1986). Surface-dwelling arthropods that overwinter as adults in temperate climates often cease foraging behaviour and seek shelter underneath plant material, rocks, or below the soil in response to colder temperatures (Sinclair, et al., 2001). This small-scale migration ensures that the arthropods overwinter in habitat which is insulated from cold-air temperature fluctuations occurring in the lower troposphere. However, not every ground dwelling species overwinters as an adult, several species time their development to overwinter as either eggs, larva, or pupa which are significantly more cold-tolerant than the other respective phases of their life cycles

(Bale & Hayward, 2010; Hayes, 1982). No matter what stage of the arthropod's life cycle is used to complete the overwintering process, all arthropods that overwinter in temperate climates go through a dormancy phase known as diapause (Bale & Hayward, 2010; Beck, 1962; Denlinger, 2002). Diapause is defined by Bale & Hayward (2010) as a genetically programmed pre-emptive dormancy that occurs as a response to environmental conditions. The behavioral characteristics of diapause are characterized by a lack of movement, abandonment of foraging behavior and suppression of metabolic functions.

The role of behavioral modifications in the context of overwintering is often overlooked. However, slight behavioral modifications such as the choice of overwintering location can have significant impacts on the probability of overwintering success (Huang et al., 2019; Sinclair et al., 2001). Similarly, the proper timing of arthropod life cycles (primarily the induction and termination of diapause) with regards to seasonality impacts both arthropod survival and ecological productivity (Beck, 1962; Denlinger, 2002; Hayes, 1982). Future research opportunities exist with regards to determining the capacity for arthropods life cycles to adapt and synchronize with variable and unstable climates in addition to developing our own understanding of how behavioral responses of arthropods to cold stress may develop and change over time.

2.2 Temperature-Dependent Development of Arthropods

Those arthropods which do manage to successfully overwinter and make it to the spring/summer growing season are still, to some capacity, limited by the amount of environmental heat available to them (Lactin et al., 1995; Lactin & Johnson, 1996, 1997, 1998, 1998). Due to the poikilothermic nature of these taxa, internal body temperature closely mimics

that of the surrounding environment (Lactin & Johnson, 1996). This means that metabolic rates, enzymatic activity, and other cellular and biochemical processes are limited by the amount of heat that the environment can provide (Bale, 1993; Finch et al., 2008; Lactin & Johnson, 1996). This relationship between body temperature and development rate has a linear shape under idealistic conditions as the rate of development observed in an individual increases from a negligible value towards an optimal value in accordance with temperature. Internal body temperature outside of the individual's range of tolerance will result in injury, retardation of development, or even death of the individual (Rebaudo & Rabhi, 2018).

Calculating performance curves like the one presented in for actual arthropod species has been done with varying degrees of success. Earlier models, such as Stinner et al., 1975, Sharpe & DeMichele, 1977, & Taylor, 1982, modelled a linear relationship between temperature and development. Harcourt & Yee, 1982, was one of the first models that began to address a non-linear response of development to increases in temperature. Lactin et al., 1995, became a widely accepted model because it added two simple correction factors to the Logan model (Logan et al., 1976) which allowed for development rate to have a non-linear response to increasing temperatures, while also allowing for incorporation of a specified lower temperature development threshold. An example of the Lactin corrected Logan model can be found in Delatte et al., 2009 as this model was used to analyze the larval development rate of the Asian Tiger Mosquito (*Aedes albopictus*) (Delatte et al., 2009).

More recently, the constant development and reengineering of these performance models has led to a plethora of options for those wishing to model arthropod development rate as a function of temperature. Critical reviews of the performance of multiple models have found that there is no model which can be universally accepted, and that model choice is a critical part

of the analysis process (Quinn, 2017; Rebaudo & Rabhi, 2018). Due to the difficulty associated with developing these curves for individual species, many studies that are concerned with forecasting arthropod lifecycle progression as a function of temperature simply calculate growing degree-days over lower temperature threshold (Forrest & Thompson, 2011). This assumes that the lower temperature threshold for that species development curve and that any increase in temperature will have a positive, linear impact on development rate (Rebaudo & Rabhi, 2018).

2.3 Importance of Microhabitat to the Success of Arthropods

The distribution of mountain arthropods occurs across what can be described as fragmented and disjunct population distributions. This is because environmental conditions in topographically complex regions drastically shift in response to microclimatological influences such as the cooling of air temperature in accordance with elevation (Lewkowicz & Bonnaventure, 2011). Arthropods which utilize upper elevation terrain have evolved many adaptations to survive harsh microclimates including physiological adaptations such as the synthesis of antifreeze molecules discussed above, in addition to behavioural and morphological adaptations such as basking, shelter seeking behaviour, and a general reduction in body size which increases the probability of finding shelter (Sømme, 1989). Examples of these survival strategies can be seen in action near to top of Mount Kenya where overnight survival for many individuals is dependent on finding suitable cover beneath stones or fallen trees (Sømme & Zachariassen, 1981). Moreover, overwinter survival of alpine spiders in the mountains of New Zealand can be estimated as a function of the size of the rocks underneath which individuals burrow (Sinclair et al., 2001). This highlights the importance of scale with which these

organisms interact with their environment and the importance of microhabitat to the establishment and survival of these species (Wellington et al., 1999).

One of the greatest problems surrounding literature focused on the impacts of temperature on arthropods is that these works are primarily published by entomologists, and most entomologists have a relatively rudimentary understanding of meteorology (Wellington et al., 1999). Several articles published in entomologically focused journals go into painstaking detail when describing the thermal biological characteristics of these taxa, only to fail in their application of this knowledge to real world environments. For decades, entomological papers have failed to recognize that the temperature experienced by a person is vastly different from the temperature experienced by an arthropod (Lembrechts et al., 2019; Wellington et al., 1999). This disconnect can be explained, in part, as an issue of scale. A person may experience a chill as they hike down into a valley where dense, cold air has been pooling on a crisp Autumn morning, while an arthropod can have the same experience by maneuvering through the boot tread pattern of a muddy footprint left behind by the hiker (Wellington et al., 1999). Failing to consider the scale at which arthropods interact with their environment muddies the outputs of ecological models to the point where their products become largely invalid (Arrington et al., 2007). If a model fails to accurately predict why, when, and where particular temperatures occur and how those temperatures are experienced by the taxa in question, then the model cannot accurately apply its knowledge of how these temperatures affect the greater biological system (Lembrechts et al., 2019; Wellington et al., 1999).

The Rocky Mountains of southwestern Alberta are an example of a larger biological system where significant changes in environmental conditions can be observed over short horizontal distances. The weather in this region of the Canadian Rockies is governed by moist air

carried inland from the Pacific Ocean via the westerlies, and cold Arctic air whose position is controlled by the polar jet stream (Cullen & Marshall, 2011). However, the influence of these larger climatological forcings on any specific location are manipulated by the heterogeneous topography and vegetation structure that is indicative of this area (AEP, 2018). For example, average monthly surface lapse rates in this region vary from $-2.2\text{ }^{\circ}\text{C km}^{-1}$ to $-8.0\text{ }^{\circ}\text{C km}^{-1}$ and the intensity and persistence of this phenomena is largely influenced by aspect, time of year, and the frequency of chinook events (Bexte, 2019). Moreover, environmental conditions at the surface level are also quite heterogeneous as changes in vegetation structure and the composition of surface materials can alter mean annual ground temperatures of high alpine regions by as much as 7°C as a function of increased airflow through voids that exist amongst blocky materials opposed to mineral soils (Harris & Pedersen, 1998). While research exists which describes microclimatological impacts on air temperature throughout this region (Bexte, 2019), more research is needed to accurately describe the surface-level distribution of heat across this region, as well as contextualize microclimatological information in a way which is meaningful for surface-dwelling arthropods (Harris & Pedersen, 1998; Lembrechts et al., 2019; Wellington et al., 1999).

2.3.1 Relationship Between Temperature and Arthropod Mortality

Mortality of arthropods living at the ground level can be determined as a function of exposure to the elements (Bale, 1996). The frequency of extreme weather events, the duration of extreme weather events and the severity of extreme weather events are all important factors to consider in the context of temperature-induced mortality (Brown et al., 2004; Marshall & Sinclair, 2015). This is because arthropod mortality can occur because of short exposure to severe conditions (e.g., $-40\text{ }^{\circ}\text{C}$), prolonged exposure to moderate conditions (e.g., $-10\text{ }^{\circ}\text{C}$), or

repeated exposure to somewhat intolerable conditions (e.g., -5 °C). As a result of the susceptibility of arthropods to temperature, they are completely reliant on cover provided by snow, vegetation, and topography to insulate them from temperature fluctuations occurring in the lower troposphere (Sinclair et al., 2001).

2.3.2 Heterogeneity of Mountain Environments

Mountain habitats present some of the most heterogeneous environments on earth. Differences in elevation, aspect, topographic position index (TPI) and slope influence climatic variables such as temperature, wind exposure, precipitation, and the availability of direct sunlight (Bonnaventure et al., 2012). As a result of the heterogeneity of these environments, there is often an incredible diversity of plant and animal life which inhabit different fragments of the diverse terrain in what can be described as fragmented and disjunct populations (Dahlhoff et al., 2019; Finch et al., 2008). Various microhabitats available to arthropods inhabiting these regions include barren exposed rocks, high-elevation grasslands, meadows, shrublands, coniferous forests, mixed woodlands, rivers, lakes and wetlands. In the mountains of southeastern Alberta, all these various ecotones occur across relatively short horizontal distances. The challenge then for arthropod biogeographers in the context of habitat suitability modelling is to determine which regions have surface-level thermal regimes that allow for successful arthropod overwintering and spring/summer development. (Arrignon et al., 2007; Senay & Worner, 2019; Tognelli et al., 2009). This task is often difficult due to the scale at which individual arthropods interact with their environment and the capacity for microclimatological forcings to significantly influence surface-level conditions.

2.3.3 Insulating Properties of Physical Environmental Features

Due to the relatively small size of terrestrial arthropods, microclimatic forcings can be just as important, if not more so, than broad scale climatic forcings (Senay & Worner, 2019; Sinclair et al., 2001). If researchers want to truly understand the processes that determine the overwintering success of arthropods, they must account for not only the larger climatic impacts such as mean annual snowfall across a mountain range, but also smaller forcings like how aspect, wind redistribution, vegetation cover and topographic depressions impact snow redistribution along a single slope (Senay & Worner, 2019; Sinclair et al., 2001). Microhabitat is particularly important for determining arthropod population dynamics due to the high fecundity of r-selected species. This is because individuals who survive the winter in small areas of refugia can often produce enough offspring to ensure the long-term survival of the species in what might largely be considered inhospitable terrain (Labeyrie, 1978). In cases where refugia is easily found and utilised by arthropods, the distribution of the species is then limited by the dispersal capabilities of the species in question as individuals radiate outward from areas of winter refugia into surrounding areas (Senay and Worner 2019).

Snow cover is of particular importance for arthropods that overwinter at the ground level because of the low thermal conductivity of snow itself (Goodrich, 1982; Bale & Hayward, 2010). The warming effects of snow cover in the context of surface temperature is twofold in that snow cover acts as a barrier between the surface and the lower atmosphere, while also trapping latent heat which is released from the ground by the refreezing of water in subsurface materials (Goodrich 1982, Lewkowitz and Ednie 2004). The capacity for snow cover to insulate the ground is also magnified as a function of depth (Bonnaventure et al., 2012; Goodrich, 1982). Non-permafrost environments (areas where sub-surface materials do not remain frozen for two

or more consecutive years) that receive early seasonal snowfall and are buried under several hundred centimeters of snow, may experience winter mean surface temperatures of around 0 °C despite much cooler winter mean air temperatures (Bonnaventure & Lewkowicz., 2008; Goodrich, 1982). However, in the absence of snow cover and vegetation cover, surface temperatures often more closely resemble lower atmospheric temperatures (Lewkoeicz & Ednie, 2004).

There are many topographic features which can influence the regional redistribution of snow across mountainous terrain such as elevation, aspect, slope, vegetation cover and TPI (Hiemstra, Liston et al. 2002). As a result of the heterogeneous distribution of snow, there can be a large change in winter mean surface temperatures over short horizontal distances (Bonnaventure & Lewkowicz, 2008; Bonnaventure et al., 2012; Lewkowicz & Ednie, 2004). The influence of snow cover, vegetation, and soil composition on thermal conductivity between the surface and the troposphere alters surface-level offsets across space (Bonnaventure & Lewkowicz, 2008; Harris & Pedersen, 1998). Currently, a large methodological gap exists amongst primary literature with respect to modelling the distribution of surface-level offsets and mapping winter surface temperatures across space (Arrington, 2007; Bonnaventure & Lamoureux, 2013; Tognelli et al, 2009). However, modelling and mapping of air temperatures in mountain environments has been done with a greater deal of success (Betxt, 2019). Development of modelling methods for annual mean ground surface temperatures (AMGST) in temperate regions is needed to fully understand the distribution of winter surface temperatures in non-permafrost regions and subsequently, where arthropods can find areas of refugia in these environments.

2.4 Empirical Statistical Modelling of Species Distributions

Accurately modelling the distribution of arthropods across space is critical to understanding the ecological roles of these taxa (Sømme & Zachariassen, 1981; Tognelli et al., 2009). The distribution of any species can be thought of as the result of the species ability to tolerate various stressors present in the environment (food and water availability, prevalence of predators, suitable temperatures, etc.) in addition to the species ability to navigate around dispersal barriers (rivers, mountains, deserts, etc.) to colonize new areas (Senay & Worner, 2019; Stinner et al., 1983). As such, the distribution of an arthropod species can be limited by any one of several different environmental parameters, including temperature (Dahlhoff et al., 2019; Schoville et al., 2015; Sømme & Zachariassen, 1981). The main limitation of relying on presence-absence data as a means of validation for calibrating empirical species distribution models is that when the species is consistently found in an area, it can be assumed that the habitat is suitable for that species (Arrington et al., 2007). However, when the species is absent, further investigation is needed to determine which environmental parameter is preventing the species from inhabiting that region, or to identify if a dispersal barrier is present (Arrington et al., 2007). This issue becomes increasingly complex as the tolerance level for different environmental stressors can be significantly different between closely related species and even between individuals of the same species (Andersen et al., 2015). As a result, the ability for empirical statistical models to accurately delineate a species distribution is limited by the quality of the input data. The input data used to either define the survival parameters for a particular species or to describe the environmental conditions of a given area can both create sources of error within the model (Arrington et al., 2007). Presenting a particularly tough challenge with regards to arthropods as contextual biological data is largely undeveloped for most species and most climatological

models lack the resolution required to describe environmental conditions experienced by these taxa (Gillespie et al., 2019; Lembrechts et al., 2019; Wellington et al., 1999).

The greatest challenge regarding the modelling of thermally suitable arthropod habitat in mountainous terrain is the creation of models with enough spatial resolution to account for the implications of microclimatological forcings (Arrignon et al., 2007; Senay & Worner, 2019; Tognelli et al., 2009). There is no coincidence that some of the most accurate predictions of arthropod distribution in mountainous habitat are developed for extensively studied species with a plethora of field data collected, and ecological data to work from (Arrington et al., 2007; Tognelli et al., 2009). Accounting for how particular environmental variables (precipitation, vegetation cover, mountain temperature inversions, etc.) impact different species in different ways is of critical importance to the development of accurate species distribution models (Andersen et al., 2015). Extensive research is required to further develop our understanding of the limits of tolerance for prominent surface-dwelling arthropods in response to various climatic variables. The coupling of newly acquired ecological data with technological and methodological advances related to increasing the resolution of spatial models will drastically improve the accuracy of models which identify thermally suitable habitat for these species (Senay & Worner, 2019).

2.5 Building and Utilization of Phenological Models

The development of phenological models can aid in predicting the emergence timing, distribution, growth, activity, fecundity, and mortality for a particular species of interest (Bentz et al., 1991; Delatte et al., 2009; Fand et al., 2014). With respect to temperature, a hypothetical arthropod will be able to endure temperatures that occur within a certain range (-4°C to 40°C for example) and if the arthropod is exposed to temperatures outside of this range (say -30°C), then

the arthropod will perish (Bale, 1996; Roland & Matter, 2013). Likewise, temperature related mortality can also occur when an arthropod is exposed to less favorable temperatures for an extended period of time (say 3°C) as this has the capacity to stunt their growth and natural development (Bale, 1996; Bentz, 1991; Finch, 2008; Lactin et al., 1995). Lastly, temperature induced mortality can also occur because of fluctuating temperatures (Marshall & Sinclair, 2015; Sinclair & Chown, 2005). Fluctuating temperatures have their largest impact on arthropod mortality during the shoulder seasons when temperatures seem to rise above and fall below 0°C on a weekly or even a daily basis, forcing arthropods to consistently re-synthesize cryoprotectant molecules (Sinclair, 2015; Sinclair & Chown, 2005; Sømme, 1964). To make matters more complicated, research shows that different developmental stages of a particular arthropod (egg vs juvenile vs adult) have different upper and lower temperature thresholds and different heat requirements to progress through their lifecycles (Bentz, 1991; Boychuk, 2012; Delatte et al., 2009). However, if the relationship between temperature and development rate is understood for every life stage of a hypothetical arthropod, then a mathematical model of the relationship can be achieved (Bentz et al., 1991; Lactin et al., 1995; Rebaudo & Rabhi, 2018).

After the relationship between phenotype and environment is understood, this opens the door with respect to habitat suitability modelling (Andersen et al., 2015; Arrington et al., 2007; Dahlhoff et al., 2019; Delatte et al., 2009). In the context of surface-dwelling arthropods and thermally suitable habitat, modelling where ecologically significant temperatures develop and persist can give researchers an idea of where species of interest are most likely to first emerge and successfully complete their lifecycle (Bentz et al., 1991; Dahlhoff et al., 2019; Delatte et al., 2009). Considering maximum and minimum survivable temperatures, the rate of development at given temperatures, and the length and stability of conditions during the growing season, areas

with optimal thermal conditions, sub-optimal thermal conditions, and intolerable thermal conditions can be delineated using computer-generated models (Andersen et al., 2015, Dahlhoff et al., 2019; Fand et al., 2014). The development of such models will prove valuable when determining management protocols for species of interest. Likewise, these models have further value when predicting the impact of climate change on these species as certain environmental parameters can be artificially manipulated in accordance with current climate projections (Bale & Hayward, 2010; Fand et al., 2014; Wang et al., 2016).

Chapter 3

An Analysis of the Influence of Thermal Heterogeneity within Mountain Environments on the Spatial Distribution and Thermal Biological Characteristics of Surface-Dwelling Arthropods

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Authorship: *Nicholas Hassink¹, Philip P. Bonnaventure¹ & Dan L. Johnson¹

¹Department of Geography and Environment, University of Lethbridge, Lethbridge, AB, T1K 3M4, Canada

*Corresponding Author email: nicholas.hassink@uleth.ca

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3.1 Abstract

Investigation into thermal distribution across a temperate mountain landscape in southern Alberta took place with the goal of contextualizing this information in a manner which was relevant to surface-dwelling arthropods. Average air and surface temperature models were created on annual and monthly time scales using in situ measurements as input data for a variety of interpolation methods employed in Arc GIS Pro (version 2.9.1). Average monthly air temperature and surface temperature models had RMSE values that ranged from 0.07 °C – 0.68°C and 0.06 °C – 2.68 °C, respectively. Surface temperature models were used to divide the 87 km² study area into six thermally distinct ecosystem classifications. Overwintering suitability within each respective ecosystem classification was determined as a function of the severity, duration, and frequency of cold exposure events experienced by arthropods overwintering at the surface. Thermal suitability during the summer months was also determined as a function of the number of net growing degree-days within each ecosystem type under threshold temperatures of 5 °C, 8 °C, and 10 °C, respectively. To compliment the meteorological work summarized in this study, empirical data regarding composition, abundance, and distribution of surface-dwelling arthropods present within Castle Provincial Park are also reported. Inferences as to the thermal biology of these taxa, and potential risks associated with increased warming due to climate change, are discussed.

3.2 Introduction

It has been estimated that between 51-62% of terrestrial arthropod species inhabiting Canadian ecosystems have been described (Langor, 2019). However, the conservation status and distribution of 53% of described terrestrial arthropod species in Canada is currently unknown (CESCC, 2016). Historical databases concerned with the abundance, distribution, and life history

of arthropods in Canada are severely underdeveloped compared to the information that is available for flowering plants and large mammals, respectively (Cameron & Hargreaves, 2020; Erland et al., 2022; Gillespie et al., 2019; Langor, 2019). Most of the historical data that is available for terrestrial arthropods is focused on species of special interest such as crop and forest pests, pollinators, biocontrol agents, or species that serve as vectors for disease transmission in humans (Colla et al., 2012; Fand et al., 2014; Nealis et al., 2016). As a result, contextual data is largely unavailable for most arthropod species, especially species that exist in remote habitats (Gillespie et al., 2019).

This is an issue of concern in our study because non-pest arthropods of southwestern Alberta provide essential ecological and economic services including but not limited to pollination, nutrient cycling, herbivory, and serving as important food sources for other animals. (Forrest & Thompson, 2011; González et al., 2003; Losey & Vaughan, 2006; Maucieri & Barclay, 2021). Additionally, key pest species and invasive species have the potential to cause serious economic and ecological damage (Cullingham et al., 2011; Meng et al., 2015). The lack of contextual data that surrounds many arthropod species also confounds issues related to global insect decline which has been documented in recent years (Hallman et al., 2017; Leather, 2017). The root cause of this decline in arthropod diversity and abundance is largely speculative at this point but the impact of climate change on emergence timing, growth and development, dispersal, fecundity, and mortality of these poikilothermic taxa is an area of active study (Bale & Hayward, 2010; Goulson, 2019; Nealis, 2020).

The southwest portion of Alberta, Canada, is bordered by the eastern slopes of the Canadian Rockies. This area includes protected natural mountain environments, including several national and provincial parks. These pristine natural areas serve as habitat for a wide variety of flora and

fauna (AEP, 2018). In the Canadian Rockies, seasonal changes in temperature strongly affect arthropod development and lifecycles throughout the course of the year (Lactin et al., 1995; Marshall & Sinclair, 2015). Overwintering success of these taxa is directly related to the severity, duration, and frequency of cold exposure events which must be endured by individuals (Marshall & Sinclair, 2015). Exposure to severely cold temperatures (less than $-35\text{ }^{\circ}\text{C}$ is not uncommon for this region), prolonged exposure to moderately cold temperatures (below $0\text{ }^{\circ}\text{C}$ temperatures can persist in this region for several months), or exposure to multiple freezing periods interspaced by periods of relief (diurnal temperature fluctuation above and below $0\text{ }^{\circ}\text{C}$ is not regionally uncommon) potentially threaten arthropod survival (ACIS, 2022; Bale, 1996; Marshall & Sinclair, 2015). During the summer months, temperature also influences critical aspects of arthropod life cycles such as emergence, development timing, activity levels, feeding rate, movement, and metabolic function (Bale & Hayward, 2010; Lactin et al., 1995; Sinclair, 2015).

The spatial and temporal thermal distribution in this temperate mountain ecosystems is highly variable compared to the grassland regions east of the Rockies (Bexte, 2019; Powell et al., 2007) Complex topography and vegetation structure of the eastern slopes of the Rockies stimulates the creation and persistence of microclimates that drastically alter thermal regimes across short horizontal distances (Bexte, 2019; Shur & Jorgenson, 2007). Furthermore, thermal distribution and the persistence of favorable conditions in these ecosystems also varies on vertical scales. Large snowpacks and dense canopy structure (or lack there of) can insulate the surface from conditions in the lower troposphere to varying degrees which can cause a disconnect between air temperature and surface temperature (Cartwright et al., 2020; Goodrich, 1982; Shur & Jorgenson, 2007). This offset between air temperature and surface temperature is

something that must be considered when modelling overwinter survival, emergence timing, and lifecycle progression for arthropods that complete life stages at or near the surface (Lactin & Johnson, 1996; 1997; 1998; 1998; Lembrechts et al., 2019).

Previous studies of arthropods in mountainous regions often lack the spatial resolution and model components required to account for the influence of microclimatic variables on conditions experienced by arthropods inhabiting surface-level environments (McClay & Hughes, 1995; Roland & Matter, 2013; Tognelli et al., 2009). Moreover, the bulk of pre-existing literature that deals with arthropod biometeorology in Alberta utilizes interpolated air temperature surfaces to describe thermal conditions which can often create inaccurate estimations of surface-level conditions (especially during the winter months) (Lactin & Johnson, 1996; 1997; 1998; 1998; Lembrechts et al., 2019). The purpose of this article is to investigate the spatiotemporal thermal distribution in the mountains of southern Alberta across both horizontal and vertical scales, to describe the impact of thermal variability on surface-dwelling arthropods. We also present accounts of the diversity of surface-dwelling arthropods found in these remote mountainous regions.

3.3 Study Area

The collective of Castle Provincial Park and Castle Wildlands Provincial Park now represents a 1,050 km² protected area in the southwestern portion of Alberta, Canada (AEP, 2018). Field studies and analysis for this project were confined to an 87 km² subsection of the West Castle Watershed. The border of this study area was delineated so the study area boundary followed the watershed boundary while encircling the perimeter of weather data recording stations. The study area included the western peaks that surround the West Castle River (Figure 3.1). Prior to 2017, the area that is now known as Castle Provincial Park was designated as publicly owned land,

allowing for construction of a private ski resort, resource exploration by industry, development of offroad trail networks for offroad vehicles, and the erection of backcountry pathways and campsites utilised by recreational hikers and explorers. Since the park's inception, most of the resource exploration and harvesting work in this area has concluded, many of the main hiking and skiing routes have been improved, proper campsites with essential facilities have been constructed, and the use of offroad vehicles has been prohibited outside of the privately owned ski resort. As a result, this temperate mountain environment now serves as relatively protected habitat for native flora and fauna, while still providing a great deal of accessibility to the public. Researchers have recently taken advantage of this situation by utilizing Castle Provincial Park as the focal point for several biological and geographical studies (AEP, 2018; Beaver, 2017; Bexte, 2019; Cartwright, 2019).

Castle Provincial Park was selected as the study area for this project for a variety of reasons. Principally, the unique topography that characterizes Castle Provincial Park serves as exceptional terrain for investigation into the formation and persistence of microclimates in temperate mountain environments. The topography of Castle Provincial Park is best described as steep-mountainous peaks, with glacially carved valleys that span an elevational gradient from approximately 1332 m to 2632 m asl. (AEP, 2018). The meteorological conditions in the West Castle Watershed are influenced by the region's continental location, northern latitude, and mountainous topography indicative of the eastern slopes of the Canadian Rockies (Cullen & Marshall, 2011; Forbes et al., 2011). Local conditions are often influenced by moist air carried inland from the Pacific Ocean via the westerlies, or by cold Arctic air whose position is influenced by the polar jet stream (Cullen & Marshall, 2011). An Alberta Government weather station named "Castle Auto" is located in the foothill region of the study area at an elevation of

1351 m asl., and has been operating since 2011. From 2012-2021, Castle Auto recorded a mean annual air temperature of 4.51 °C, a maximum air temperature of 37.2 °C (10-08-2018) and a minimum air temperature of -38.2 °C (11-01-2017) (Alberta Government, 2022). Precipitation data is collected at the Environment Canada weather station “Beaver Mines”, located 13.5 km Northeast of Castle Auto station, and has recorded a 30-year precipitation average (1980-2010) of 679.8 mm/year (ECCC, 2022).

The diversity and abundance of biotic organisms living in Castle Provincial Park is of interest for this project. The landscape is a patchwork of ecoregions which can crudely be defined as lower elevation grassland/transitioning to foothills, lower elevation woodlands, upper elevation coniferous forests, alpine meadows and exposed rockfaces (AEP, 2018). The foothills topography is scattered throughout the park, forming grassland highways that connect to the larger prairies east of the park boundary. Foothill locations in the park are defined by relatively drier climatic conditions and loose, productive soil that supports a wide variety of grasses, shrubs, sedges, and wildflowers, such as Shrubby Cinquefoil (*Pentaphylloides floribunda*), Sagebrush (*Artemisia tridentata*), Crested Wheatgrass (*Agropyron cristatum*), and Mountain Timothy (*Phleum alpinum*) (Kershaw et al., 2016) (Figure 3.2). Lower elevation woodlands provide a moist, cooler environment compared to the foothills which gives rise to a canopy that is defined by the presence of White Birch (*Betula papyrifera*), White Spruce (*Picea glauca*), Engelman Spruce (*Picea engelmannii*), Douglas Fir (*Pseudotsuga menziesii*), and Lodgepole Pine (*Pinus contorta*) (Figure 3.2). The understory of these woodlands is home to a variety of shrubs and forbs, such as Green Alder (*Alnus viridis*), False Green Hellebore (*Veratrum viride*), Thimbleberry (*Rubus parviflorus*), and Common Snowberry (*Symphoricarpos albus*) (Figure 3.2). The canopy of Castle Provincial Park includes Sub-Alpine Larch (*Larix lyallii*) and Limber

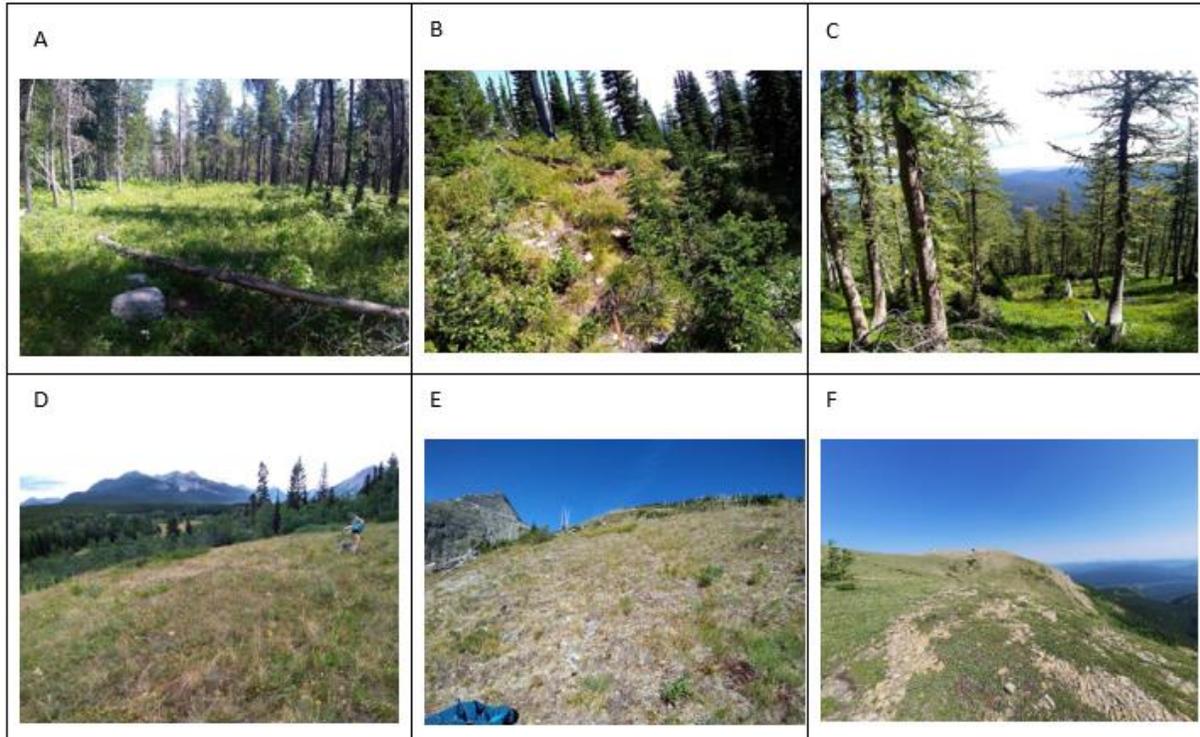


Figure 3.2: Mid-summer photographs of different ecosystem types present in Castle Provincial Park. A is a flat, mixed woodland located along the Syncline Brook trail at 1400 m asl. B is an upper elevation, conifer forest situated along a South facing slope along the North Haig Lake trail at an elevation of 1850 m. C is a high mountain forest dominated by Sub-Alpine Larch (*Larix lyallii*) which is situated along a North facing slope near Syncline Peak at an elevation of 2200 m. D represents a flat lower elevation grassland located just west of Highway 744 at approximately 1400 m in elevation. E represents an alpine meadow situated along a south facing slope along the Paradise Lake trail at an elevation of 1900 m. F represents a rocky, alpine environment dominated by bryophytes which is situated on top of Barnaby Ridge at an elevation of 2200 m.

3.4 Methods

3.4.1 Field Data Collection

3.4.1.1 Air Temperature Data Collection

The Bonnaventure Lab for Permafrost Science (BLPS) has maintained an air and ground temperature sensor network within the West Castle Watershed of Castle Provincial Park, Alberta, Canada since 2016 (Figure 3.1). The deployment of these station locations aimed to maximize heterogeneity across elevation, aspect, and ecoregion. Hourly air temperature data were recorded using Onset HOBO MX230 or MX2305 wireless temperature data loggers which record

temperature with an accuracy of $\pm 0.2^{\circ}\text{C}$ between an operational range of -40 to 70°C . These temperature loggers were all secured in Onset HOBO RS1 solar radiation shields which protected the loggers from direct sunlight, harsh winds, and precipitation. Air temperature recording units were fastened to the downslope side of trees at a height of roughly 1.5-2.5 m using a pipe clamp to ensure the temperature data logger would not be buried under snow during the winter months. In the absence of trees, air temperature recording units were fastened to the top of an 8-foot-tall piece of steel fencing post which was hammered into the ground and secured in place with 4 metal cables attached to framing nails. Installation and servicing of 13 air temperature recording stations for this research occurred in mid-late summer of 2020 until a corresponding end date in 2021. Hourly air temperature data from September 15th, 2020 – September 15th, 2021, was also downloaded from two Alberta Climate Information Service (ACIS) weather stations “Castle Auto” and “West Castle” (Alberta Government, 2022) (Figure 3.1).

The air temperature logger of recording site WS 5 failed during the field study. However, historical data were previously recorded at this site from October of 2016 - September of 2018. As a result, historical data which most closely resembled September 2020 - September 2021 climate conditions recorded by other stations were used to aid in the development of a synthetic year. Once all the air temperature data had been compiled, one complete year of air temperature data was available at 15 different locations in Castle Provincial Park (Figure 3.1). All together the air temperature sensor network was comprised of sensors orientated along slopes facing each cardinal direction, in grassland, forested, and above treeline environments, spanning an elevational gradient from 1351 m – 2412 m asl.

3.4.1.2 Ground Temperature Data Collection

A total of six iButton temperature data loggers (manufactured by Maxim Integrated) which record temperatures from -40 °C to 85 °C, with an accuracy of $\pm 1^\circ\text{C}$, operated in Castle Provincial Park from summers 2017 to 2021. Due to the limited memory of iButtons, temperature readings were recorded at 4-hour time intervals. Several HOBO MX 2201 and HOBO UA-002-64 temperature data loggers were installed to supplement the existing network. Both HOBO MX 2201 and HOBO UA-002-64 have an accuracy of $\pm 0.5^\circ\text{C}$ for temperatures between -20 to 70 °C which was suitable for Castle because a winter surface temperature of 0 °C persisted throughout much of the region apart from high elevation, topographically exposed regions where fluctuations below -10 °C were regularly observed. These loggers recorded hourly temperatures from the summer of 2020 to a corresponding date in the summer of 2021. The additional temperature data loggers bolstered the surface sensor network in the West Castle Watershed from 6 up to a total of 36 active ground temperature recording stations, all of which were buried under soil at a depth of 2-5cm and marked with an orange stake. HOBO surface temperature loggers were installed at all 18 arthropod collection sites (1 logger malfunctioned) that spanned 6 different microhabitat types and 13 additional loggers were placed underneath each respective air temperature recording station. The inclusion of these sensors provided the study with accurate, hourly temperature readings for 30 representative locations in Castle Provincial Park in addition to interval (4-hour) data at 6 additional stand-alone locations.

The locations of the ground temperature sensors in this network allowed for sampling within different regions that were each characterised by microclimate. Multiple loggers were placed below cliff faces, along ridgelines, on top of mountain peaks, in alpine meadows, in dense coniferous forests, and in lower elevation grasslands. This was done to determine the extent to

which ground surface temperatures fluctuate across different ecosystem types in the West Castle Watershed. The number of operational surface temperature loggers in each ecosystem type was 6 and 7 except for lower elevation, grassland ecosystems where only 4 surface temperature loggers were installed. This was primarily due to the homogeneous topography and vegetation of grassland ecosystems.

Winter surface temperature measurements were further supplemented by the collection of Basal Temperature of Snow (BTS) point measurements. BTS point sampling was easy to employ along snow shoeing trails, cross-country skiing routes, and terrain accessible via chairlifts operated by Castle Mountain Resort, which allowed measurements to be taken at locations which captured the spatial heterogeneity of this region. BTS point sampling methodology is centered around the assumption that late winter surface temperatures in non-permafrost environments will remain at 0°C due to the insulating properties of snow (Haeberli, 1973). However, in permafrost environments (or areas comprised of rocky substrate) subsurface water beneath the active layer is frozen year-round (or water simply cannot be retained by the substrate), and as a result no latent heat is released from the re-freezing of subsurface components. This allows for surface temperatures in environments dominated by rocky substrates or the presence of permafrost to dip below -3°C despite sufficient snow cover (Lewkowicz & Ednie, 2004).

The equipment used for BTS point collection consisted of a thermistor, data logger, and an avalanche probe (Bonnaventure et al., 2012). A thermistor connected to a thermistor cable (E348-TMC6-HD, accuracy: $< \pm 0.2^{\circ}\text{C}$, resolution: $< \pm 0.03^{\circ}\text{C}$) was taped to the base of a carbon fibre avalanche probe using thermally conductive aluminum tape and thrust through the snowpack to the ground-snow interface. Readings were then recorded when the thermistor cable was plugged into a HOBO 4-Channel Analog Data Logger (UX120-006M, accuracy: $\pm 0.15^{\circ}\text{C}$,

resolution: 0.002°C). After an initial wait period of 5 minutes had elapsed, temperature readings were recorded at 1-minute intervals for the following 5 minutes so that a regression equation could be fit to the data to estimate a surface temperature value after 30 minutes of exposure (Bonnaventure et al., 2012). As a result, a single BTS point was the product of the average estimated 30-minute reading taken from three different temperature probes at a location of interest. In the field, these 3 probes are spaced near one other (< 10 m separation) in a triangle formation to account for micro-scale variations in terrain. A total of 59 BTS point measurements were taken at representative points throughout Castle Provincial Park during the late winter months of 2020 and 2021.

3.4.1.3 Collection, Storage, and Processing of Surface-Dwelling Arthropods

Vernon pitfall traps (plastic ground inserts) partially filled with propylene glycol were utilized as the primary method of collecting surface-dwelling arthropods in addition to sweep net samples collected while following the terms and conditions outlined in Alberta Parks Research and Collection Permits (Permit numbers 20-231 and 21-037). Vernon pitfall traps provided several benefits over simple homemade traps in that they were sturdy enough to survive strong winds, resistant to tampering by animals, and pale enough in colour to easily blend into the landscape. The modified rain guards of Vernon pitfall traps protected arthropod samples from birds and other scavengers and included a guard that deterred larger creatures such as amphibians and rodents, reducing bycatch and negative environmental impact. The total number of pitfall traps that could be installed and regularly serviced by the field team during the time allotted for this study was 90 traps. These traps were spread out across 6 different microecosystem types to determine the diversity and relative abundance of representative surface-dwelling arthropods within each microecosystem type, resulting in a total of 18 sampling sites (3 replicated per

microecosystem type). This approach was justified by under the assumption that at least 8-10 different families of arthropods would be present within each microecosystem type, given 6 microecosystem types of interest, a minimum of 15 sampling sites would have been needed to achieve 95% confidence with regards to conclusions made about the composition of the surface-dwelling arthropod community throughout this region.

Initially, there were no surface temperature readings that could be used as a reference for determining where to setup arthropod collection sites. As a result, these sites were chosen based on habitat type and accessibility via local hiking trails and winter BTS point measurement data that was collected during February and March of 2020. Every arthropod sampling site consisted of 5 Vernon pitfall traps (18 sampling sites x 5 traps per site = 90 traps total) and a single stand-alone HOBO MX 2201 or HOBO UA-002-64 temperature data logger buried at a depth of 2-5 cm. Each sampling site collected 3 samples over the course of the 2020 summer sampling season (melt, mid summer, and fall). This allowed for observance of emergence timing for different guilds of arthropod and provided insights as to how the composition of the surface-dwelling arthropod community changed throughout the course of the growing season. Each of these sampling periods took place over a minimum time span of 2-weeks to limit the influence of specific weather events on collection numbers while ensuring that traps in sun exposed areas did not dry out. The longest sampling period lasted a total of 50 days due to authorization requirements from Castle Mountain Resort to access this site paired with chance encounters with Black Bears (*Ursus americanus*) that prevented the field team from accessing this site on consecutive occasions. Luckily, the location in question was densely forested and while traps did run low on propylene glycol, they did not run dry. This sampling technique was also repeated in the summer of 2021 but due to resource limitations only 1 round of sampling was conducted

during the mid-summer months (July and August). As a result, 322 out of a possible 360 pitfall trap samples were collected over the course of the 2020 and 2021 summer seasons. Several traps were dug up by wildlife during the sampling period resulting in loss of 38 total samples.

Once the arthropod samples had been collected, the contents of the trap were transferred into a 250 ml mason jar. Within 24 hours of collection, the contents of the trap were run through a strainer and the biological contents of the sample were transferred to a clean, 250 ml mason jar and submerged in a 70% ethanol solution. These jars were then stored in a fridge at 4°C for a period ranging from several days up to several months before all samples could all be properly processed. After processing, a small number of individuals from representative species were pinned while the rest were returned to a mixture of 70% ethanol for long term storage.

Processing of arthropod samples consisted of examining each individual arthropod and identifying it to a Family-level taxonomic classification based on physical characteristics. Identifications were later validated through use of several field guides, monographies, and consultation with experts (Anderson & Peck, 1985; Borror & White, 1970; Bright, 1976, 1993; Dondale & Redner, 1978, 1982, 1990; Eaton & Kauffman, 2007; Hancock & Hancock, 2015; Ives & Wong, 1988). This process was time consuming as physical characteristics of over 25, 000 individuals were examined with a dissecting microscope to produce family-level identifications and track population numbers across different spatial and temporal scales. Key specimens of interest (rare species, species of ecological significance or species with high regional abundance) were identified to the level of species via consultation with experts.

3.4.2 Data Processing and Analysis

3.4.2.1 Creation of Average Air Temperature Models

Hourly temperature readings from station sites were used to calculate monthly air temperature averages, annual mean air temperature (AMAT) and other thermal attribute values (maximum, minimum) at each respective site. The lowest elevation air temperature recording station in the study area was ACIS site “Castle Auto” which was located at 1351m asl. Castle Auto was based in an open and unforested region of the park which made it an ideal base location for calculating Surface Lapse Rates (SLRs) (Bonnaventure et al., 2012). North, East, South, and West SLRs were calculated based on the observed differences in average recorded air temperatures between high mountain locations and Castle Auto. For example, WS 12 is located at an elevation of 2026 m asl. and is situated at the base of a large North facing bowl. The average monthly temperature at WS 12 in January of 2021 was $-6.97\text{ }^{\circ}\text{C}$, while it was only $-2.50\text{ }^{\circ}\text{C}$ at Castle Auto. This meant that the observed rate of cooling along North facing slopes in the month of January was $-6.63\text{ }^{\circ}\text{C km}^{-1}$. SLRs for East, South, and West facing slopes were calculated using the same technique described above. SLRs for Northeast, Southeast, Southwest, and Northwest facing slopes were calculated as a function of the average between the lapse rates measured at relevant cardinal directions (i.e., the lapse rate along Northeast slopes was determined to be the average between the North facing slopes and East facing slopes). SLRs for areas with flat orientations (mountain peaks, alpine benchlands and alpine lakes) were calculated by averaging the lapse rate values across all the other 8 possible orientations (Table 3.1).

The development of these aspect and period specific SLRs allowed for the creation of an aspect corrected elevation model that allowed for air temperatures to be estimated across the entire study area whilst negating the influences of topography. This was accomplished by

lowering all points to a uniform elevational plain (e.g., Lewkowitz et al., 2012) (1337 m asl. the lowest observational site). This artificially warmed the recorded site temperatures using the specific SLRs previously described (January, north-facing for example). Once these values for temperature had been plotted in a GIS, either Inverse Distance Weighting (IDW) or Empirical Bayesian Kriging were used to create an interpolated surface which estimated temperatures across the entire study area at a 10 m x 10 m resolution. Inverse distance weighting utilized an optimized power function that was calculated by the Geostatistical Wizard in ArcGIS Pro (version 2.9.1) (ESRI, USA). This function provided the most accurate results in finalized average air temperature models for most months of the year and the AMAT model (RMSE values ranging from 0.06 - 0.14 °C). While Empirical Bayesian Kriging produced more accurate results for the months of February, March, April, and November.

Once aspect corrected elevation surfaces (spanning the lowest elevation in the study area) had been created, the influences of topography on air temperature values was incorporated using SLR's in conjunction with a digital elevation model (DEM). A high-resolution DEM was used to cool values relative to the actual pixels topographic position in raster calculator (DEM was retrieved from Altalis.com). This alteration was made to the previously mentioned 117 aspect corrected elevation models. The resulting surfaces provided low-precision estimates for most of the study area as they assumed that the entire region existed across a uniform aspect. This was remedied by extracting sections of each aspect-corrected elevation model which existed across the correct aspect in reality and pairing them together to create a finished surface. This finalized product was an air temperature model which estimated average air temperature values that were statistically similar compared to field measured points (Table 3.2).

3.4.2.2 Creation of Average Surface Temperature Models and Delineation of Thermally Defined Ecosystems

Average ground temperature models are the product of interpolated surfaces derived from the 36-point measurements. The input point measurement data for January, February, March, and December models was bolstered by the inclusion of 59 BTS point measurements. The interpolation method used to create these models was EBK Regression which is a tool that is found in the Geostatistical Wizard attachment in ArcGIS Pro (version 2.9.1). EBK Regression produced the most accurate results of several interpolation methods that were attempted (IDW, Kriging, 3D Kriging, etc.). EBK Regression, which allowed for the inclusion of explanatory variables, can be thought of as a hybrid between Empirical Bayesian Kriging and Linear Regression that combines the benefits of mean estimation via Empirical Bayesian Kriging with the strength of model error estimation that comes from Linear Regression. The explanatory variables included in this interpolation analysis were elevation, aspect, slope, topographic position index (TPI), and landcover classification. All these variables are DEM derived apart from landcover. Landcover was sourced from a 100 m x 100 m landcover classification file provided by Agriculture & Agri-Foods Canada, 2008 (AAFC, 2008). Landcover values were simplified to match observed classifications in the field including values of NODATA, water bodies, grasslands, forest, or barren and exposed rock.

The creation of these surface temperature models allowed for the delineation of thermally defined ecosystems based on modelled AMGST and landcover classification. Grassland regions below 1700 m asl. were classified as lower elevation grasslands (LEG). Likewise, forested regions below 1700 m asl. were classified as lower elevation woodlands (LEW). Forested regions above 1700 m asl. with a AMGST above 4.0 °C were classified as upper elevation

forested – warm (UEFW) while areas with a AMGST below above 4.0 °C were classified as upper elevation forested – cold (UEFC). Similarly, Alpine areas above treeline with an AMGST above 4.7 °C were classified as upper elevation alpine – warm (UEAW) while areas with a AMGST below 4.7 °C were classified as upper elevation alpine – cold (UEAC). Threshold temperatures of 4.0 °C in upper elevation forested environments and 4.7 °C in alpine environments were chosen because these values evenly divided the number of arthropod collection sites in each of the 6 thermally defined ecosystem classifications.

3.4.2.3 Average Air and Surface Temperature Model Validation

Average air and surface temperature models were validated through the computation of root mean squared error (RMSE) statistics (Chai & Draxler, 2014). This was achieved by extracting modelled temperature estimates at locations where known temperature measurements were available. The error or difference between modelled and measured temperatures at each individual location were then squared to remove negative values from the dataset. These squared errors were then summed to create a total error estimate (Chai & Draxler, 2014). This large total error estimate was then value was divided by the number sampling points to get an average error estimate and the square root of this average error estimate was reported as the RMSE value for the model in question (Chai & Draxler, 2014). RMSE values were calculated for several interpolation methods that were exercised (Inverse Distance Weighting, Kriging, 3D Kriging, Natural Neighbour, Spline, etc.) and the method which produced the lowest RMSE values were used for creation of the final models.

3.4.2.4 Relevant Climatic Conditions for Surface-Dwelling Arthropods

Hourly temperature readings recorded by ground sensors allowed for the calculation of climate statistics in a context that was relevant to the overwintering success and lifecycle progression of surface-dwelling arthropods. Statistics stem from field recorded measurements and are reported based on ecosystem type. AMGST was calculated for each site based on hourly (or 4-hour) readings that took place from the summer of 2020 to a corresponding date in 2021. Average, maximum, and minimum AMGST's recorded in each respective ecosystem type are reported in Table 3.6. Maximum and minimum surface temperature readings recorded in each respective ecosystem type are also reported (Table 3.6). Minimum estimated days without snow cover was calculated based on the determination of snowpack establishment and a snowpack melt dates. Here, the principal date which displays a loss of diurnal fluctuation in surface-level temperature and a persistence of temperatures at or below 0 °C for the following consecutive 7-day period served as criteria for snowpack establishment (Way & Lewkowicz, 2018). The inverse of these conditions served as criteria for snowpack melt (Way & Lewkowicz, 2018). The minimum estimated time without snow cover is reported in days for each respective ecosystem type (Table 3.6). The maximum number of days without a surface temperature reading above 0 °C for each ecosystem type is reported in Table 3.6. The number of freeze-thaw cycles was calculated for each site based on the criteria that a single freeze-thaw cycle consisted of temperature reading above 0 °C, dipping below 0 °C for at least two consecutive hours before then rising back above 0 °C. The maximum number of freeze-thaw cycles recorded within each ecosystem type is reported (Table 3.6).

The quantification of the impact of temperature on surface-dwelling arthropods during the growing season was completed using a somewhat more simplistic approach. Due to the

somewhat linear relationship between temperature and arthropod development rate that was established by Lactin et al., 1995, a growing degree day model was employed to quantify suitability of habitat for lifecycle progression. The “ $(\max + \min)/2 - \text{threshold}$ ” method was utilised to calculate growing degree days using daily maximum and minimum temperatures in accordance with threshold temperatures of 5 °C, 8 °C, and 10 °C (Herms, 2004). The average number of days (out of 365) where a positive growing degree day value was recorded within each microhabitat type are reported in Table 3.7. Finally, average surface level offset within each ecosystem type, calculated as the product of average air temperature – average surface temperature, are reported in Table 3.4. Air temperature values at stand alone ground sensors were derived from air temperature models.

3.4.2.5 Estimating Future Thermal Conditions in Castle Provincial Park

After air and surface temperature models were created for the study area, analysis into potential thermal regime change according to future climate projections was completed. Climate NA was used to extract historical air temperature measurements for the year of 2020 at three points within the watershed (Wang et al., 2016). The three points included a 1351 m elevation point in the northeast, a 1848 m elevation point in the southwest, and a 2412 m elevation point in a somewhat central location in the study area. These points were selected because they were sites where measured data was available for comparison with Climate NA outputs while also offering geographic coverage of the study across both horizontal and vertical orientations. An AMAT value was extracted for each of these locations in addition to an average monthly air temperature value for the months of February and July (The coldest and warmest months of the year according to recorded 2020-2021 data). Climate NA extracted these statistics for 2050 and 2100 using the Shared Socioeconomic Pathway (SSP) 585 climate scenario (a highly aggressive

climate change scenario which estimates that CO₂ emissions triple by 2075 compared to 2020 levels) (Hausfather & Peters, 2020; Wang et al., 2016). Through this process it was determined that the magnitude of warming on 30-year and 70-year time scales was the same at all three input points (Wang et al., 2016). As a result, both air temperature models and ground temperature models produced using 2020-2021 data were warmed by a geographically fixed value proposed by Climate NA to create predictive temperature surfaces for 2050 and 2100, respectively.

3.5 Results

3.5.1 Air Temperature Analysis and Modelling

The average AMAT temperature at ACIS stations “Castle Auto” and “West Castle” from September 2020 – September 2021 was 0.81 °C warmer than the previous 9-year average (2012-2021) (Alberta Government, 2022). However, September 2020 – September 2021 conditions were still 0.45°C cooler than what was recorded during the 2015 calendar year (Alberta Government, 2022). The annual average Surface Lapse Rate (SLR) observed along a south facing slope from September 2020-September 2021 was -5.13°C km⁻¹. This SLR was -1.68°C km⁻¹ larger in magnitude than the previous 9-year average but only -0.34 °C km⁻¹ larger in magnitude than what was observed in the 2021 calendar year. Recorded average SLRs at every cardinal direction from summer 2020 – summer 2021 can be found in Table 3.1. Average SLRs ranged from -9.44 °C km⁻¹ to -0.20 °C km⁻¹. The strongest average SLRs were observed in November (-8.63 °C km⁻¹ average across all aspects) while the weakest occurred in July (-2.34 °C km⁻¹ average across all aspects). The greatest average SLRs were recorded along slopes with north facing aspects (-6.26 °C km⁻¹ annual average) while the weakest were recorded along south facing slopes (-5.13 °C km⁻¹ annual average). Finally, the average SLR recorded across 8 cardinal directions for the annual sample period was -5.76 °C km⁻¹.

Table 3.1: Average surface lapse rates measured in Castle Provincial Park from late summer of 2020 – late summer of 2021. Results are broken down by orientation of the slope which data recorders were situated on and month when air temperature data was recorded. Results are reported in °C km⁻¹.

Aspect	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
N	-6.63	-4.39	-9.44	-8.89	-8.06	-6.42	-4.03	-1.01	-4.97	-5.82	-8.64	-6.65	-6.25
NE	-6.75	-4.46	-8.50	-8.57	-7.75	-5.90	-3.05	-2.50	-4.56	-5.66	-8.79	-6.83	-6.11
E	-6.86	-4.53	-7.55	-8.24	-7.44	-5.38	-2.07	-3.98	-4.16	-5.50	-8.95	-7.00	-5.97
SE	-6.23	-2.36	-6.63	-7.36	-6.94	-5.08	-1.58	-4.24	-4.34	-5.37	-8.61	-7.86	-5.55
S	-5.61	-0.20	-5.71	-6.48	-6.44	-4.78	-1.09	-4.50	-4.53	-5.24	-8.27	-8.72	-5.13
SW	-5.91	-2.11	-6.37	-7.02	-6.37	-4.52	-1.62	-4.41	-5.07	-5.33	-8.47	-7.66	-5.40
W	-6.21	-4.01	-7.04	-7.56	-6.31	-4.27	-2.15	-4.31	-5.61	-5.41	-8.67	-6.60	-5.68
NW	-6.42	-4.20	-8.24	-8.23	-7.18	-5.34	-3.09	-2.66	-5.29	-5.62	-8.65	-6.63	-5.96
Flat	-6.33	-3.28	-7.43	-7.79	-7.06	-5.21	-2.34	-3.45	-4.82	-5.49	-8.63	-7.24	-5.76

Average air temperature models were produced for the study area in Castle Provincial Park on monthly as well as on annual time scales. Modelled average monthly air temperature values range from -15.00 °C in February to 19.40 °C in July (Figure 3.3). Modelled AMAT values range from -2.34 °C to 5.74 °C (Figure 3.3). The average AMAT for the entire study area was 3.05 °C. Root mean squared error (RMSE) values calculated from differences in modelled vs measured average air temperature values at 15 air temperature recording stations are reported in Table 3.2. The annual mean air temperature model yielded a RMSE value of 0.14 °C. The month with the largest RMSE value was July with a value of 0.68 °C while the smallest RMSE value of 0.07 °C was observed in August. The RMSE values for the monthly average air temperature models ranged from 0.07 °C to 0.68 °C.

Table 3.2: Root mean squared error calculations for the annual mean air temperature model and monthly average air temperature models. Root mean squared error values are reported in °C. Interpolation method utilized in modelling process (Inverse Distance Weighting or Kriging) is listed.

Time Period	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Interpolation Method	Kriging	IDW	IDW	IDW	IDW	IDW	IDW	IDW	IDW	IDW	Kriging	IDW	IDW
RMSE of Final Model °C	0.65	0.27	0.12	0.13	0.11	0.12	0.10	0.07	0.10	0.09	0.68	0.11	0.14

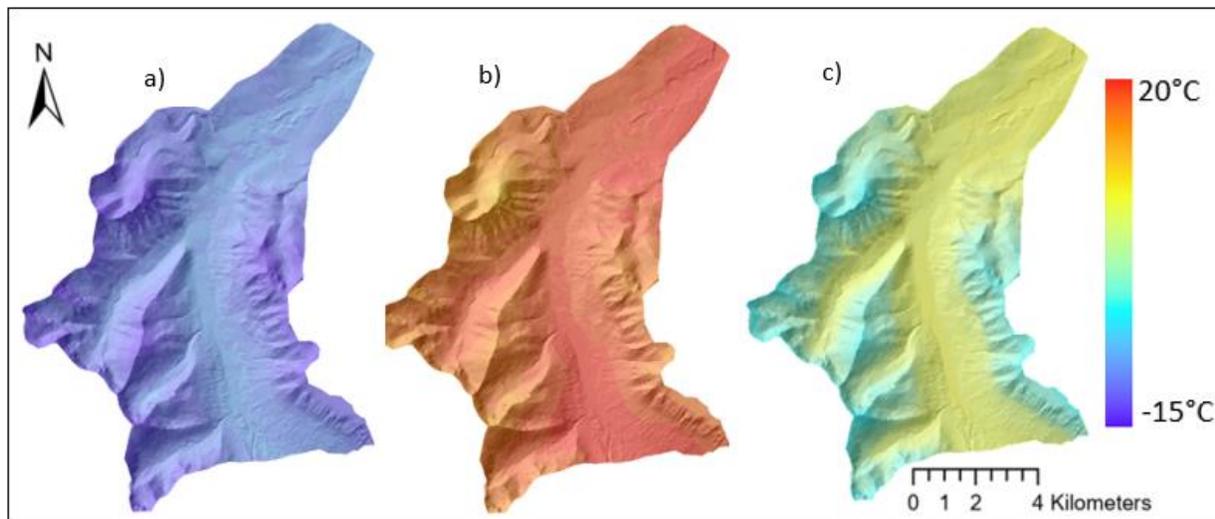


Figure 3.3: Average air temperature models displayed using the same temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features. a) represents the month of February, b) represents the month of July, and c) represents the annual model.

3.5.2 Surface Temperature Analysis and Modelling

Annual Mean Ground Surface Temperature (AMGST) values at the temperature recording stations ranged from 7.03°C to -0.09 °C. The coldest month at the surface was February as the mean average surface temperature across all stations was -1.68 °C, while one station averaged -12.16 °C (WS 5). Conversely, the warmest month at the surface was July as the mean average surface temperature across all stations was 14.61 °C, while one station averaged 21.15 °C (WS 9). As far as extreme thermal conditions at the surface level, the coldest temperature recorded was -21.17 °C (WS 5) and the maximum recorded temperature was 51.18 °C (UEFW 1).

Average surface temperature models were produced for the study area in Castle Provincial Park on monthly as well as annual time scales. Results for February, July, and the annual model are displayed in Figure 3.4. Root mean squared error (RMSE) values calculated from differences in modelled vs measured average surface temperature values at 36 surface

temperature recording stations and 59 BTS point measurement locations, respectively (Table 3.3). Modelled monthly surface temperature values range from -8.46 °C in February to 23.17 °C in July. The coldest winter surface temperatures occurred in exposed, upper elevation areas with no tree cover. Conversely, the warmest summer surface temperatures occurred on mid-elevation slopes which had southern exposure and no forest cover. Forested areas produced less variable surface temperatures compared to unforested environments during every month of the year. Modelled AMGST values ranged from -0.78 °C to 8.57 °C. The average AMGST for the entire study area was 4.68 °C. The AMGST model yielded a RMSE value of 0.41 °C. The month with the largest RMSE value was June with a value of 2.68 °C while the smallest RMSE value of 0.06 °C was observed in April. The RMSE values for the monthly average surface temperature models ranged from 0.06°C to 2.68 °C.

Table 3.3: Root mean squared error calculations for the annual mean ground surface temperature model and monthly average surface temperature models. Root mean squared error estimations are reported in °C.

Time Period	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RMSE of Final Model °C	0.41	1.41	1.57	1.25	0.06	1.52	2.68	1.44	2.07	1.20	0.88	0.78	1.25

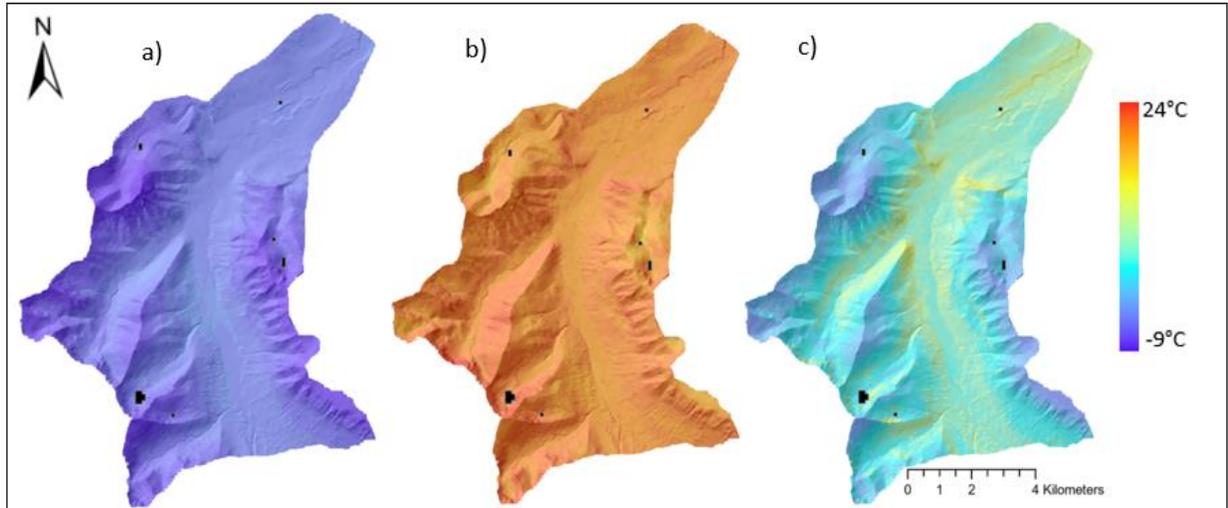


Figure 3.4: Average surface temperature models displayed using the same temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features. Black cells in the surfaces represent bodies of water. a) represents the month of February, b) represents the month of July, and c) represents the annual model.

3.5.3 Surface-layer Offsets

Surface-level offsets were determined at 36 surface temperature recording locations.

Positive offsets indicate that the ground is cooler than the air while negative offsets indicate that the ground is warmer than the air. Average surface-level offsets ranged from as far negative (surface warmer than air) as $-14.29\text{ }^{\circ}\text{C}$ to as positive (surface cooler than air) as $8.55\text{ }^{\circ}\text{C}$.

February had the most negative surface-level offsets averaging at $-11.03\text{ }^{\circ}\text{C}$ across all 36 stations (Figure 3.5). July had the most positive surface-level offsets averaging at $2.50\text{ }^{\circ}\text{C}$ across all stations. The month with the least intense surface-level offsets was August with an average value of $0.28\text{ }^{\circ}\text{C}$. On an annual scale, the average surface-level offset was $-1.42\text{ }^{\circ}\text{C}$ across all 36 sites.

Average surface level offsets within each ecosystem type for every month of the year are reported in Table 3.4. When analyzing the absolute values of recorded surface-level offsets within different ecosystem types, it can be determined that the offset values change across the different regions. UEFC ecosystems have the largest disconnect between air and surface

temperature with an absolute average surface-level offset value of 4.74 °C. Whereas surface temperatures in UEAC ecosystems closely mirror air temperatures producing an absolute average surface-level offset value of 2.03 °C for these regions.

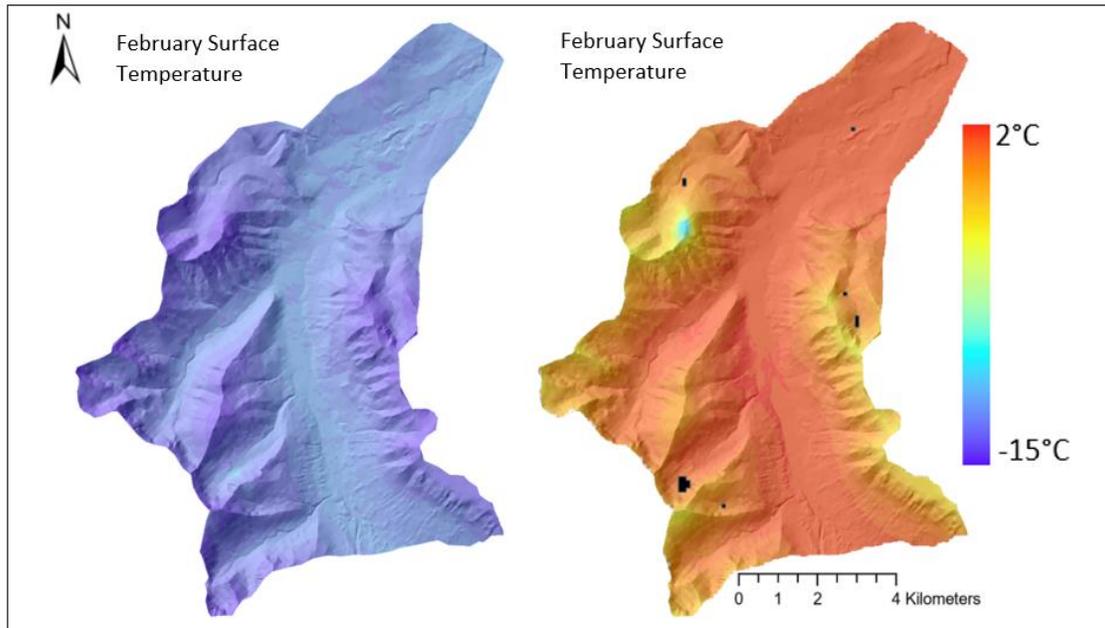


Figure 3.5: Average air and surface temperatures for the month of February displayed on the same temperature scale under a Hillshade layer set to 50% transparency to highlight topographic features. Black cells in the surface temperature model represent water bodies. Average February offsets range from -14.29°C to -2.42°C.

Table 3.4: Average surface-level offsets recorded within different ecosystem types. Where LEG represents lower elevation grassland ecosystems, LEW represents lower elevation woodland ecosystems, UEFW represents upper elevation forested – warm ecosystems, UEFC represents upper elevation forested – cold ecosystems, UEAW represents upper elevation alpine – warm ecosystems, and UEAC represents upper elevation alpine – cold ecosystems. UEFW and UEFC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.0 °C while UEAW and UEAC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.7 °C. Results are reported in °C.

Ecosystem Type	Avg Annual Offset (°C)	Avg Jan Offset (°C)	Avg Feb Offset (°C)	Avg Mar Offset (°C)	Avg Apr Offset (°C)	Avg May Offset (°C)	Avg June Offset (°C)	Avg July Offset (°C)	Avg Aug Offset (°C)	Avg Sept Offset (°C)	Avg Oct Offset (°C)	Avg Nov Offset (°C)	Avg Dec Offset (°C)
LEG	-1.29	-2.79	-10.39	0.66	0.17	-0.92	0.60	1.89	-0.82	0.41	-5.62	-3.03	-1.86
LEW	-0.14	-3.79	-11.28	0.16	1.58	2.44	4.41	5.48	2.26	2.53	-1.11	-1.77	-2.27
UEFW	-1.92	-5.90	-13.18	-2.21	-0.39	1.68	1.86	0.72	-1.41	0.54	-3.39	-3.62	-4.31
UEFC	-1.56	-6.67	-13.27	-3.74	-1.88	2.87	5.51	4.37	3.41	2.52	-3.06	-4.96	-5.31
UEAW	-2.53	-3.33	-10.62	-2.05	-1.27	-0.74	-1.71	1.40	-3.21	-1.34	-4.44	-3.60	-3.08
UEAC	-1.05	-2.19	-6.47	-1.59	-0.83	2.53	0.40	0.92	0.83	0.68	-2.58	-3.39	-2.81

3.5.4 Thermal Ecosystem Modelling

Maps depicting ecosystem coverage in the study area are shown in Figure 3.6 while a summary of each ecosystems relative size in the study area can be found in Table 3.5. Lower elevation (below 1700 m asl.) grasslands (LEG) and woodlands (LEW) covered 49.8% of the study area in Castle Provincial Park (42.69 km²). The area of the LEW ecosystem was the most extensive of all, accounting for 39.42% of the study area (33.79 km²). Upper elevation ecosystems were distinguished by landcover type and AMGST. The most extensive ecosystem type in the upper elevations was alpine sites with AMGST values below 4.7 °C (UEAC). These areas covered 27.61% of the study area (23.66 km²). The smallest ecosystem in the study area was upper elevation forested sites with a AMGST above 4.0 °C (UEFW) as these areas only accounted for 6.52% of the study area (5.50 km²). When the same temperature thresholds were used to define ecosystem types using AMAT values as opposed to AMGST values, UPFW and UPAW (Upper elevation alpine – warm) ecosystems were completely lost (Figure 3.6).

Table 3.5: Surface-level thermal ecosystem extent across elevations over 1700 m asl. Extents are delineated based on landcover classification and either modelled annual mean air temperature or annual mean ground surface temperature produced from field collected data.

Ecosystem Type	Upper Elevation Forrested - Warm		Upper Elevation Forrested - Cold		Upper Elevation Alpine - Warm		Upper Elevation Alpine - Cold	
	MAAT	MAGST	MAAT	MAGST	MAAT	MAGST	MAAT	MAGST
Temperature used to Delineate Boundaries								
Area km2	0.00	5.59	11.72	6.13	0.00	7.63	31.30	23.66
Percent Study Area	0.00%	6.52%	13.67%	7.15%	0.00%	8.91%	36.52%	27.61%

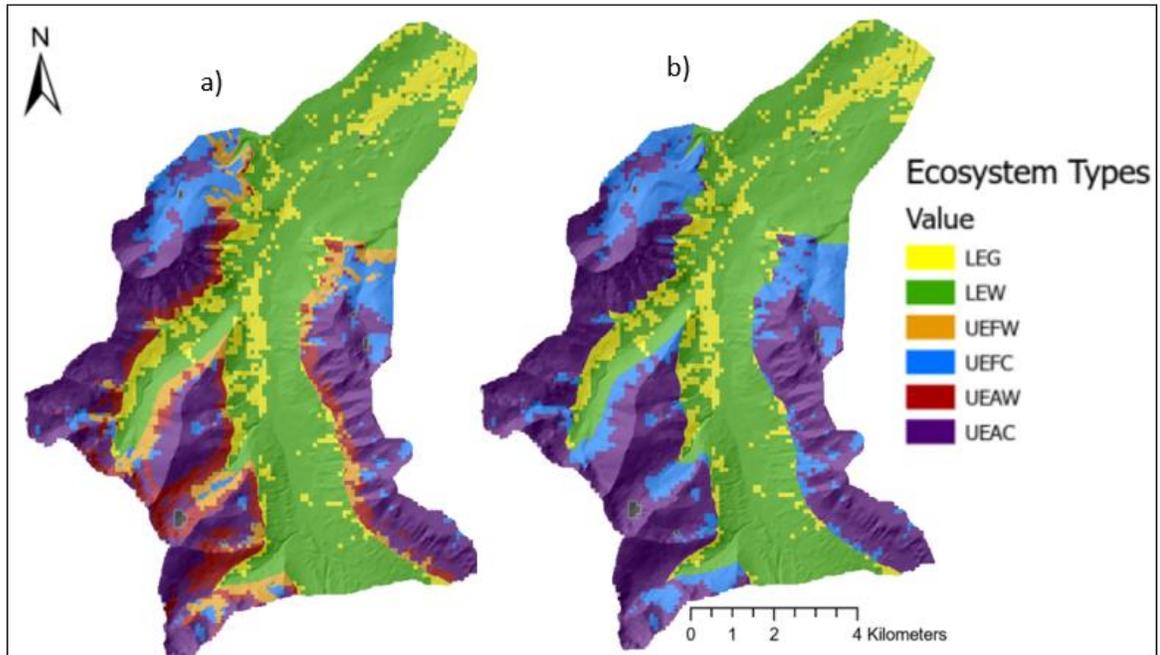


Figure 3.6: Surface-Level thermal ecosystem coverage within the defined study. a) represents ecosystem coverage based on annual mean ground surface temperature values. Black cells indicate water bodies. b) represents ecosystem coverage based on annual mean air temperature values.

3.5.5 Thermal Distribution Relevant to the Success of Surface-dwelling Arthropods.

Climate statistics relevant to the overwinter survival and general lifecycle progression of surface-dwelling arthropods were computed based on data from 36 surface temperature data recorders. LEG sites had the warmest average AMGST value of 6.39 °C while UEAC registered the coolest AMGST value at 1.9 °C. The warmest AMGST recorded in Castle Provincial Park during our sampling period was 7.03 °C while the coldest was -0.09 °C. Minimum recorded surface temperatures also varied across different ecosystem types with one UEAC site reaching -21.17 °C on February 13th while the coldest any UEFW site reached was -1.33 °C on September 20th (the coldest air temperature readings at these sites both occurred on February 11th). Maximum recorded surface temperatures varied from 51.18 °C at a UEFW site to 28.00 °C at a LEW site. UEAC sites posted the shortest minimum estimated snow-free period at 107 days

(June 8th – Oct. 12th) which was 67 days (March 26th – Nov 13th) shorter than the shortest estimate recorded at any LEG site. Maximum consecutive days below 0 °C was most significant at a UEAC site which was below freezing for 214 consecutive days, 158 days longer than the coldest LEW site. LEW sites experienced the fewest number of freeze-thaw cycles compared to other ecosystems with the most unstable site only registering 7 cycles. UEFW and UEAW sites saw much greater fluctuations in surface-level temperature during the shoulder seasons as each ecosystem type has sites record 45 freeze-thaw cycles within the same 1-year sample period.

Table 3.6: Climate statistics relevant to the overwinter survival and lifecycle progression of surface-dwelling arthropods broken down by ecosystem classification. Where LEG represents lower elevation grassland ecosystems, LEW represents lower elevation woodland ecosystems, UEFW represents upper elevation forested – warm ecosystems, UEFC represents upper elevation forested – cold ecosystems, UEAW represents upper elevation alpine – warm ecosystems, and UEAC represents upper elevation alpine – cold ecosystems. UEFW and UEFC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.0 °C while UEAW and UEAC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.7 °C. Results are reported in °C.

Ecosystem Type	Average AMGST (°C)	Max AMGST (°C)	Min AMGST (°C)	Min Surface Temp (°C)	Max Surface Temp (°C)	Minimum Estimated Days Without Snowcover (Per Year)	Maximum Consecutive Days Below 0°C (Per Year)	Maximum Number of Freeze-Thaw Cycles (Per Year)
LEG	6.39	7.03	6.08	-4.88	33.29	174.00	81.00	25.00
LEW	4.85	5.62	3.90	-4.64	28.00	114.00	56.63	7.00
UEFW	5.06	6.10	4.09	-1.33	51.18	119.00	101.25	36.00
UEFC	3.19	3.89	2.11	-5.58	31.49	107.00	156.38	45.00
UEAW	5.28	6.57	4.82	-10.21	46.00	134.00	126.33	45.00
UEAC	1.90	4.70	-0.09	-21.17	30.00	125.00	214.83	27.00

Growing-degree days were calculated (using the (max+min)/2 – threshold method) at every surface temperature logger using 5°C, 8°C, and 10°C as threshold temperatures. The average number of positive growing days recorded over a consecutive 365-day period within each thermal ecosystem classification are reported in Table 3.7. Similarly, growing-degree days were at a weather station in each respective thermal ecosystem classification using both air and surface temperature measurements. The number of growing days recorded at each weather station over a consecutive 365-day period using either air temperature or surface temperature are reported in Table 3.8.

Table 3.7: Average number of net growing days (per year) recorded within each thermal ecosystem type using 5°C, 8°C, and 10°C as threshold temperatures, respectively.

Ecosystem Classification	Average Number of Net Growing Days (5°C)	Average Number of Net Growing Days (8°C)	Average Number of Net Growing Days (10°C)
LEG	172	152	136
LEW	140	116	86
UEFW	134	121	108
UEFC	107	78	52
UEAW	148	130	116
UEAC	116	91	72

Table 3.8: Future climate conditions produced by values modelled in the synthetic year to specifications produced by Climate NA under the Shared Socioeconomic Pathway 585 climate scenario.

Ecosystem Classification	Number of Net Growing Days (Air Temperature)	Number of Net Growing Days (Surface Temperature)	Additional Net Growing Days Estimated by Air Temperature
LEG	172	167	5
LEW	165	149	16
UEFW	145	118	27
UEFC	130	114	16
UEAW	156	144	12
UEAC	130	114	16

3.5.6 Arthropod Diversity, Distribution, & Abundance

The use of Vernon pitfall traps allowed for the capture of 26,178 surface-dwelling arthropods including beetles (Coleoptera), mites (Acari), harvestmen (Opiliones), spiders (Araneae), true insects (Hemiptera), springtails (Collembola), grasshoppers and crickets (Orthoptera), millipedes (Julida), bristle tails (Archaeognatha), centipedes (Lithobiomorpha) and other rarer insects and arachnids to be captured. The relative abundance of each of these groups follows the aforementioned order with beetles and spiders accounting for 49.50% and 12.08% of sampled individuals, respectively. A total of 12 families of spiders, 14 families of beetles, 5 families of true bugs, and 4 families of grasshoppers were identified. The most common family of beetles found in Castle Provincial Park were Rove beetles (Staphylinidae) which numbered as many as 403 individuals per trap and accounted for 63% of all collected beetles. The next most

found beetle were Ground beetles (Carabidae) which numbered as many as 80 individuals per trap and accounted for 13% of all beetles collected. Likewise, Wolf spiders (Lycosidae) accounted for 44% of all spiders collected while Ground spiders (Gnaphsonidae) accounted for 27% of surface-dwelling arachnids.

Most of the families of surface-dwelling beetles and spiders tended to inhabit certain habitat and could not be found everywhere on the mountain. While seven of the 14 identified families of beetles were present within every thermal eco-region, only two out of 12 families of spiders displayed a mountain wide distribution. For beetles, UEAW environments were the most hospitable as 12 different families were found utilizing this habitat compared to UEAC environments which only supported 8 different families. Similarly, UEAC and UEFC environments were the most inhospitable for spiders as only six families were found utilizing these habitats compared to 10 families that were found in LEW regions. The presence or absence of major orders and families is summarized in Table 3.9.

Table 3.9: Presence or absence of prominent orders and families of surface-dwelling arthropods amongst pitfall trap samples collected within six thermally distinct ecosystem classifications during the 2020 and 2021 growing seasons. Where LEG represents lower elevation grassland ecosystems, LEW represents lower elevation woodland ecosystems, UEFW represents upper elevation forested – warm ecosystems, UEFC represents upper elevation forested – cold ecosystems, UEAW represents upper elevation alpine – warm ecosystems, and UEAC represents upper elevation alpine – cold ecosystems. UEFW and UEFC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.0 °C while UEAW and UEAC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.7 °C.

Order	Family	Common Name	LEG	LEW	UEFW	UEFC	UEAW	UEAC
Sub-Class Acari	Multiple Unspecified	Mites	✓	✓	✓	✓	✓	✓
Araneae	Araneidae	Orb-Weavers	✓	✓	✓	✓	✗	✗
Araneae	Clubionidae	Sac Spiders	✓	✓	✓	✓	✓	✗
Araneae	Gnaphosidae	Ground Spiders	✓	✓	✓	✓	✓	✓
Araneae	Linyphiidae	Sheet Weavers	✓	✗	✓	✗	✗	✓
Araneae	Liocraniidae	Narrow-Headed Spiders	✗	✓	✗	✗	✓	✗
Araneae	Lycosidae	Wolf Spiders	✓	✓	✓	✓	✓	✓
Araneae	Opiliones	Harvestmen	✓	✗	✓	✗	✓	✓
Araneae	Philodromidae	Running Crab Spider	✓	✓	✓	✗	✓	✗
Araneae	Salticidae	Jumping Spider	✓	✓	✓	✗	✓	✓
Araneae	Tetragnathidae	Long-Jawed Spiders	✗	✓	✗	✓	✗	✗
Araneae	Theridiidae	Comb-footed Spiders	✗	✓	✗	✓	✗	✗
Araneae	Thomisidae	Crab Spiders	✓	✓	✓	✗	✓	✓
Archaeognatha	Multiple Unspecified	Bristle Tails	✓	✓	✓	✓	✓	✓
Coleoptera	Carabidae	Ground Beetles	✓	✓	✓	✓	✓	✓
Coleoptera	Cerambycidae	Longhorn Beetles	✗	✓	✓	✓	✓	✗
Coleoptera	Chrysomelidae	Leaf Beetles	✓	✗	✗	✗	✓	✗
Coleoptera	Cicindelinae	Tiger Beetles	✗	✓	✗	✗	✓	✗
Coleoptera	Coccinellidae	Ladybugs	✓	✓	✓	✓	✓	✓
Coleoptera	Curculionidae	True Weevils	✓	✓	✓	✓	✓	✓
Coleoptera	Elateridae	Click beetles	✓	✓	✓	✓	✓	✗
Coleoptera	Lepturinae	Longhorn Beetles	✗	✗	✓	✓	✗	✗
Coleoptera	Lycidae	Net-Winged Beetles	✓	✗	✗	✓	✗	✗
Coleoptera	Nitidulidae	Sap Sucking Beetles	✓	✓	✓	✓	✓	✓
Coleoptera	Scarabidae	Scarab beetles	✓	✓	✓	✓	✓	✓
Coleoptera	Silphidae	Carrion Beetles	✓	✓	✓	✓	✓	✓
Coleoptera	Staphylinidae	Rove beetles	✓	✓	✓	✓	✓	✓
Coleoptera	Tenebrionidae	Darkling Beetles	✓	✓	✓	✓	✓	✓
Collembola	Multiple Unspecified	Springtails	✓	✓	✓	✓	✓	✓
Hemiptera	Cicadellidae	Leafhoppers	✓	✓	✓	✗	✓	✗
Hemiptera	Miridae	Plant Bugs	✓	✓	✓	✓	✓	✓
Hemiptera	Nabidae	Damsel Bugs	✓	✓	✓	✓	✓	✓
Hemiptera	Pentatomidae	Stink Bugs	✓	✓	✓	✓	✓	✓
Hemiptera	Reduviidae	Assassin Bugs	✓	✓	✓	✗	✓	✗
Julida	Multiple Unspecified	Millipedes	✓	✓	✓	✓	✓	✓
Lithobiomorpha	Multiple Unspecified	Stone Centepides	✓	✓	✓	✓	✓	✓
Orthoptera	Acrididae	Spur-Throated Grasshoppers	✓	✓	✓	✓	✓	✓
Orthoptera	Grylloblattidae	Northern Rock Crawlers	✗	✗	✗	✗	✗	✓
Orthoptera	Prophalangopsidae	Hump-Winged Crickets	✓	✗	✓	✓	✓	✗
Orthoptera	Rhaphidophoridae	Camel Crickets	✓	✓	✓	✓	✓	✓

The abundance of surface-dwelling arthropods was not consistent across six thermally distinct ecoregions as the total number of individuals caught per trap, per day, during the study period ranged from 0.24 individuals in LEG & UEAC regions to 0.53 individuals in LEW &

UEFW regions (Table 3.10). While the diversity and abundance of surface-dwelling arthropods varied spatially, the numbers of individuals collected also changed on temporal scales. Seasonal variability in arthropod abundance was recorded as the number of individual arthropods caught per pitfall trap, per day, ranged from 0.20 individuals in the early season, to 0.25 individuals in mid-season to 0.19 individuals in the late season. Likewise, annual variability was also observed as the average number of individual arthropods caught per trap, per day, during the mid-season sampling period increased from 0.25 individuals in 2020 to 0.37 individuals in 2021. Changes in the spatio-temporal abundance of arthropods is most evident in commonly found families with all encompassing distributions such as Staphylinidae and Lycosidae. The relationship between Lycosidae abundance and ecosystem classification is statistically significant (Figure 3.7; ANOVA: $F_{5,2} = 2.55$, $p < 0.05$) and the relationship between Lycosidae abundance and timing of sample collection is also significant (Figure 3.7; ANOVA: $F_{2,5} = 5.89$, $p < 0.05$). Likewise, the relationship between Staphylinidae abundance and ecosystem classification was also statistically significant (Figure 3.8; ANOVA: $F_{5,2} = 7.17$, $p < 0.005$). However, the relationship between Staphylinidae abundance and timing of sample collection was not significant (Figure 3.8; ANOVA: $F_{2,5} = 1.20$, $p > 0.05$).

Table 3.10: Number of individual surface-dwelling arthropods collected in each thermally defined ecosystem throughout the duration of the study considering the number of days traps were active and the number of traps which were successfully collected. UEFW and UEFC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.0 °C while UEAW and UEAC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.7 °C.

Ecosystem Classification	Number of Arthropods Caught (Per Trap, Per Day)
Lower Elevation Grassland	0.24
Lower Elevation Woodland	0.53
Upper Elevation Forrested - Warm	0.53
Upper Elevation Forrested - Cold	0.46
Upper Elevation Alpine - Warm	0.26
Upper Elevation Alpine - Cold	0.24

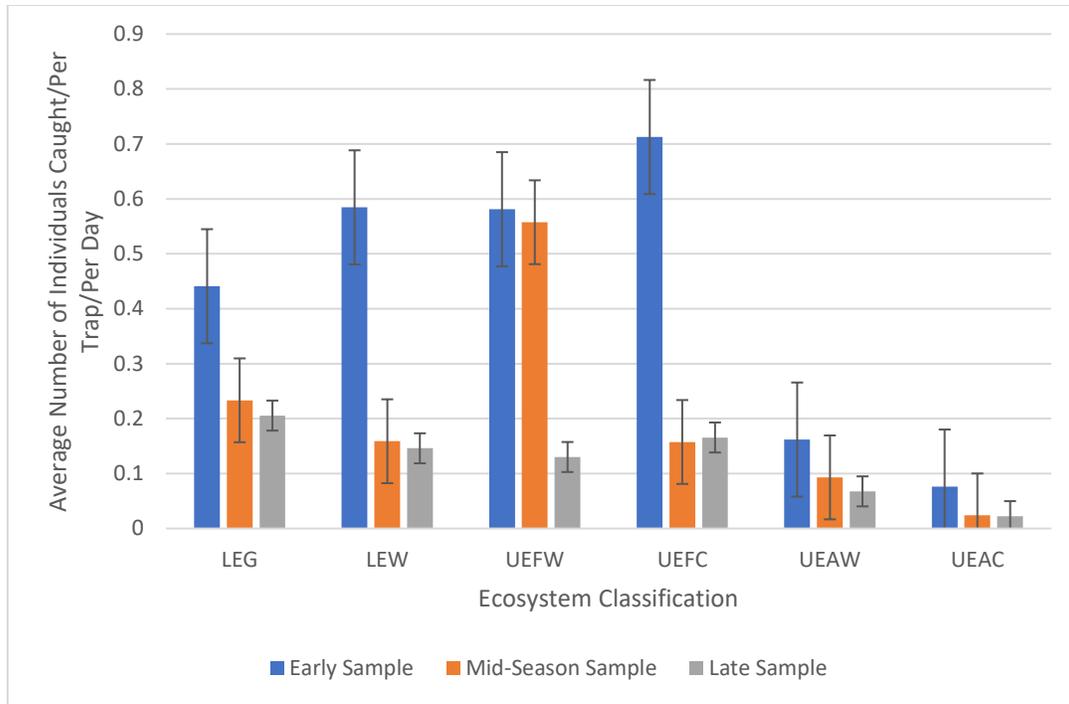


Figure 3.7: The effect of thermal ecosystem classification and seasonality on the abundance of Lycosidae found within pitfall trap samples during the 2020 growing season. Where LEG represents lower elevation grassland ecosystems, LEW represents lower elevation woodland ecosystems, UEFW represents upper elevation forested – warm ecosystems, UEFC represents upper elevation forested – cold ecosystems, UEAW represents upper elevation alpine – warm ecosystems, and UEAC represents upper elevation alpine – cold ecosystems. UEFW and UEFC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.0 °C while UEAW and UEAC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.7 °C. Values are means \pm standard error bars, n=1,433.

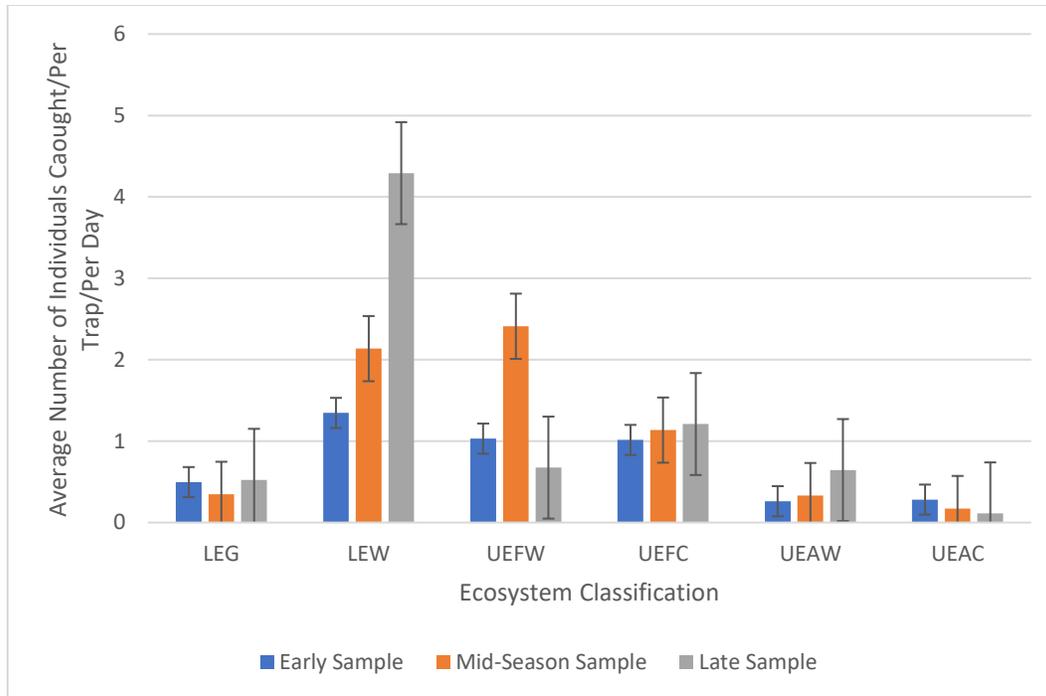


Figure 3.8: The effect of thermal ecosystem classification and seasonality on the abundance of Staphylinidae found within pitfall trap samples during the 2020 growing season. Where LEG represents lower elevation grassland ecosystems, LEW represents lower elevation woodland ecosystems, UEFW represents upper elevation forested – warm ecosystems, UEFC represents upper elevation forested – cold ecosystems, UEAW represents upper elevation alpine – warm ecosystems, and UEAC represents upper elevation alpine – cold ecosystems. UEFW and UEFC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.0 °C while UEAW and UEAC ecosystems are categorized based upon mean annual ground surface temperature above or below 4.7 °C. Values are means \pm standard error bars, n=8,192.

3.5.7 Notable Findings and Species of Interest

Several Notable species of interest were found because of this investigation. Some of these species include the Northern Rock Crawler (*Grylloblatta campodeiformis*), the Great Grig, (*Cyphoderris monstrosa*), a Snakefly (*Aquillini aqyalla*), and several Snail-eating Harvestman (*Taracus*) (Figure 3.9). Northern Rock Crawlers were absent until late summer (early September) when they presented as a prominent species in largely unvegetated, high mountain terrain above 2000 m asl. Healthy populations of Northern Rock Crawlers were found on both Syncline Peak and Barnaby Ridge in consecutive years (2020-2021), representing 2 previously

undocumented populations of the highly specialized endemic Orthopteran. A single adult Great Grig (*Cyphoderris monstrosa*) was found in a high mountain forest near 2200 m asl. This rare Orthopteran is a representative of one of only two species of Hump-winged Cricket that is found in Canada (Morris & Gwynne, 1978). A single snakefly was found in an alpine region near Haig Lake, representing a sighting of an increasingly rare and elusive Dipteran. Finally, a total of four Snail-eating Harvestmen were found spanning three separate collection sites. These sites were all forested environments, two of which were lower elevation sites but the third was located at 2200 m asl. Serving as another recent account of the highly specialized opilionid in a mountain environment (Bragg & Holmberg, 2009).



Figure 3.9: Specimens of interest collected In Castle Provincial Park using Vernon Pitfall Traps during the summer of 2020. a) Northern Rock Crawler (*Grylloblatta campodeiformis*). b) the Great Grig, (*Cyphoderris monstrosa*). c) A Snakefly (*Aquilini aqyalla*). d) A Snail-eating Harvestman (*Taracus*).

Another unexpected finding was the presence of relatively large numbers of Bristle Tails (*Archaeognatha*) in Castle Provincial Park. Over the course of this project, a total of 450 bristle tails were collected with as many as 54 individuals being found in a single trap. The distribution of these creatures was also widespread as they were found within every thermal ecosystem classification.

3.5.8 Climate Projections

Climate NA predicted that the average AMAT in the study area would warm by a geographically fixed magnitude of 1.9 °C compared to 2020 observations by the year 2050 under the SSP 585 climate scenario. Furthermore, the average AMAT in 2100 would be 5.3°C warmer than what was observed in 2020 under the same scenario. This increased the average AMAT in the study area from 3.05 °C to 8.35 °C by the year 2100. Similarly, the average AMGST in this region increased from 4.68 °C to 9.98 °C during the same period. The impacts of this warming on the synthetic AMAT model are displayed in Figure 3.10. As no predictive models with the ability to forecast the influence of climate change on surface temperature currently exist, surface temperature models were warmed by the same magnitude as air temperature models (Figure 3.11). The impacts of this warming on the extent of thermally distinct upper elevation ecosystems are depicted in Figure 3.12. Statistics relevant to the rate of expansion or decline of surface-level thermal regimes are displayed in Table 3.11.

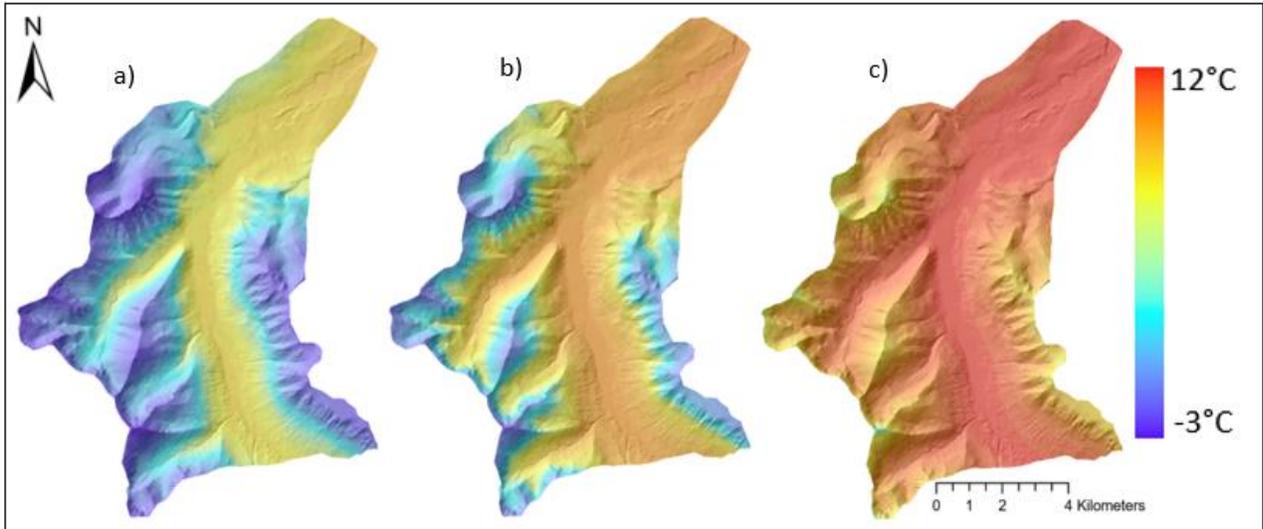


Figure 3.10: Annual mean air temperature models displayed on the same temperature scale underneath a Hillshade layer set to 50% transparency to highlight the regions topography. a) depicts the synthetic year. b) depicts 2050. C) depicts 2100. Models for the years 2050 and 2100 were produced by heating the entire synthetic year model using values produced by Climate NA under the Shared Socioeconomic Pathway 585 climate scenario.

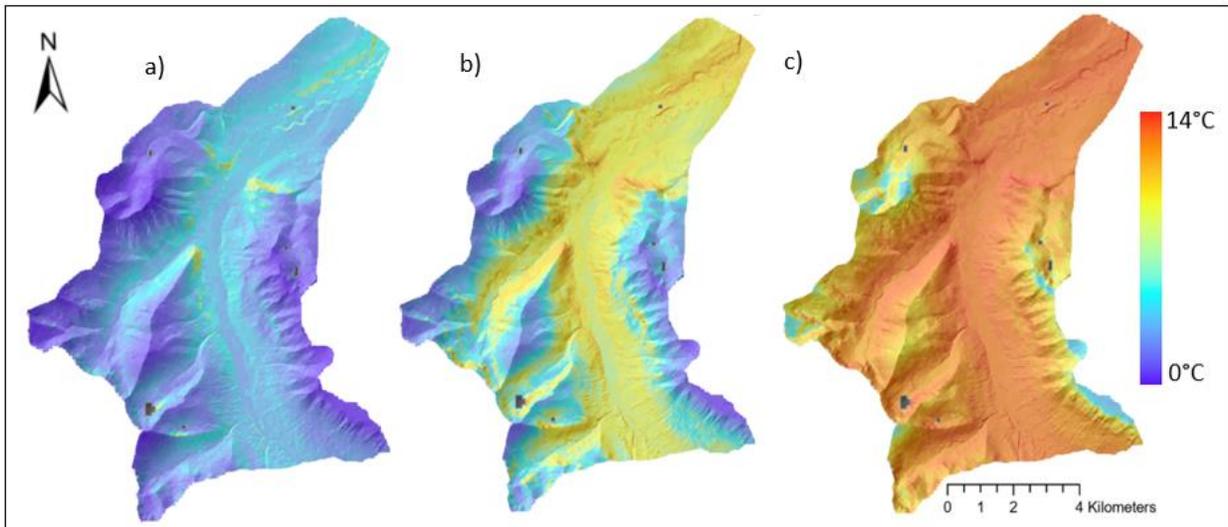


Figure 3.11: Annual mean ground surface temperature models displayed on the same temperature scale underneath a Hillshade layer set to 50% transparency to highlight the regions topography. a) depicts the synthetic year. b) depicts 2050. C) depicts 2100. Models for the years 2050 and 2100 were produced by heating the entire synthetic year model using values produced for air temperature warming by Climate NA under the Shared Socioeconomic Pathway 585 climate scenario.

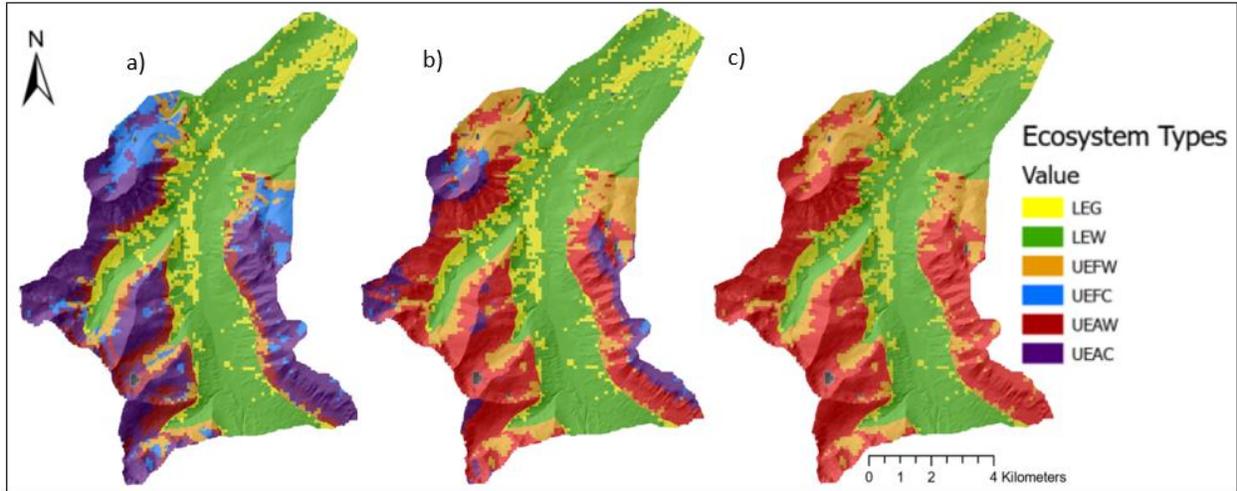


Figure 3.12: Change in the spatial extent of thermally defined surface-level ecosystems from 2021 to 2100. a) depicts the synthetic year derived from collected data. b) depicts 2050. C) depicts 2100. Rate of warming within ecosystems stemmed from values produced by Climate NA under the Shared Socioeconomic Pathway 585 climate scenario.

Table 3.11: Future climate conditions produced by values modelled in the synthetic year to specifications produced by Climate NA under the Shared Socioeconomic Pathway 585 climate scenario.

Year	Average AMAT (°C)	Average AMGST (°C)	UEFW Area (Km2)	UEFC Area (Km2)	UEAW Area (Km2)	UEAC Area (Km2)
2021	3.05	4.68	5.50	6.13	7.63	23.66
2050	4.95	6.58	10.81	0.90	24.14	7.16
2100	8.35	9.98	11.72	0.00	31.30	0.00

3.6 Discussion

The core of this study aims to illustrate how the complex topography within Castle Provincial Park leads to spatial and temporal microclimates which can differ greatly at both the air and surface level. Air and surface temperature models were only based off one year’s worth of data collected between the summer of 2020 and the summer of 2021 as opposed to 30-year climate normal which would have been ideal (Ernakovich et al., 2014; Kienzle, 2017). This was because historical temperature data for this region was not available at the spatial resolution required to capture microclimatological forcings that persist throughout this region (Alberta

Government, 2022). The AMAT during this sampling period was 0.81 °C warmer than the previous 9-year average at 2 ACIS weather stations which had historical data (Alberta Government, 2022). However, the recorded AMAT at these stations during the sample period were not as warm (0.45 °C cooler) as conditions observed during the 2015 calendar year (Alberta Government, 2022). Producing the model using data from a warm year, but not an extremely warm year, was an optimal scenario as the model will hold relative accuracy as to what can be expected in the short term (~5 years) as well as the long term (~15 years) as average climatic conditions continue to warm (Kienzle, 2017; Wang et al., 2016).

Modelled temperature surfaces estimated that AMAT values in the study area ranged from -2.34 °C to 5.74 °C, while AMGST values ranged from -0.78 °C to 8.57 °C. Variability in air temperature models was largely explained by the influence of aspect and elevation on surface lapse rates (Bexte, 2019; Rolland, 2003). Surface temperature distribution was also influenced by aspect and elevation to an extent but was more so determined by landcover and TPI. This was because both landcover and TPI largely determined the capacity for snow retention and exposure to direct sunlight, influencing surface-level offsets on spacial and temporal scales (Cartwright et al., 2020; Goodrich, 1982; Shur & Jorgenson, 2007). These surface-level offsets created climatic conditions that were significantly different from what was experienced in the lower troposphere. As a result, the thermal biological characteristic of successful surface-dwelling arthropods varied across different eco-regions as a function of the severity, duration, and frequency of exposure to cold as well as the duration and suitability of thermal conditions during the growing season (Bale, 1991, 1996; Lactin et al., 1995; Marshall & Sinclair, 2015). Moving forward, milder winter conditions, a longer snow-free season, and more extreme summer temperatures are likely to alter the life history characteristics of poikilothermic taxa in this region while also expanding

or reducing the amount of thermally suitable habitat for individual species (Bale & Hayward, 2010; Schoville et al., 2015; Wang, 2016).

3.6.1 Air and Ground Temperature Model Analysis and Associated Errors

The air and ground temperature models that were produced for this region of Castle Provincial Park represent an important advancement in both our understanding of thermal distribution in temperate mountain environments and our understanding of the thermal biology of poikilothermic taxa inhabiting these areas (Bale, 1991; Gubler et al., 2011; Harris & Pedersen, 1998; Marshall & Sinclair et al., 2015). The bulk of primary literature concerned with temperature modelling relative to arthropods in southern Alberta is concerned with prairie environments and temperatures influence on crop pests and biocontrol agents (Lactin & Johnson, 1996; 1997; 1998; 1998; McClay, 1996;). While some works attempt to also include mountainous terrain into their analysis, their models often lack the spatial resolution and sophistication needed to account for microclimatic variability that exists outside of the prairies (McClay, 1996; Powell et al., 2007). Moreover, a great many primary sources that address arthropod population forecasting in southern Alberta only address summer conditions and assume that the offset between air temperature and surface temperature is negligible during the growing season (McClay & Hughes, 1995; McClay, 1996). The data presented throughout this study proves that air temperature is often an unreliable indicator of surface temperature in mountain environments, especially during the winter months (Bonnaventure & Lamoureux, 2013; Goodrich, 1982; Shur & Jorgenson, 2007).

3.6.1.1 Air Temperature Modelling

Air temperature models showed that the variability of thermal conditions were largely a product of elevation and aspect. Whereby, upper elevation, north facing regions were comparatively cooler than lower elevation locations, or mid-elevation regions with southern exposure (Bexte, 2019; Cartwright et al., 2020). Exceptions to this were observed during the late winter months because of air temperature inversions, which occasionally formed as cold, dense air pooled in lower elevation regions (Bexte, 2019; Rolland, 2003). Inversions in this region typically did not last more than 24 hours but occurred frequently enough to significantly decrease the magnitude of February SLR values compared to January, March, and April (Bexte, 2019; Rolland, 2003). The repeated occurrence of chinooks and air temperature inversions throughout the month of February lead to variable input data which explains potential sources of error in February compared to other months (Bexte, 2019; Pigeon & Jiskoot, 2008).

As an example of the climatic variability in February, the maximum and minimum air temperatures recorded at WS 3 (an air sensor located on top of an exposed ridge at 2189 m asl.) had a range of 33.68 °C (-0.73 °C to -34.41 °C) compared to 14.80 °C in January (0 °C to -14.80 °C) and 21.19 °C in March (6.09 °C to -15.10). Likewise, the maximum and minimum air temperatures recorded at Castle Auto (an air sensor located in an open field at 1351 m asl.) had a range of 44.20 °C in February (8.70 °C to -35.50 °C) compared to 27.60 °C in January (6.40 °C to -21.20 °C) and 34.20 °C in March (16 °C to -18.20 °C) (Alberta Government, 2022). This makes sense as from February 6th – February 14th, 2021, the mean average air temperature at Beaver Mines station was – 26.89 °C, while the mean average air temperature for the rest of the month was -5.04 °C (ECCC, 2022). During this Polar Vortex from February 6th – February 14th (2021) no wind measurements could be recorded. However, after the cold snap extreme chinook

winds persisted in the region bringing warmer temperatures as the average maximum daily wind gust from February 18th- 28th (2021) was 79 km/h (ECCC, 2022). The average maximum daily wind gust speed recorded at this station in January and March of the same year was 50 km/h and 52 km/h, respectively. (ECCC, 2022).

The monthly air temperature models with the largest RMSE values (November and January) both employed Empirical Bayesian Kriging to develop aspect corrected elevation models (Krivoruchko & Gribov, 2019). Inverse Distance Weighting (IDW) proved to be the most accurate interpolation method for developing aspect corrected elevation models for other months of the year when utilized with an idealized power function produced by the GeoStatistical Wizard in Arc GIS Pro (Version 2.9.1) (Philip & Watson, 1982; Watson & Philip, 1985). However, the idealized power function value for IDW interpolation using January and November input data was 100 (default setting is 2) which is far above the maximum extreme value of 30 proposed by Watson & Philip (1985). The cause of these extreme optimized power functions for IDW interpolations using January and November input data stem from similar readings occurring at multiple input points. These similar readings (within 0.1 °C) effectively reduced horizontal variability within the interpolation surface to the point where mean absolute error was minimized by the creation of large temperature domes with ridged boundaries (Philip & Watson, 1982; Watson & Philip, 1985). As this was not indicative of reality, an alternative interpolation method (Kriging) had to be utilized in these instances (Krivoruchko & Gribov, 2019). The installation of additional air temperature data recorders would have allowed for all air temperature models to be produced utilizing IDW as the interpolation method to produce aspect corrected elevation models.

3.6.1.2 Ground Temperature Modelling

The average RMSE value for the average monthly surface temperature models was 1.34 °C, which was far greater than the average RMSE value of 0.21 °C produced by monthly average air temperature models. While a high degree of accuracy for surface temperature models was achieved for some months (e.g., April, RMSE = 0.06 °C), many months had RMSE estimates over 1.0 °C. This additional error can in part be attributed to the influence of subsurface water content on surface temperature which was not accounted for in our modelling process (Ács et al., 1991; Bonnaventure & Lamoureux, 2013). Additional error in surface temperature models can also be attributed to surface-level offsets and the difficulties associated with modelling this phenomenon (Goodrich, 1982; Smith & Riseborough, 1996). Due to the insulating properties of vegetation and snow, thermal conductivity between the surface and the atmosphere can be constrained to varying degrees (Bonnaventure & Lewkowicz, 2008; Goodrich, 1982; Smith & Riseborough, 1996). As a rule of thumb, surface temperatures are often warmer in winter months and cooler in summer months when compared to air temperatures (Bonnaventure et al., 2017; Juliussen & Humlum, 2007). The magnitude of these offsets changed across both spatial and temporal boundaries as the average monthly offset recorded within any ecosystem type ranged from 0.17 °C in LEG sites during April to 13.27 °C in UEFC sites during February. The most extreme offset recorded occurred at WS 8, at 6:00 am on February 9th, 2021, when the ground was 43.20 °C warmer than the air (recorded air temperature -43.03 °C, recorded ground temperature 0.17 °C).

3.6.1.3 Surface Temperature Offsets

Modelling surface-level offsets proved difficult as we did not have input files with the resolution necessary to accurately represent canopy composition, snowpack depth, and the composition of subsurface materials for our study area across both spatial and temporal scales (Ács et al., 1991; Cartwright et al., 2020). This made it challenging to interpolate an offset surface as we did not have all the explanatory layers necessary to describe the variability observed in recorded offsets. For example, while WS 8 was experiencing an offset of -43.20 °C, WS 3 was experiencing an offset of -16.58 °C. As this is a preliminary study into offset modelling, surface-temperature models were derived from recorded measurements at 36 surface temperature sensor locations using a regression algorithm (EBK Regression) that incorporated DEM derived layers and a landcover file as explanatory variables to aid in the interpolation (Krivoruchko & Gribov, 2019). Future studies will be able to analyze the influence of DEM derived variables on surface-level offsets while also accounting for the influence of other variables such as soil texture and soil moisture (Ács et al., 1991).

3.6.2 Terrain Morphology and Ecosystem Delineation

Within the study area, 49.80 % of terrain lies between 1332 m – 1700 m asl., while the remaining (50.20%) lies between 1700 m - 2632 m asl (AEP, 2018). Coniferous forests are the dominant vegetation throughout the entire study region as they cover 53.09% of the total landscape. Alpine meadows and above treeline environments account for 36.52% of the total area while at the lower elevations, grassland highways reach inward from the parries east of the park accounting for 10.38% of the given study area (AAFC, 2008). Surface-level thermal conditions below 1700 m asl. differ between forest and grassland environments but are relatively consistent within their respective ecosystem types. Grassland ecosystems (LEG) had the warmest

average annual surface temperatures recorded in the study area. F3 was a flat, open, grassland site located at 1387 m asl. The recorded AMGST at F3 was 7.03 °C while the modelled AMAT at this site was 5.10 °C. Prolonged, direct sun exposure heated surface materials at F3 to temperatures as warm as 32.69 °C during the summer months while winter snow cover constricted temperatures to a lower threshold of -1.80 °C (Harris & Pedersen, 1998; Shur & Jorgenson, 2007; Young et al., 1997). Other grassland sensors recorded similar thermal conditions to F3, explaining why an average annual offset of -1.29 °C persists throughout this ecosystem (Harris & Pedersen, 1998; Shur & Jorgenson, 2007; Young et al., 1997).

In the forest below 1700 m asl. (LEW) AMGST values more closely resemble AMAT values. Dense conifer cover and a healthy understory insulate the surface from direct sunlight which creates more moderate temperatures during the summer months (Shur and Jorgenson, 2007; Young et al., 1997). Additionally, dense vegetation protects the snowpack from direct sunlight and increased surface friction minimizes snow redistribution by wind (Cartwright et al., 2020). This allows for establishment of deep snowpacks that insulate the surface from extreme cold during winter (Goodrich, 1982). Ground temperature sensor 1 was in a densely forested site located in a topographic depression near the West Castle River (1371 m asl.). Insulation from vegetation and topography limited maximum surface temperature at this site to 28 °C, while ample snow cover kept minimum surface temperatures slightly below 0 °C (Goodrich, 1982; Shur & Jorgenson, 2007; Young et al., 1997). As a result, a recorded AMGST of 5.62 °C was observed at this site while the modelled AMAT value was 5.41 °C. Above 1700 m asl., the spatial distribution of surface-level temperature becomes increasingly variable (Harris & Pedersen, 1998; Sinclair & Chown, 2005). In forested environments on the upper portion of the mountain, recorded AMGST values ranged from 6.10 °C – 2.11 °C. In these forests, 5.50 km²

had AMGST values above 4.0 °C (UEFW), while 6.13 km² had AMGST values below 4.0 °C (UEFC). Despite this, all upper elevation, forested habitat had modelled AMAT values below 4.0 °C. This indicates that UEFW environments received enough snow cover in the winter and adequate sun exposure in the summer to offset surface temperatures to the point where annual measurements were warmer at the surface than in the lower atmosphere (Goodrich, 1982; Shur and Jorgenson, 2007). The most extreme example of this observed at UEFW arthropod collection site 2 where the recorded AMGST was 5.67 °C, while the modelled AMAT value was 3.15 °C.

Further upslope, in alpine environments the variability in surface level temperatures increased compared to what was observed in UEFW and UEFC environments, respectively. Recorded AMGST values above treeline ranged from 6.57 °C to -0.09 °C. In these regions a 7.63 km² area had AMGST values above 4.7 °C (UEAW), while 23.66 km² had AMGST values below 4.7 °C (UEAC). Like upper elevation, forested environments, the entire above treeline area in the park had AMAT temperatures below 4.7 °C. Despite this, alpine areas with south facing exposure received enough snow cover to insulate them from severe cold during the winter months, while also receiving enough sunlight during the warmer months to thaw out the snowpack early and heat up surface-level materials (Goodrich, 1982; Shur and Jorgenson, 2007; Young et al., 1997). Unforested areas occurring at elevations slightly above 1700 m asl. also shared thermal characteristics that were like lower elevation, grassland environments. The largest recorded annual offset in an alpine environment occurred at Ground temperature Sensor 2 which had a recorded AMGST of 6.57 °C, but a modelled AMAT of 3.26 °C. While most AMGST readings were warmer than AMAT values, UEAC arthropod collection site 3 was an exception to this rule as this site was in an alpine area at an elevation of 2064 m asl. and was orientated towards the top of a north facing bowl. This site was shielded from direct sunlight for

most of the day which limited the upper temperature readings during the summer months. In addition to this, UEAC arthropod collection site 3 was in an atmospherically turbulent region which led to much of the snowfall in this area being redistributed by wind, exposing the surface to and allowing temperatures to drop as low as -16.86°C (Harris & Pedersen, 1998; Shur and Jorgenson, 2007). Extreme cold in the winter and moderate heat in the summer lead to a recorded AMGST value of 1.04, with a modelled AMAT value of 1.25°C at this location.

3.6.3 Thermal Suitability of Various Ecoregions

In the context of overwinter site selection, LEW locations provide the most ideal surface - level thermal conditions. While the minimum recorded temperature at any LEW site was 3.31°C colder than the minimum recorded temperature at a UEFW site, UEFW sites can experience up to 44.62 more days below 0°C in addition to 29 extra freeze-thaw cycles. This is because snow cover at the higher elevations establishes sooner and takes longer to melt, extending the amount of time at or below 0°C (Cartwright et al., 2020; Goodrich, 1982). Furthermore, diurnal fluctuation in air temperatures is more severe at higher elevations which drastically increases the number of freeze-thaw cycles (Sinclair & Chown, 2005). Grassland environments are unlikely to kill overwintering arthropods through exposure to extreme cold as surface temperatures never fell below -4.88°C (Bale, 1996; Marshall & Sinclair, 2015; Ohyama & Asahina, 1972). Grassland environments also produced the longest snow-free season by 40 days and over 20 fewer days below 0°C compared to upper elevation environments. The deadliest aspect of the winter in grassland environments then was the number of freeze-thaw cycles as up to 25 cycles were observed at LEG arthropod collection site 1 during the 2020-2021 winter season (Bale, 1991; Marshall & Sinclair, 2015). The frequency of freeze-thaw cycles in grassland

environments can be attributed to the absence of snow cover during shoulder seasons when overnight air temperatures dip below 0 °C (Cartwright et al., 2020; Goodrich, 1982).

Overwintering conditions become more inhospitable in accordance with elevation as AMGST values plummet (Bale, 1996; Marshall & Sinclair, 2015). UEFC environments do not display extremely cold surface temperatures in the context of overwintering arthropods as the minimum recorded temperature in this ecosystem type was -5.58 °C (Bale, 1991; Ohyama & Asahina, 1972). However, UEFC environments can still pose a threat to overwintering arthropods as surface temperatures sit below 0 °C for over 150 consecutive days and can experience as many as 45 freeze-thaw cycles (Bale, 1991; Marshall & Sinclair, 2015). Snowpacks in these areas can persist into June, or even July depending on the severity of the preceding winter (field observations). Due to the extreme elevation of these regions, overnight temperatures have the capacity to fall below 0 °C on almost any given day, explaining the large number of freeze-thaw cycles that can be observed. Above treeline environments have the most inhospitable winter surface-level thermal regimes. These exposed areas are prone to snow redistribution by strong westerly winds that persist throughout this region, allowing for surface temperature to fall as low as -10.21 °C and -21.17 °C in UEAW and UEAC environments, respectively (Cartwright et al., 2020; Goodrich, 1982; Harris & Pedersen, 1998). The exposed nature of these environments allows for an increased influence of aspect and elevation on surface temperature (Bonnaventure & Lewkowicz, 2008; Young et al., 1997). As a result, UEAW sites can stay below 0 °C for over 125 consecutive days while UEAC sites can sit below freezing for up to 214 consecutive days. A high number of freeze-thaw cycles can be observed in both UEAW and UEAC environments. However, UEAC environments often display fewer freeze-thaw cycles as they can retain snow cover for longer (Cartwright et al., 2020; Goodrich, 1982).

Those arthropods that can endure the winter are still limited, to an extent, by heat availability as they progress through their development stages (the rate of developmental progression is the inverse of time spent in a stage) (Lactin et al., 1995). When looking at the length and intensity of the summer growing season it was determined that LEG environments provide the warmest conditions based on any temperature threshold. The average number of growing days recorded in LEG environments is at least 20 days longer than any other ecosystem type no matter the threshold temperature with regional data recorded showing surface temperatures capable of surpassing 30 °C. Conversely, forested environments provide a more insulated environment as UEFC environments average 84 fewer net growing days compared to LEG environments based on a 10 °C threshold. Providing a challenge for arthropods utilizing upper elevation terrain, or densely forested areas as their rate of development will have to be more efficient at cooler temperatures respective to grassland species (Lactin et al., 1995).

3.6.4 Composition of the Surface-dwelling Arthropod Community

Forested environments hosted nearly twice the number of surface-dwelling arthropods compared to grassland and alpine regions. While multiple factors have the capacity to influence the abundance of arthropods (predation, food availability, moisture, competition, etc.), from a thermal standpoint this is interesting because forests provide an insulated environment with respect to variable conditions in the lower atmosphere (Dahlhoff et al., 2019; Shur & Jorgenson, 2007). This indicates that most surface-dwelling arthropods in this region are equipped for more moderate conditions with respect to summer and winter temperatures (Dahlhoff et al., 2019). However, this is not to say that grassland regions and upper elevation terrain were barren as many prominent families such as Staphylinidae and Lycosidae were found across all regions of the mountain. Furthermore, extremist species such as the Northern Rock Crawler (*Grylloblatta*

campodeiformis) are exclusively found in the most thermally inhospitable and exposed regions near the top of the mountain.

While several families of arthropods were able to colonize the entire mountain, a great many were restricted to specialized environments (Dahlhoff et al., 2019; Schoville et al., 2015; Sinclair et al, 2001). Generalist's such as Lycosidae, Gnaphsonidae, Staphylinidae, and Carabidae that could inhabit the entire mountain typically clustered in below treeline environments but were also reliably found in low numbers at higher elevations. However, several families including Theridiidae and Lycidae could only be found in lower elevations and never made their way up slope (Dahlhoff et al., 2019). Moreover, specialized species such as the Buckell's Timberline Grasshopper (*Buckellacris nuda*) were commonly observed along hiking trails and other relative open vegetation above 1600 m asl. and were occasionally captured in upper elevation pitfall traps but were never once spotted or captured at lower elevations (Schoville et al., 2015).

The diversity amongst surface-dwelling arthropods in temperate mountain environments is truly staggering (CESCC, 2016; Langor, 2019). Throughout the course of this investigation, seven orders and 35 families were identified, representing an unprecedented number of species. Analysis of diversity in this study was largely limited by a lack of familiarity with more cryptic orders (Collembola, Julida, etc.), a general lack of resources and a strict timetable. As a result of this, identification could only be completed at the family level for most of the 26,178 specimens collected. To combat these setbacks more time was devoted to Araneae, Coleoptera, and Orthoptera as these orders accounted for the majority of biomass within samples and were comparatively easier to identify. Still, despite the relatively short sampling period and a limited number of traps which could be serviced in the field, meaningful quantitative and qualitative data

relative to the composition of the surface-dwelling arthropod community was produced from this investigation. A catalogue of families found within this region was produced and their distributions across heterogeneous mountain terrain was documented. Furthermore, four extremely rare and elusive species were found, further developing our understanding of the respective ranges of these organisms. Moreover, the coupling of field observations with relevant climate statistics improves our understanding of the thermal biology of documented organisms. Representing a major advancement in our understanding of the surface-dwelling arthropod community in a region which previously had limited to no monitoring or management of these taxa.

3.6.5 Climate Change Modelling Scenarios

Climate NA predicted a uniform increase in AMAT of 1.90 °C across the entire study area by 2050, while also predicting an increase of 5.3 °C by 2100 compared to observed 2020 temperatures under the SSP 585 climate scenario (Wang et al., 2016). Climate NA predicted uniform warming across the entire study area because this software was developed to model the influence of greenhouse gas emissions on climate variables at a continental scale. Thus, this tool does not have the resolution to account for the micro-scale distribution of temperature within the 87 km² study area (Wang et al., 2016). However, the AMAT model produced in this study does account for present day micro-scale variations in climate. By heating the entire AMAT model produced in this study to the specifications outlined by Climate NA it is possible to then model the micro-scale distribution of temperature in this area under a future climate scenario. At this point it is important to note that this approach did not consider the role of elevation dependent warming on future climate models, nor were these models able to account for any future changes in vegetation structure or snow cover distribution (Betts et al., 1997; Lapp et al., 2005; Pepin et

al., 2015). This exercise merely investigated the micro-scale distribution of temperature across mountain terrain based on a macro-scale prediction of potential future climatic conditions. As there are limited options to explore estimations of future surface-level temperatures under different climate scenarios in mountain environments, surface temperature models were warmed at the same rate as air temperature models. This analysis did not have the aim of perfectly predicting future climatic conditions, but rather to draw attention as to how potential thermal distribution in this region may come to change over time. However, this is only one element of a very complex set of interactions which produce habitat. Therefore, it highlights the need for further investigation into the impacts of climate change on mountain environments.

As AMAT values warm, and consequently AMGST values warm, warming impacts will not be felt evenly across spatial and temporal scales (Ernakovich et al., 2014; Grabherr et al., 2010; Kienzle, 2017). It has been determined that upper elevations will warm at an accelerated rate due to their comparative exposure to the troposphere. This means that the general thermal conditions of high mountain environments will begin to resemble the climate experienced at lower elevations, reducing the impact of elevation on temperature (Ernakovich et al., 2014; Grabherr et al., 2010). This will generally expand the range thermally suitable habitat for surface-dwelling arthropods as winter conditions become more moderate and warmer summer conditions promote metabolic function, activity levels, and general growth and development (Bale & Hayward, 2010). Warmer surface temperatures could have a profound impact on the life history strategies of arthropods in this area as the growing season lengthens and warmer temperatures increase development rates (Bale & Hayward, 2010; Lactin et al., 1995). Emergence timing and the induction of diapause for most arthropod lifecycles are synchronized with other ecological processes (flowers blooming for example), and it is unclear how warmer climate conditions

might impact the timing of arthropod lifecycles with respect to other ecological processes (Beck, 1962; Denlinger, 2002; Forrest & Thomson, 2011; Hayes, 1982). Warmer temperatures throughout the growing season may also allow species whose lifecycle is limited by the length of the growing season to increase in number as they expand their range and aim to progress through multiple generations within the same calendar year (Anthony et al., 2019; Bale & Hayward, 2010)

On a temporal scale it is estimated that the rate of warming will be more pronounced in winter months (Ernakovich et al., 2014; Kienzle, 2017; Wang, 2016). More moderate winter conditions should hypothetically increase overwinter survival as a by-product of limiting the severity, duration, and frequency of cold exposure experienced by overwintering arthropods (Bale & Hayward, 2010; Marshall & Sinclair, 2015). However, more moderate winter conditions may lead to an increase in winter mortality rates experienced by arthropods as a function of exposure to extreme cold (Bale, 1991). Castle Auto station has been collecting air temperature measurements near the Central Highway in Castle Provincial Park since 2012. From 2012 – 2021, the warmest minimum recorded annual air temperature was $-27.8\text{ }^{\circ}\text{C}$ and the coldest was $-38.2\text{ }^{\circ}\text{C}$ (Alberta Government, 2022). Even as average climate conditions begin to warm, this area will still be capable of reaching extremely cold temperatures because of polar vortices (Mitchell et al., 2012). Extremely cold air located over the North Pole is kept in place by prevailing wind patterns (the westerlies) and in recent years these winds have become weaker, more erratic, and unpredictable, allowing polar air masses to drift further south (Mitchell et al., 2012). As it currently stands, surface-dwelling arthropods are protected from these extreme cold events by insulation that is largely provided by snow cover (Goodrich, 1982). However, warmer winter conditions are poised to reduce the average snowpack depth across this region, potentially

exposing overwintering arthropods to extreme cold events in a manner which they are not equipped to survive (Bale, 1991; Kienzle, 2017; Lapp et al., 2005; Marshall & Sinclair, 2015).

3.7 Summary and Conclusions

Modelled AMAT values in Castle Provincial Park range from -2.34 °C to 5.74 °C while modelled AMGST values range from -0.8 °C to 8.57 °C. The distribution of air temperature can largely be explained as a product of elevation and aspect (Lewkowicz & Bonnaventure, 2011). While air temperatures can be accurately modelled via the incorporation of aspect and time period specific SLR's with interpolated temperature surfaces. The distribution of surface temperatures is much harder to quantify as complex topography and vegetation structure influence snow redistribution and intensity of direct sunlight, creating variable offsets as a product of insulation (Cartwright et al., 2020; Goodrich 1982; Shur & Jorgenson, 2007). These offsets can be modelled (to an extent) through the incorporation of DEM derived variables and landcover classifications as explanatory variables in 3D interpolated surface. Future publications will be able to more accurately model surface temperatures through the inclusion of additional explanatory variables such as soil moisture content, soil texture, and snowpack depth (Ács et al., 1991; Cartwright et al., 2020).

The thermal spatiotemporal distribution throughout this region profoundly impacts the thermal biological requirements for poikilothermic taxa inhabiting these regions (Bale, 1996; Marshall & Sinclair, 2015; Lactin et al., 1995). Heat during the summer months was concentrated in grassland environments as well as unforested, south facing ridges. Whilst forested regions are comparatively cooler during the summer, they provide idealized winter refugia at or beneath the surface-level due to deep snowpacks which are established via filtering out direct solar radiation and minimization snow redistribution by wind (Cartwright et al., 2020;

Shur & Jorgenson, 2007). The establishment of deep snowpacks in forested environments is beneficial to overwintering insects as the snow limits the duration, severity, and frequency of cold exposure events (Marshall & Sinclair, 2015). However, species that can withstand numerous freeze-thaw cycles might prosper from longer growing seasons and more intense summer temperatures experienced in lower elevation, grassland locations (Lactin et al., 1995). Further up the mountain, overwintering conditions become more extreme as the number of freeze-thaw cycles can increase 7-fold, minimum surface temperatures become highly variable and, in some cases, reach -20 °C, while sub-zero conditions can persist for months on end. Despite these extreme conditions, native varieties of arthropods, including extremophiles such as Northern Rock Crawlers (*Grylloblatta campodeiformis*), have been able to colonize the far reaches of this landscape whilst serving in a wide variety of ecological roles.

The diversity amongst surface-dwelling arthropods in this region is utterly staggering as numerous orders, families, and species are found across fragmented and disjunct populations that pepper the mountain landscape (Sinclair et al., 2001). While forested areas harbour most individuals and species, grassland and alpine regions serve as key habitat for specialized, rare, and endangered species (Schoville et al., 2015). Gaps currently exist amongst primary literature with regards to the diversity, range, and life history of these taxa, especially those inhabiting remote terrain (Gillespie et al., 2019). While this study represents a quantitative look at the surface-dwelling arthropod community, research opportunities are plentiful with regards the quantitative analysis of environmental factors which influence the survival and distribution of these organisms (Dahlhoff et al., 2019). This work is of the upmost importance as it will drastically impact our ability to conserve ecologically and economically important varieties of terrestrial arthropods.

Moving forward, warmer temperatures are expected to persist in this region as a function of climate change (Kienzle, 2017; Wang et al., 2016). The impacts of this warming will be greatest during winter months and will occur at a faster rate in high elevation environments (Ernakovich et al., 2014; Kienzle, 2017; Pepin et al., 2015). The ecological consequences of this warming are difficult to quantify (Bale & Hayward, 2010). Warmer temperatures will most likely result in the regional extirpation or relocation of extremophiles such as *Grylloblatta campodeiformis* (Schoville, 2015). Additional ecological concerns related to climatic warming involve the loss of synchronicity between arthropod life cycles and other ecological processes, increased metabolic rates during winter months contributing to mortality, and reduced snowpack depth increasing rates of winterkill during extreme weather events (Bale & Hayward, 2010; Barlett, 2004; Forrest & Thompson, 2011; Sinclair, 2015). However, warmer climatic conditions could also prove beneficial for a variety of species as their rate of lifecycle progression increases and the range of thermally suitable habitat accessible to them expands up-slope (Dahlhoff et al., 2019; Lactin et al., 1995). As it currently stands, research opportunities exist to investigate the influence of climate change on microclimate formation in temperate mountain environments and the impacts that this warming will have on life history characteristics of poikilothermic taxa inhabiting these regions (Bale & Hayward, 2010; Barlett, 2004; Roland & Matter, 2013).

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Chapter 4 – Conclusions

4.1 Chapter Outline

The primary objective of this thesis was to describe the horizontal and vertical distribution of thermal conditions across a temperate mountain landscape in a context which was relevant for surface-dwelling arthropods. The central question which this thesis addressed was how surface-level thermal conditions change across temperate mountain environments and how does this variability impact the thermal biological characteristics of species inhabiting these regions. To answer this question, a complete year's worth of temperature data (collected from numerous locations spanning six thermally distinct eco-regions) was utilized to model average atmospheric and surface-level thermal conditions, quantify surface level offsets, and produce ecologically relevant climatic statistics. In addition to this, surface dwelling arthropods were collected at temperature recording stations to identify prominent families and species which can survive under variable thermal conditions. Finally, microclimatic conclusions regarding the distribution of thermal conditions in Castle Provincial Park were paired with microclimatological

estimates of future climatic conditions to make estimates as to how the abundance and distribution of thermal conditions in this region may change moving forward. The purpose of this chapter is to summarise major findings and conclusions, discuss the significance of these findings, and make recommendations for future research related to this topic.

4.2 Summary of Major Findings

Modelled air and surface temperatures predicted that over the course of the 2020-2021 sampling season, AMAT values ranged from $-2.34\text{ }^{\circ}\text{C}$ to $5.74\text{ }^{\circ}\text{C}$. The coldest month of the year was February where modelled monthly average air temperatures ranged from $-7.22\text{ }^{\circ}\text{C}$ to $-15.60\text{ }^{\circ}\text{C}$. Conversely, July was the warmest month of the year as modelled monthly average air temperatures ranged from $11.70\text{ }^{\circ}\text{C}$ to $19.41\text{ }^{\circ}\text{C}$. The most extreme air temperatures recorded in February and July were -43.03°C and $38.16\text{ }^{\circ}\text{C}$, respectively. The distribution of thermal conditions throughout the lower troposphere was modelled for both monthly and annual time scales via the incorporation of aspect and time-period specific lapse rates into interpolated temperature surfaces. Surface lapse rates ranged from $-9.44\text{ }^{\circ}\text{C km}^{-1}$ on north facing slopes in March to $-0.20\text{ }^{\circ}\text{C km}^{-1}$ along south facing slopes in February. The average surface lapse rate temperature recorded across every cardinal direction (including flat) for the one-year sample period was $-5.76\text{ }^{\circ}\text{C km}^{-1}$.

Surface temperatures throughout this region failed to mirror air temperatures in a predictable manner. Surface-level offsets were produced as a by-product of the insulating properties of snow and vegetation which limited thermal conductivity between the surface and the lower atmosphere (Goodrich, 1982; Lembrechts et al., 2019). Recorded surface-level offsets ranged from as positive (air warmer than ground) as $14.59\text{ }^{\circ}\text{C}$ in summer months to as negative (ground warmer than air) as $-43.20\text{ }^{\circ}\text{C}$ in winter months. Complex vegetation structure and

snowpack distribution throughout this region made it increasingly unrealistic to derive surface temperature as a product of air temperature (Lembrechts et al., 2019). Thus, surface temperature models were interpolated from field measurements (temperature logger data and BTS points) using a 3D interpolation method (EBK Regression) that allowed for the incorporation of a landcover layer and DEM derived layers as explanatory variables. Modelled AMGST values ranged from $-0.78\text{ }^{\circ}\text{C}$ to $8.57\text{ }^{\circ}\text{C}$ with hot spots concentrated in unforested areas at lower elevations and above treeline areas that occurred at mid-range elevations with southern exposure. At the surface, February was the coldest month of the year with modelled average monthly temperatures ranging from $1.32\text{ }^{\circ}\text{C}$ to $-8.46\text{ }^{\circ}\text{C}$ while July was the warmest month with modelled average monthly temperatures ranging from $8.19\text{ }^{\circ}\text{C}$ to $23.17\text{ }^{\circ}\text{C}$.

Further analysis into the distribution, timing, and magnitude of surface-level offsets provided noteworthy results. The largest surface-level offsets occurred in winter as snow cover provided additional thermal insulation between the surface and the atmosphere, however, late-summer offsets were still considerable in magnitude (Goodrich, 1982). The largest winter offsets were observed in forested regions at mid-level elevations where snowpack depth could be maximized (Cartwright et al., 2020). The largest recorded offset in this study occurred at 1791 m asl. at a station which was situated at the base of a topographic depression amidst dense conifer cover. In these regions where snow is protected from wind redistribution and direct sunlight by vegetation and topography, snowpack establishment happens early, and persists long into the spring (Cartwright et al., 2020). This prolonged snow cover shortens the growing season by several weeks compared to what would be estimated using air temperature alone. However, once summer conditions have taken hold, the magnitude of surface-level offsets are diminished but both positive and negative offsets can still be found throughout the region. Negative offsets in

the summer months occur in above treeline environments where rocky substrate is exposed to direct sunlight and heats at an accelerated rate compared to atmospheric components.

Conversely, strongly positive offsets are observed in densely forested regions at lower elevations where the looming canopy and crowded understory limit the amount of sunlight received at the surface and restrict overall thermal conductivity within the system (Shur & Jorgenson, 2007).

The climatic variability of this region was contextualized relative to the formation and persistence of ecologically significant temperatures for surface-dwelling arthropods.

Overwintering conditions were described relative to the severity, duration, and frequency of cold exposure events endured by individuals, while the implications of summer temperatures on development and lifecycle progression were rationalized by calculating growing degree days under multiple threshold temperatures (5 °C, 8 °C, and 10 °C) (Lactin & Johnson, 1998; Marshall & Sinclair, 2015). These ecologically relevant climate statistics were produced for six thermally distinct eco-regions to quantify the distribution of surface-level thermal regimes across a temperate mountain landscape. LEW environments (39.42% of the study area) provided the best overwintering conditions as minimum surface temperatures never dropped below -5 °C, exposure to sub zero temperatures never lasted more than 57 consecutive days, and no more than seven freeze-thaw cycles were ever recorded. Conversely, UEAW environments (27.61% of the study area) provided the least ideal overwintering conditions as minimum surface temperatures fell as low as -22.47 °C, exposure to sub zero temperatures lasted up to 215 consecutive days, and as many as 27 freeze-thaw cycles were recorded. In the summer months, LEG environments (10.38% of the study area) posted the longest estimated minimum snow-free period (174 days) and had at least 20 additional growing days at every threshold temperature compared to any other ecosystem classification. On the other end of the spectrum, UEFC environments (7.15% of

the study area) hosted the lowest number of growing days at every threshold temperature, averaging between 65-84 fewer days compared to LEG environments depending on the threshold temperature.

A total of 26, 178 surface dwelling arthropods were collected over the course of two summer growing seasons. Individuals collected represented 7 orders, over 35 different families and numerous different species. Including several rare and highly specialized species such as *Cyphoderris monstrosa* and *Grylloblatta campodeiformis*, the latter of which had never been previously documented in this area (Schoville et al., 2015). Families of organisms collected serve in a wide range of ecological roles including but not limited to decomposition (Tenebrionidae), herbivory (Curculionidae), parasitism (Ixodidae), predation (Lycosidae), and serving as important food sources to birds and larger organisms (Acrididae) (González et al., 2003; Losey & Vaughan, 2006; Maucieri & Barclay, 2021). Surface-Dwelling arthropods were most numerous in forested regions while grassland and alpine habitat served as refugia for more specialized species such as *Buckellacris nuda*. The more generalist varieties of arthropods (Lycosidae & Staphylinidae) were present throughout the park, and while they were consistently found in low numbers at high mountain locations, they were truly prolific in lower elevation forests.

Under the SSP 585 climate scenario (a highly aggressive climate scenario), Climate NA projects that by the years 2050 and 2100, the annual average air temperature in Castle Provincial Park will increase by 1.9 °C and 5.3 °C relative to observed 2020 values, respectively (Wang et al., 2016). As Climate NA was developed to model potential climate scenarios on a continental scale, the software lacks the resolution needed to account for the influence of microclimatological forcings in this region. However, this estimate of future macroclimatological

conditions was used to uniformly warm the AMAT model described in this document which does account for microclimatological forcing present in this region. In addition to this, surface temperature models were also heated to the same extent as air temperature models as no software currently exists which can model impacts of climate change on surface temperatures in mountain environments. While the argument can be made that this approach is overly simplistic, it is important to note the purpose of this exercise. This exercise was not meant to produce a flawless model of future climatic conditions, rather, this exercise serves as a preliminary look at how the distribution of thermal regimes in the future may change relative to what is observed today. This was done to generate discussion with regards to how climate change may influence the life history strategies, thermal biology, and distribution of terrestrial mountain arthropods (Bale & Hayward, 2010; Dahlhoff et al., 2019).

An increase in regional AMAT's of several degrees is likely to cause climatic conditions in upper elevations to resemble conditions currently observed more closely at lower elevations (Ernakovich et al., 2014). Ultimately resulting in the loss of UEFC and UEAW ecosystem classifications. Likewise, climatic conditions at lower elevations are likely to warm above current records than have been documented for this region (Wang et al., 2016). The implications of this warming for arthropods are difficult to quantify as both positive and negative outcomes are possible (Bale & Hayward, 2010). On the plus side, warmer temperatures could provide relief for species whose lifecycles are currently limited by the amount of environmental heat available to them from their environment, allowing for faster lifecycle progression and occurrence of multiple generations within a single growing season (Lactin et al., 1995; Wellington et al., 1999). In addition to this, some species may experience range expansion as the extent of thermally suitable habitat accessible to them expands up mountain, resulting in less

fragmented and disjunct population distributions (Dahlhoff et al., 2019). On the other hand, warmer temperatures can also pose a serious threat to other varieties of arthropods. Extreme heat during the summer months can serve as a source of mortality for species whose upper temperature thresholds are close to current annual maximums such as *Grylloblatta campodeiformis* with an upper temperature threshold is approximately 28 °C (Schoville et al., 2015). Warmer temperatures in the shoulder seasons will lengthen the growing season which will be advantageous for some varieties of arthropods but detrimental for others whose lifecycles are synchronized with other ecological processes such as flowers blooming (Forrest & Thompson, 2011). Finally, warmer temperatures during the winter months threaten overwintering arthropods by increasing metabolic rates of species that overwinter as adults or juveniles, starving them to death (Irwin & Richard, 2003; Sinclair, 2015). Warmer winter temperatures will also reduce snowpack depth across this region, increasing exposure of overwintering taxa to variable conditions in the lower atmosphere, including extreme cold events cause by polar vortices (Bale, 1991; Cullen & Marshall, 2011; Goodrich, 1982).

4.3 Significance of Findings

The air and surface temperature models produced represent significant advancements in temperature modelling as it pertains to mountain arthropods. Previous research regarding temperature forecasting to predict arthropod distribution and abundance in this region largely utilized interpolated surfaces built using data collected at government weather stations (Powell et al., 2007). As a result, many temperature models that exist for these mountain environments lack the spatial resolution and overall sophistication to account for the influence of microclimatic variables on temperature (Arrington et al., 2007). Furthermore, previous research commonly assumes that thermal conditions in the lower atmosphere are representative of conditions

experience by arthropods, which can be an inaccurate assumption for mountain species which complete portions of their lifecycle at or below surface-level (Lactin & Johnson, 1996; 1997; 1998; 1998; Lembrechts et al., 2019). Conclusions acquired from investigation carried out in this thesis have determined that the distribution of thermal conditions throughout these temperate mountain environments is highly variable and can significantly change across relatively short horizontal and vertical scales.

The use of shelter belts, boulder fields, and sub terranean habitat by arthropods for cover during overwintering has been extensively studied (Sinclair et al., 2001). This research provides further support that forested environments located at lower elevations offer the most favorable overwintering conditions as a function of their ability to reduce the severity, duration, and frequency of cold exposure events endured by individuals. Further up the mountain, one or more of these elements impacting overwintering success become less optimal. Harsher overwintering conditions and a shorter, less intense growing season reduces the number of species capable of establishing in these regions whilst allowed for the success of specialized species such as *Grylloblatta campodeiformis*. The discovery of *Grylloblatta campodeiformis* in a region where it had previously not been documented is an example of how the composition of the surface-dwelling arthropod community is not static throughout the mountains and how more work is needed to describe the distribution and conservation status of arthropods inhabiting remote areas (Schoville et al., 2015).

Moving forward, the composition of surface-dwelling arthropod communities is likely to change as a response to climate change. While future climate modelling outlined in this document was relatively simplistic, it provided support to the basic conclusion that temperatures in the mountains are going to become warmer (Wang et al., 2016). This warming will likely be

prosperous for some varieties of arthropods, leading to range expansion and shorter generation times (Dahlhoff et al., 2019; Lactin et al., 1995). Meanwhile, warmer conditions may simultaneously prove disastrous for other varieties of arthropods as an extreme heat, increased exposure to extreme cold, increased winter metabolic rates, and a general loss of synchronicity between arthropod life cycles and other ecological processes may threaten regional extirpation (Bale & Hayward, 2010; Forrest & Thompson, 2011; Irwin & Richard, 2003). While the degree to which these environments will warm is yet to be determined, it is fair to assume that the expansion of warmer climate zones with annual surface temperatures above 4.0 °C is imminent.

4.4 Future Recommendations

This investigation brought to light many possible avenues of future research which could not be explored in this document due to time constraints, budgetary limitations, logistical issues, and other extenuating circumstances that stemmed from restrictions enforced to help battle the COVID-19 pandemic. Potential future research topics include:

- This project was largely unfunded which severely limited the number of temperature data loggers (both air and ground) that could be purchased, installed, and serviced by the volunteer field staff. Future studies that employ similar methods of temperature modelling in temperate mountain environments would benefit from increased temperature sensor coverage (especially at the surface-level).
- Further sampling and documentation of terrestrial arthropods in remote mountain environments is needed to identify previously undiscovered species as well as supplement contextual datasets for these economically and ecologically important taxa. This work will advance our understanding of the distribution, abundance, and ecology of these species and aid future conservation efforts.

- Development of surface temperature models which account for the influence of soil moisture, soil texture, landcover, snowfall, and DEM derived variables are needed to more accurately describe thermal conditions experienced by surface-dwelling taxa.
- The development of software which can incorporate the influence of microclimatological forcings (such as elevation dependent warming) on future climate scenarios is needed to answer more localized questions regarding the impacts of climate change.
- Development of models which can estimate snowpack depth under future climate scenarios are needed to help quantify the degree to which overwintering arthropods may be exposed to extreme cold events in years to come.
- Research opportunities exist to further develop our understanding of the life history strategies of arthropods inhabiting remote habitat. This includes work to help develop our understanding of their thermal biology and the impact of warmer temperatures on their distribution and life-cycle progression.
- Work drawn in this process is relevant to mid-latitude regions of the Rocky Mountains boarding Canada and the United States but other areas of interest with similar topography and climate exist in the South American Andies, European Alps, and the Himalayas.

Investigation into microclimate formation in mountainous terrain and the impacts that these microclimates have on surface-dwelling arthropods has uncovered several different avenues of future research. While the impacts of temperature on poikilothermic taxa have been extensively reviewed, models depicting where ecologically significant temperatures persist in a context that is relevant to these creatures are comparatively underdeveloped. A great deal of work is needed to catalog undiscovered species and develop our understanding of the life-history strategies and

historical biological characteristics of species who do not directly impact humans, such as non-pest species and species inhabiting remote areas. This work is worth doing as developing our understanding of where ecologically significant temperatures persist will prove vital in arthropod conservation efforts amidst a changing climate.

4.5 References

- Ács, F., Mihailović, D. T., & Rajković, B. (1991). A coupled soil moisture and surface temperature prediction model. *Journal of Applied Meteorology and Climatology*, 30(6), 812-822.
- Agriculture & Agri-Food Canada. (2008). *GeoBase land cover product version 1.2*.
- Alberta Climate Information Service. (2022). *Current and historical Alberta weather station data viewer*. Retrieved February 12th, 2022, from <https://www.acis.alberta.ca/acis/weather-data-viewer.jsp>.
- Alberta Environment & Parks. (2018). *Castle Mountain management plan*. Retrieved February 12th, 2022, from https://www.albertaparks.ca/media/6494620/castle_management_plan.pdf.
- Alberta Government. (2017). *List of elements in Alberta – Invertebrates – Insects: selected groups*. Retrieved March 12, 2020, from <https://open.alberta.ca/opendata/list-of-elements-in-alberta-invertebrates-insects-selected-groups>
- Alberta Parks. (2020). *Castle Provincial Park: Information and facilities*. Retrieved March 12, 2020, from <https://www.albertaparks.ca/parks/south/castle-pp/>
- Andersen, J. L., Manenti, T., Sørensen, J. G., MacMillan, H. A., Loeschcke, V., Overgaard, J., & Woods, A. (2015). How to assess drosophila cold tolerance: Chill coma temperature and lower lethal temperature are the best predictors of cold distribution limits. *Functional Ecology*, 29(1), 55-65.
- Anthony, S. E., Buddle, C. M., Høye, T. T., & Sinclair, B. J. (2019) Thermal limits of summer-collected *Pardosa* wolf spiders (Araneae: Lycosidae) from the Yukon Territory (Canada) and Greenland. *Polar Biology*, 42(11), 2055-2064.
- Arrignon, F., Deconchat, M., Sarthou, J.P., Balent, G., & Monteil, C. (2007). Modelling the overwintering strategy of a beneficial insect in a heterogeneous landscape using a multi-agent system. *Ecological Modelling*, 205(4), 423-436.
- Bale, J. (1991). Insects at low temperature: A predictable relationship? *Functional Ecology*, 5(2), 291-298.
- Bale, J. S. (1993). Insects in the cold. *Endeavour*, 17(3), 132-137.
- Bale, J. S. (1996). Insect cold hardiness: A matter of life and death. *European Journal of Entomology*, 93, 369-382.
- Bale, J. S., & Hayward, S. A. (2010). Insect overwintering in a changing climate. *Journal of Experimental Biology*, 213(6), 980-994.
- Bartlett, M. G., Chapman, D. S., & Harris, R. N. (2004). Snow and the ground temperature record of climate change. *Journal of Geophysical Research*, 109(4), 148-162.
- Basset, Y., Cizek, L., Cuénoud, P., Didham, R. K., Guilhaumon, F., Missa, O., . . . Schmidl, J. (2012). Arthropod diversity in a tropical forest. *Science*, 338(6113), 1481-1484.
- Beaver, B. (2017). *Analysis of habitat fragmentation and ecosystem connectivity within the Castle Parks, Alberta, Canada: 1-97* [Master's thesis, Youngstown State University]. Youngstown State University Library. Retrieved on February 10th, 2020, from https://etd.ohiolink.edu/!etd.send_file?accession=ysu1514364341712234&disposition=inline
- Beck, S. D. (1962). Photoperiodic induction of diapause in an insect. *The Biological Bulletin*, 122(1), 1-12.

- Bentz, B. J., Logan, J. A., & Amman, G. D. (1991). Temperature-dependent development of the mountain pine beetle (Coleoptera: Scolytidae) and simulation of its phenology. *The Canadian Entomologist*, 123(5), 1083-1094.
- Betts, R. A., Cox, P. M., Lee, S. E., & Woodward, F. I. (1997). Contrasting physiological and structural vegetation feedbacks in climate change simulations. *Nature*, 387(6635), 796-799.
- Bexte, K. J. (2019). *A spatio-temporal analysis of near-surface air temperature within the West Castle Watershed, Alberta*. 1-113 [Master's thesis, University of Lethbridge]. University of Lethbridge Research Repository. Retrieved on February 12th, 2022, from <https://opus.uleth.ca/handle/10133/5549>.
- Bonnaventure, P. P., Hillaire-Marcel, C., & Lewkowicz, A. G. (2008). Mountain permafrost probability mapping using the BTS method in two climatically dissimilar locations, northwest Canada. *Canadian Journal of Earth Sciences*, 45(4), 443-455.
- Bonnaventure, P. P., & Lamoureux, S. F. (2013). The active layer: A conceptual review of monitoring, modelling techniques and changes in a warming climate. *Progress in Physical Geography: Earth and Environment*, 37(3), 352-376.
- Bonnaventure, P. P., Lamoureux, S. F., & Favaro, E. A. (2017). Over-winter channel bed temperature regimes generated by contrasting snow accumulation in a high arctic river. *Permafrost and Periglacial Processes*, 28(1), 339-346.
- Bonnaventure, P. P., & Lewkowicz, A. G. (2008). Mountain permafrost probability mapping using the BTS method in two climatically dissimilar locations, northwest Canada. *Canadian Journal of Earth Sciences*, 45(4), 443-455.
- Bonnaventure, P. P., Lewkowicz, A. G., Kremer, M., & Sawada, M. C. (2012). A permafrost probability model for the southern Yukon and northern British Columbia, Canada. *Permafrost and Periglacial Processes*, 23(1), 52-68.
- Borror, D. J., & White, R. E. A. (1970). *Field guide to insects: America north of Mexico*. Houghton Mifflin Company.
- Boyчук, E. C. (2012). *Cold tolerance of each life stage of the sub-alpine willow leaf beetle, Chrysomela aeneicollis* [Master's thesis, Western University]. Electronic Thesis and Dissertation Repository. <https://ir.lib.uwo.ca/etd/978/>
- Bradshaw, C. J., Leroy, B., Bellard, C., Roiz, D., Albert, C., Fournier, A., . . . Courchamp, F. (2016). Massive yet grossly underestimated global costs of invasive insects. *Nature communications*, 7(1), 1-8.
- Bragg, P. D., & Holmberg, R.G. (2009). The Harvestment (Arachnida, Opiliones) of British Columbia. *Journal of the Entomological Society of British Columbia*, 106(1), 29-38.
- Brenning, A., Gruber, S., & Hoelzle, M. (2005). Sampling and statistical analyses of BTS measurements. *Permafrost and Periglacial Processes*, 16(4), 383-393.
- Bright, D. E. (1976). *The bark beetles of Canada and Alaska: Coleoptera: Scolytidae, Insects and Arachnids of Canada handbook series*. Canadian Government Publishing Centre.
- Bright, D. E. (1993). The weevils of Canada and Alaska. *Volume 1: Coleoptera: Curculionoidea, excluding Scolytidae and Curculionidae, Insects and Arachnids of Canada Handbook Series*. Canadian Government Publishing Centre.
- Brown, C., Bale, J., & Walters, K. (2004). Freezing induces a loss of freeze tolerance in an overwintering insect. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 271(1547), 1507-1511.

- Cameron, V., & Hargreaves, A. L. (2020). Spatial distribution and conservation hotspots of mammals in Canada. *FACETS*, 5(1), 692-703.
- Canadian Endangered Species Conservation Council. (2016). *Wild Species 2015: The General Status of Species in Canada*. Retrieved February 12th, 2022, from http://www.registrelep.sara.gc.ca/virtual_sara/files/reports/Wild%20Species%202015.pdf
- Cartwright, K. (2019). *Spatio-temporal variations in snow depth and associated driving mechanisms in a temperate mesoscale mountainous watershed*: 1-141 [Master's thesis, University of Lethbridge]. University of Lethbridge Research Repository. Retrieved on February 12th, 2022, from <https://hdl.handle.net/10133/5415>
- Chai, T., & Draxler, R. R. (2014). Root mean square error (RMSE) or mean absolute error (MAE). *Geoscientific Model Development Discussions*, 7(1), 1525-1534.
- Colla, S. R., Gadallah, F., Richardson, L., Wagner, D., & Gall, L. (2012). Assessing declines of North American bumble bees (*Bombus* spp.) using museum specimens. *Biodiversity and Conservation*, 21(14), 3585-3595.
- Cullen, R. M., & Marshall, S. J. (2011). Mesoscale temperature patterns in the Rocky Mountains and Foothills region of southern Alberta. *Atmosphere-Ocean*, 49(3), 189-205.
- Cullingham, C. I., Cooke, J. E. K., Dang, S., Davis, C. S., Cooke, B. J., & Coltman, D. W. (2011). Mountain pine beetle host-range expansion threatens the boreal forest. *Molecular Ecology*, 20(10), 2157-2171.
- Dahlhoff, E. P., Dahlhoff, V. C., Grainger, C. A., Zavala, N. A., Otepola-Bello, D., Sargent, B. A., . . . & Rank, N. E. (2019). Getting chased up the mountain: High elevation may limit performance and fitness characters in a montane insect. *Functional Ecology*, 33(5), 809-818.
- Delatte, H., Gimonneau, G., Triboire, A., & Fontenille, D. (2009). Influence of temperature on immature development, survival, longevity, fecundity, and gonotrophic cycles of *Aedes albopictus*, vector of chikungunya and dengue in the Indian Ocean. *Medical Entomology*, 46(1), 33-41.
- Denlinger, D. L. (2002). Regulation of diapause. *Annual Review of Entomology*, 47(1), 93-122.
- Dondale, C. D., & Redner, J. H. (1978). *The Crab Spiders of Canada and Alaska: Araneae: Philodromidae and Thomisidae, Insects and Arachnids of Canada Handbook Series*. Canadian Government Publishing Centre.
- Dondale, C.D., & Redner, J.H. (1982). *The Sac Spiders of Canada and Alaska: Araneae: Clubionidae and Anyphaenidae, Insects and Arachnids of Canada Handbook Series*. Canadian Government Publishing Centre.
- Dondale, C.D., & Redner, J.H. (1990). *The Wolf Spiders, Nurseryweb Spiders, and Lynx Spiders of Canada and Alaska: Araneae: Lycosidae, Pisauridae, and Oxyopidae, Insects and Arachnids of Canada Handbook Series*. Canadian Government Publishing Centre
- Eaton, E. R., & Kauffman, K. (2007). *Field Guide to Insects of North America*. Houghton Mifflin Company.
- Environment and Climate Change Canada. (2022). *Historical data*. Retrieved February 12th, 2022, from https://climate.weather.gc.ca/historical_data/search_historic_data_e.html.
- Erland, L. A. E., Turi, C. E., & Murch, S. J. (2022). Preliminary assessment of the conservation status of medicinal plant species in Canada. *Botany*, 100 (2), 247-260.

- Ernakovich, J. G., Hopping, K. A., Berdanier, A. B., Simpson, R. T., Kachergis, E. J., Steltzer, H., & Wallenstein, M. D. (2014). Predicted responses of arctic and alpine ecosystems to altered seasonality under climate change. *Global Change Biology*, 20(10), 3256-3269.
- Fand, B. B., Tonnang, H. E. Z., Kumar, M., Bal, S. K., Singh, N. P., Rao, D. V. K. N., Kamble, A. L., Nangare, D. D., Minhas, P. S. (2014). Predicting the impact of climate change on regional and seasonal abundance of the mealybug *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae) using temperature-driven phenology model linked to GIS. *Ecological Modelling*, 288(1), 62-78.
- Finch, O. D., Löffler, J., & Pape, R. (2008). Assessing the sensitivity of *melanoplus frigidus* (orthoptera: Acrididae) to different weather conditions: A modeling approach focussing on development times. *Insect Science*, 15(2), 167-178.
- Forbes, K. A., Kienzle, S. W., Coburn, C. A., Byrne, J. M., & Rasmussen, J. (2011). Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada. *Climatic Change*, 105(3-4), 555-576.
- Forrest, J. R., & Thomson, J. D. (2011). An examination of synchrony between insect emergence and flowering in rocky mountain meadows. *Ecological Monographs*, 81(3), 469-491.
- Gillespie, M. A. K., Alfredsson, M., Barrio, I. C., Bowden, J., Convey, P., Coulson, S. J., . . . Hoyer, T. T. (2019). Circumpolar terrestrial arthropod monitoring: A review of ongoing activities, opportunities and challenges, with a focus on spiders. *Ambio*. 49(2), 704-717.
- González, G., Seastedt, T. R., & Donato, Z. (2003). Earthworms, arthropods and plant litter decomposition in aspen (*Populus tremuloides*) and lodgepole pine (*Pinus contorta*) forests in Colorado, USA: The 7th international symposium on earthworm ecology· Cardiff· Wales· 2002. *Pedobiologia*, 47(5-6): 863-869.
- Goodrich, L. E. (1982). The influence of snow cover on the ground thermal regime. *Canadian geotechnical journal*, 19(4), 421-432.
- Grabherr, G., Gottfried, M., & Pauli, H. (2010). Climate change impacts in alpine environments. *Geography Compass*, 4(8), 1133-1153.
- Goulson, D. (2019). The insect apocalypse, and why it matters. *Current Biology*, 29(19), 967-971.
- Haeberli, W. (1973). The base temperature of the winter snow cover as a possible indicator for the processing of permafrost in the alpine. *Journal of Glaciology and Glacial Geology*, 1(2), 221-227.
- Hallmann, C. A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., ... and de Kroon, H. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PloS one*, 12(10), 0185809.
- Hancock, J., & Hancock, K. (2015). *Spiders of western Canada*. Lone Pine Publishing.
- Harcourt, D. G., & Yee, J. M. (1982). Polynomial algorithm for predicting the duration of insect life stages. *Environmental Entomology*, 11(3), 581-584.
- Harris, S. A., and Pedersen, D. E. (1998). Thermal regimes beneath coarse blocky materials. *Permafrost and Periglacial Processes*, 9(2), 107-120.
- Hausfather, Z. & Peters, G. (2020). “Emissions – the business as usual” story is misleading. *Nature*, 577(1): 618-620.
- Hayes, J. L. (1982). A study of the relationships of diapause phenomena and other life history characters in temperate butterflies. *The American Naturalist*, 120(2), 160-170.
- Hermes, D. A. (2004). Using degree-days and plant phenology to predict pest activity. *Integrated Pest Management of Midwest Landscapes*, 58 (1), 49-59.

- Hiemstra, C. A., Liston, G. E., & Reiners, W. A. (2002). Snow redistribution by wind and interactions with vegetation at upper treeline in the medicine bow mountains, Wyoming, USA. *Arctic, Antarctic, and Alpine Research*, 34(3), 262-273.
- Huang, J., Li, G., Lei, H., Fan, C., Tian, C., Chen, Q., . . . Feng, H. (2019). Behaviour and cold hardiness of the purple stem borer in winter, colonizing more northerly latitudes. *bioRxiv*, 81(9), 417-447.
- Irwin, J. T., & Lee, J., Richard E. (2003). Cold winter microenvironments conserve energy and improve overwintering survival and potential fecundity of the goldenrod gall fly, *Eurosta solidaginis*. *Oikos*, 100(1), 71-78.
- Ives, W. G. H., & Wong H. R. (1988). *Tree and shrub insects of the prairie provinces*. Canadian Forestry Service.
- Juliussen, H., & Humlum, O. (2007). Towards a TTOP ground temperature model for mountainous terrain in central-eastern Norway. *Permafrost and Periglacial Processes*, 18(2), 161-184.
- Kershaw, L., MacKinnon, A., Pojar, J. (2016). *Plants of the Rocky Mountains*. Partners Publishing.
- Kienzle, S. W. (2017). Has it become warmer in Alberta? Mapping temperature changes for the period 1950–2010 across Alberta, Canada. *The Canadian Geographer /Le Géographe Canadien*, 62(2), 144-162.
- Krivoruchko, K., & Gribov, A. (2019). Evaluation of empirical Bayesian kriging. *Spatial Statistics*, 32, 100368.
- Labeyrie, V. (1978). The significance of the environment in the control of insect fecundity. *Annual review of entomology*, 23(1), 69-89.
- Lactin, D. J., Holliday, N.J., Johnson, D. L., & Craigen, R. (1995). Improved rate model of temperature-dependent development by arthropods. *Environmental Entomology*, 24(1), 68-75.
- Lactin, D.J., & Johnson, D.L. (1996). Effects of insolation and body orientation on internal thoracic temperature of nymphal *Melanoplus packardii* (Orthoptera: Acrididae). *Environmental Entomology*, 25(2), 423-429.
- Lactin, D. J., & Johnson, D. L. (1997). Response of body temperature to solar radiation in restrained nymphal migratory grasshoppers (Orthoptera: Acrididae): Influence of orientation and body size. *Physiological Entomology*, 22(2), 131-139.
- Lactin, D. J., & Johnson, D. L. (1998). Convective heat loss and change in body temperature of grasshopper and locust nymphs: relative importance of wind speed, insect size and insect orientation. *Journal of Thermal Biology*, 23(1): 5-13.
- Lactin, D. J., & Johnson, D. L. (1998). Environmental, physical, and behavioural determinants of body temperature in grasshopper nymphs (Orthoptera: Acrididae). *The Canadian Entomologist*, 130(5), 551-577.
- Langor, D. W. (2019). The diversity of terrestrial arthropods in Canada. *Zookeys*, 819(9), 9-40.
- Lapp, S., Byrne, J., Townsend, I., and Kienzle, S. (2005). Climate warming impacts on snowpack accumulation in an alpine watershed. *International Journal of Climatology*, 25(4), 521-536.
- Leather, S. R. (2008). *Insect Sampling in Forrest Ecosystems*. Imperial College of Science, Technology and Medicine.
- Leather, S. R. (2017). “Ecological armageddon”-more evidence for the drastic decline in insect numbers. *Annals of Applied Biology*, 172(1), 1-3.

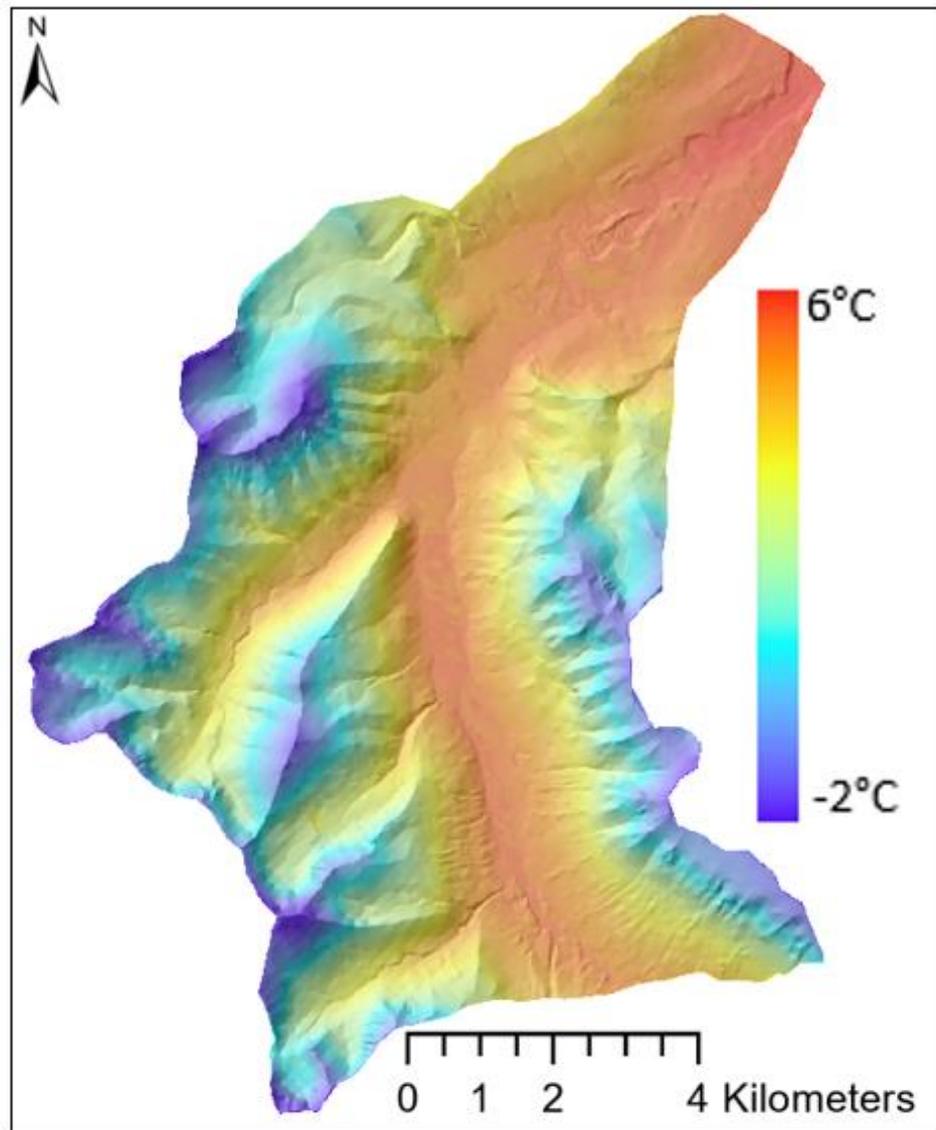
- Lembrechts, J. J., Lenoir, J., Roth, N., Hattab, T., Milbau, A., Haider, S., ... & Nijs, I. (2019). Comparing temperature data sources for use in species distribution models: From in-situ logging to remote sensing. *Global Ecology and Biogeography*, 28(11), 1578-1596.
- Lewkowicz, A. G., and Bonnaventure, P.P. (2011). Equivalent elevation: a new method to incorporate variable surface lapse rates into mountain permafrost modelling. *Permafrost and Periglacial Processes*, 22(2), 153-162.
- Lewkowicz, A. G., & Ednie, M. (2004). Probability mapping of mountain permafrost using the BTS method, wolf creek, yukon territory, Canada. *Permafrost and Periglacial Processes*, 15(1), 67-80.
- Logan, J. A., Wollkind, D. J., Huyt, S. C., & Tanigoshi, L.K. (1976). An analytic model for description of temperature dependent rate phenomena in arthropods. *Environmental Entomology*, 5(6), 1133-1140.
- Losey, J. E., & Vaughan, M. (2006). The economic value of ecological services provided by insects. *Bioscience*, 56(4), 311-323.
- Marshall, K. E., & Sinclair, B. J. (2015). The relative importance of number, duration and intensity of cold stress events in determining survival and energetics of an overwintering insect. *Functional Ecology*, 29(3), 357-366.
- Maucieri, D. & Barclay, R. M. (2021). Consumption of spiders by the little brown bat (*Myotis lucifugus*) and the long-eared myotis (*Myotis evotis*) in the Rocky Mountains of Alberta, Canada. *Canadian Journal of Zoology*, 99(3): 221-226.
- McClay, A. S. (1996). Biological control in a cold climate: Temperature responses and climatic adaptation of weed biocontrol agents. *Proceedings of the International Symposium on Biological Control of Weeds*, 9, 377-383, 1996.
- McClay, A. S. & Hughes, R. B. (1995). Effects of temperature on developmental rate, distribution, and establishment of *Calophasia lunula* (Lepidoptera, Noctuidae), a biocontrol agent for toadflax (*Linaria* spp.). *Biological Control*, 5(3), 368-377.
- McEvoy, P., Cox, C., & Coombs, E. (1991). Successful biological control of ragwort, *Senecio jacobaea*, by introduced insects in Oregon. *Ecological Applications*, 1(4), 430-442.
- Meng, P., Hoover, K., & Keena, M, A. (2015). Asian longhorned beetle (Coleoptera: Cerambycidae), an introduced pest of maple and other hardwood trees in North America and Europe. *Journal of Integrated Pest Management*, 6(1).
- Mitchell, D. M., Osprey, S. M., Gray, L. J., Butchart, N., Hardiman, S. C., Charlton-Perez, A. J., & Watson, P. (2012). The effect of climate change on the variability of the Northern Hemisphere stratospheric polar vortex. *Journal of the Atmospheric Sciences*, 69(8), 2608-2618.
- Morris, G. K., & Gwynne, D. T. (1978). Geographical distribution and biological observations of *Cyphoderris* (Orthoptera: Haglidae) with a description of a new species. *Psyche*, 85(2-3),147-167.
- Nealis, V. G. (2020). Weather and insects in a changing climate. *Journal of the Entomological Society of British Columbia*, 116(1), 3-16.
- Nealis, V. G., DeMerchant, I., Langor, D., Noseworthy, M. K., Pohl, G., Porter, K., ... & Waring, V. (2016). Historical occurrence of alien arthropods and pathogens on trees in Canada. *Canadian Journal of Forest Research*, 46(2), 172-180.
- Ohyama, Y., & Asahina, É. (1972). Frost resistance in adult insects. *Journal of Insect Physiology*, 18(2), 267-282.

- Oliveira, C., Auad, A., Mendes, S., & Frizzas, M. (2014). Crop losses and the economic impact of insect pests on Brazilian agriculture. *Crop Protection*, *56*, 50-54.
- Pepin, N., Bradley, R. S., Diaz, H. F., Baraër, M., Caceres, E. B., Forsythe, N., ... & Yang, D. Q. (2015). Elevation-dependent warming in mountain regions of the world. *Nature climate change*, *5*(5), 424-430.
- Philip, G. M., & Watson, D. F. (1982). A precise method for determining contoured surfaces. *Australian Petroleum Exploration Association Journal*, *22*(1), 205-212.
- Pigeon, K. E., & Jiskoot, H. (2008). Meteorological controls on snowpack formation and dynamics in the southern Canadian Rocky Mountains. *Arctic, Antarctic, and Alpine Research*, *40*(4), 716-730.
- Pimentel, D., Zuniga, R., & Morrison, D. (2005). Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological economics*, *52*(3), 273-288.
- Powell, L.R., Berg, A. A., Johnson, D. L., & Warland, J. S. (2007). Relationships of pest grasshopper populations in Alberta, Canada to soil moisture and climate variables. *Agricultural & Forest Meteorology*, *144*(1-2), 73-84.
- Quinn, B. K. (2017). A Critical review of the use and performance of different function types for modelling temperature-dependent development of arthropod larvae. *Journal of Thermal Biology*, *63*(1), 65-77.
- Rebaudo, F., & Rabhi, V. B. (2018). Modeling temperature-dependent development rate and phenology in insects: Review of major developments, challenges, and future directions. *Entomologia Experimentalis et Applicata*, *166*(8), 607-617.
- Roland, J., & Matter, S. F. (2013). Variability in winter climate and winter extremes reduces population growth of an alpine butterfly. *Ecology*, *94*(1), 190-199.
- Rolland, C. (2003). Spatial and seasonal variations of air temperature lapse rates in alpine regions. *Journal of Climate*, *16*(7), 1032-1046.
- Schoville, S. D., Slatyer, R. A., Bergdahl, J. C., & Valdez, G. A. (2015). Conserved and narrow temperature limits in alpine insects: Thermal tolerance and supercooling points of the ice-crawlers, *Grylloblatta* (Insecta: Grylloblattodea: Grylloblattidae). *Journal of Insect Physiology*, *78*(1), 55-61.
- Senay, S. D., & Worner, S. P. (2019). Multi-scenario species distribution modeling. *Insects*, *10*(3), 65-87.
- Sharpe, P. J. H., & DeMichele, D. W. (1977). Reaction kinetics of poikilotherm development. *Journal of Theoretical Biology*, *64*(4), 649-670.
- Shur, Y. L., & Jorgenson, M. T. (2007). Patterns of permafrost formation and degradation in relation to climate and ecosystems. *Permafrost and Periglacial Processes*, *18*(1), 7-19.
- Slivacrom Group of Companies. (2022). *Altalis*. Retrieved February 5, 2020, from <https://www.altalis.com/>
- Sinclair, B. J. (2015). Linking energetics and overwintering in temperate insects. *Journal of Thermal Biology*, *54*, 5-11.
- Sinclair, B. J., & Chown, S. L. (2005). Deleterious effects of repeated cold exposure in a freeze-tolerant sub-antarctic caterpillar. *Journal of Experimental Biology*, *208*(5), 869-879.
- Sinclair, B. J., Lord, J. M., & Thompson, C. M. (2001). Microhabitat selection and seasonality of alpine invertebrates. *Pedobiologia*, *45*(2), 107-120.
- Sinclair, B. J., Vernon, P., Klok, C. J., & Chown, S. L. (2003). Insects at low temperatures: An ecological perspective. *Trends in Ecology & Evolution*, *18*(5), 257-262.

- Slatyer, R. A., Nash, M. A., Miller, A. D., Endo, Y., Umbers, K. D., & Hoffmann, A. A. (2014). Strong genetic structure corresponds to small-scale geographic breaks in the Australian alpine grasshopper *Kosciuscola tristis*. *BMC evolutionary biology*, *14*(1), 204.
- Smith, M., & Riseborough, D. (1996). Permafrost monitoring and detection of climate change. *Permafrost and Periglacial Processes*, *7*(4), 301-309.
- Sømme, L. (1964). Effects of glycerol on cold-hardiness in insects. *Canadian Journal of Zoology*, *42*(1), 87-101.
- Sømme, L. (1982). Supercooling and winter survival in terrestrial arthropods. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *73*(4), 519-543.
- Sømme, L. (1989). Adaptations of terrestrial arthropods to the alpine environment. *Biological Reviews*, *64*(4), 367-407.
- Sømme, L., & Zachariassen, K. E. (1981). Adaptations to low temperature in high altitude insects from Mount Kenya. *Ecological Entomology*, *6*(2), 199-204.
- Soroka, J., Grenkow, L., Cárcamo, H., Meers, S., Barkley, S., & Gavloski, J. (2020). An assessment of degree-day models to predict the phenology of alfalfa weevil (Coleoptera: Curculionidae) on the Canadian Prairies. *The Canadian Entomologist*, *152*(1), 110-129.
- Stinner, R., Barfield, C., Stimac, J., & Dohse, L. (1983). Dispersal and movement of insect pests. *Annual Review of Entomology*, *28*(1), 319-335.
- Stinner, R. E., Butler, G. D., Bacheler, J. S., & Tuttle, C. (1975). Simulation of temperature-dependent development in population dynamics models. *The Canadian Entomologist*, *107*(11), 1167-1174.
- Slatyer, R. A., Nash, M. A., Miller, A. D., Endo, Y., Umbers, K. D., & Hoffmann, A. A. (2014). Strong genetic structure corresponds to small-scale geographic breaks in the Australian alpine grasshopper *Kosciuscola tristis*. *BMC Evolutionary Biology*, *14*(1), 1-13.
- Tauber, M.J., Tauber, C.A. & Masaki, S. (1986). *Seasonal Adaptations of Insects*. Oxford: Oxford University Press.
- Taylor, F. (1982). Sensitivity of physiological time in arthropods to variation of its parameters. *Environmental Entomology*, *11*(3), 755-763.
- Tognelli, M. F., Roig, S. A., Marvaldi, A., Flores, G. E., & Lobo, J. M. (2009). An evaluation of methods for modelling distribution of Patagonian insects. *Revista Chilena de Historia Natural*, *82*(3), 347-360.
- Wang, T., Hamann, A., Spittlehouse, D., & Carroll, C. (2016). Locally downscaled and spatially customizable climate data for historical and future periods for North America. *PLoS one*, *11*(6), 0156720.
- Watson, D. F., & Philip, G. M. (1985). A refinement of inverse distance weighted interpolation. *Geoprocessing*, *2*(1), 315-327.
- Way, R. G., & Lewkowicz, A. G. (2018). Environmental controls on ground temperature and permafrost in Labrador, northeast Canada. *Permafrost and Periglacial Processes*, *29*(2), 73-85.
- Wellington, W. G., Johnson, D. L., & Lactin, D. J. (1999). Weather and Insects. *Ecological Entomology*, 313-353.
- Young, K. L., Woo, M. K., & Edlund, S. A. (1997). Influence of local topography, soils, and vegetation on microclimate and hydrology at a high Arctic site, Ellesmere Island, Canada. *Arctic & Alpine Research*, *29*(3), 270-284.

Appendix A

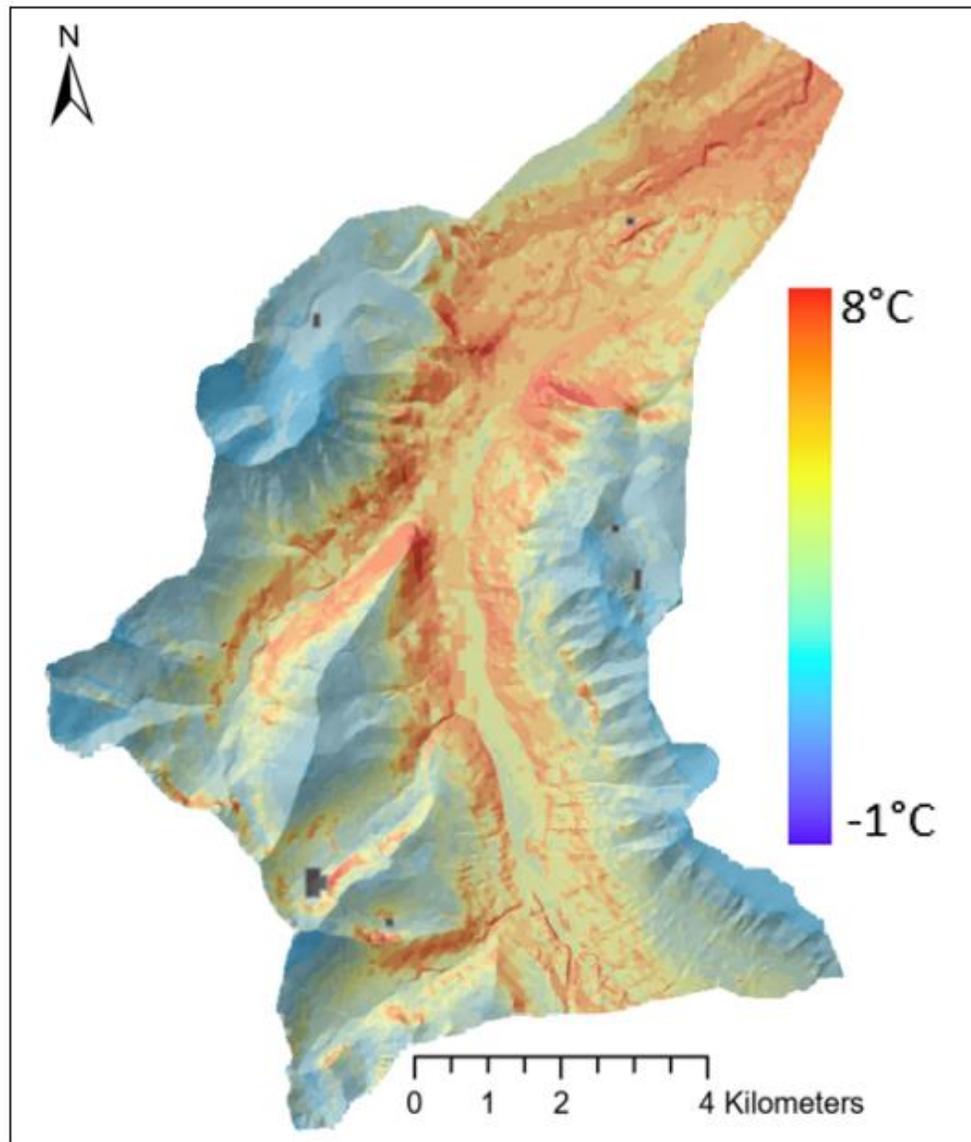
AMAT model produced for an 87 km² study area located within the West Castle region of Castle Provincial Park.



Appendix A:1. AMAT model displayed using a unique temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.

Appendix B

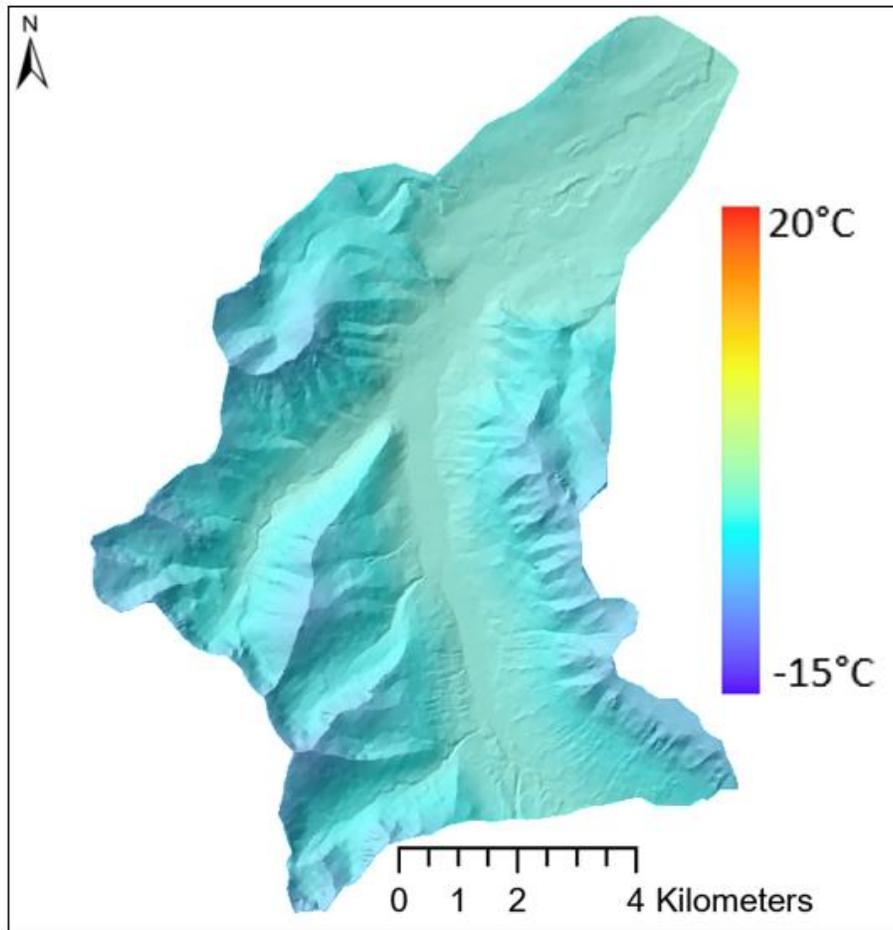
AMGST model produced for an 87 km² study area located within the West Castle region of Castle Provincial Park.



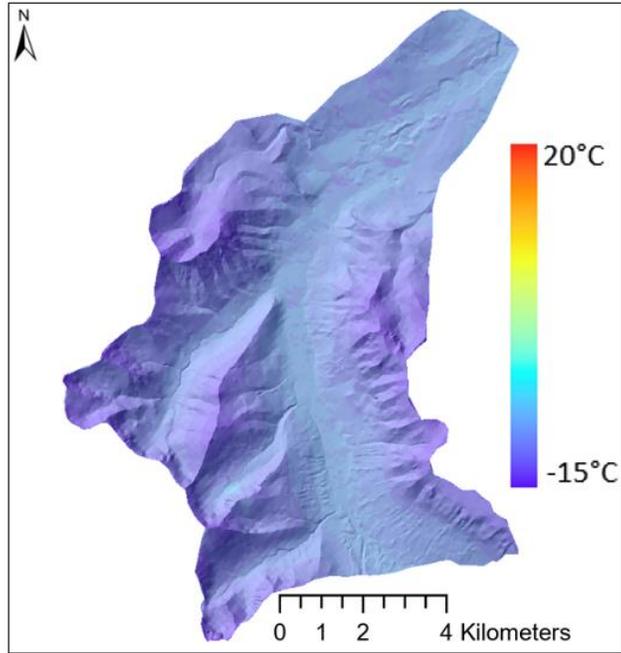
Appendix B:1. AMAT model displayed using a unique temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.

Appendix C

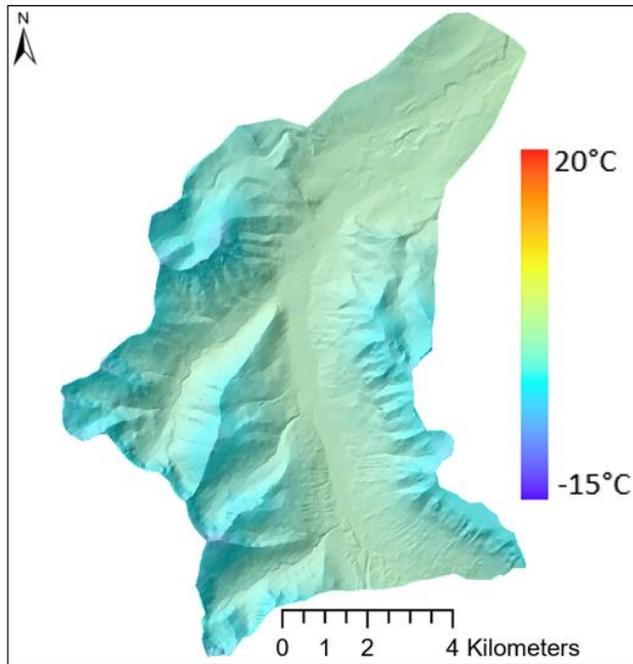
Average monthly air temperature models produced for an 87 km² study area located within the West Castle region of Castle Provincial Park.



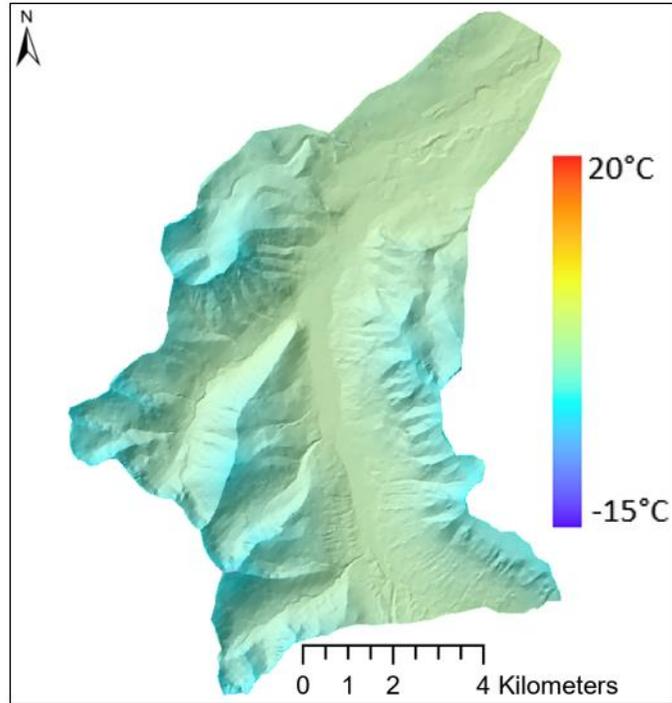
Appendix C:1. Average air temperature model for the month of January displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



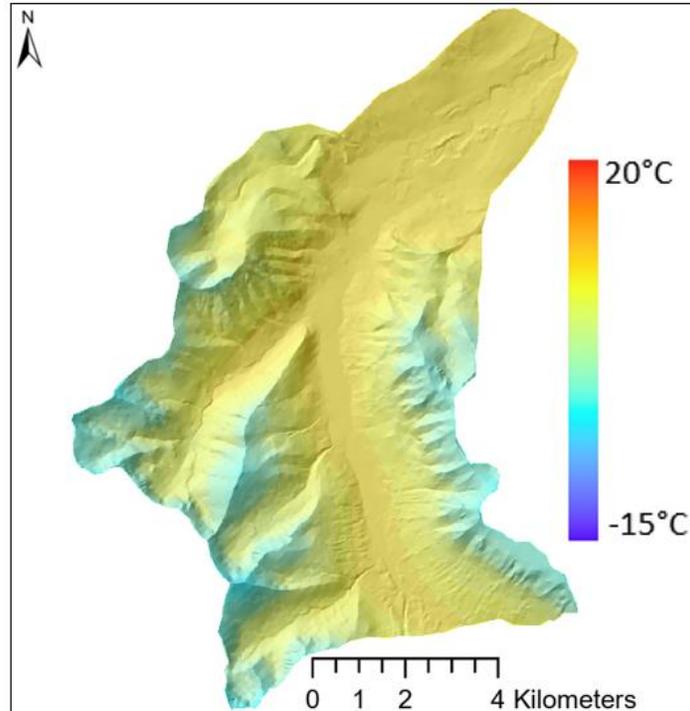
Appendix C:2. Average air temperature model for the month of February displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



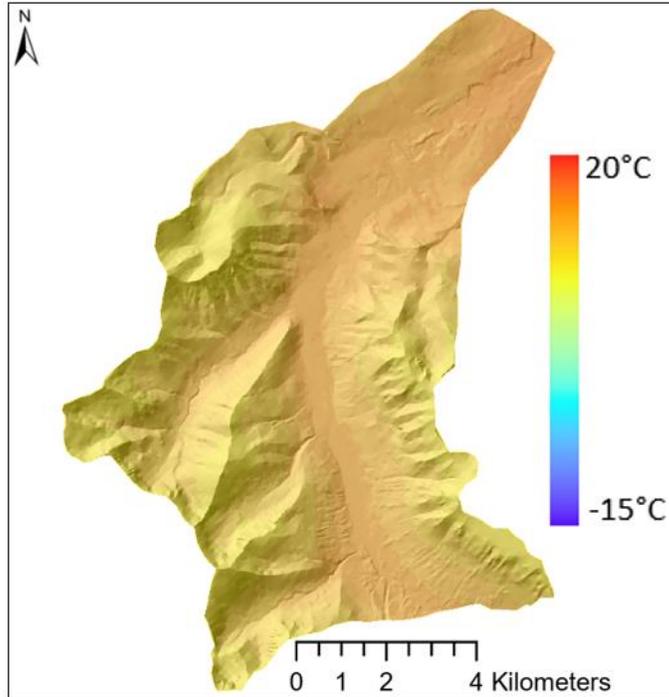
Appendix C:3. Average air temperature model for the month of March displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



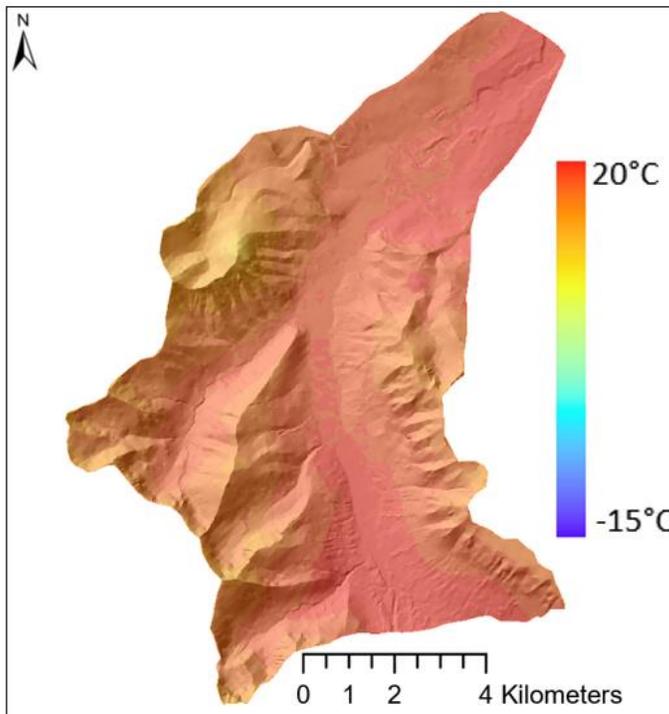
Appendix C:4. Average air temperature model for the month of April displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



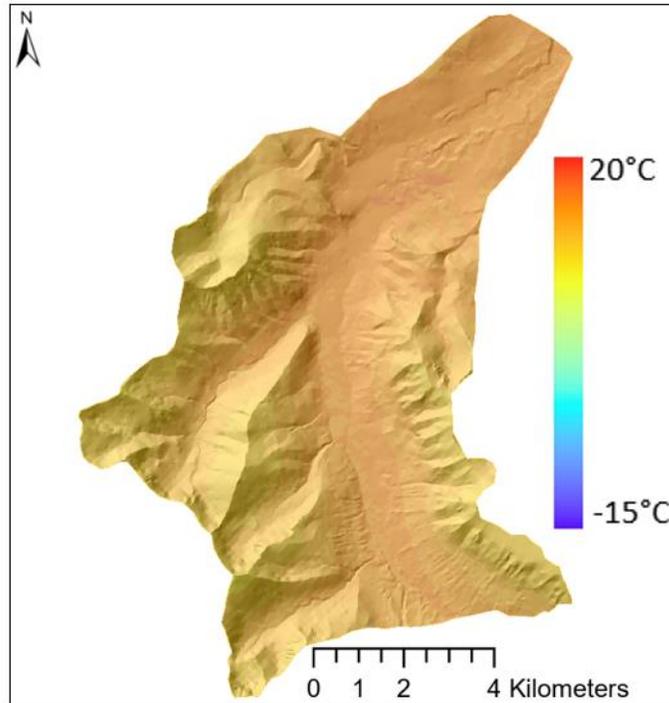
Appendix C:5. Average air temperature model for the month of May displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



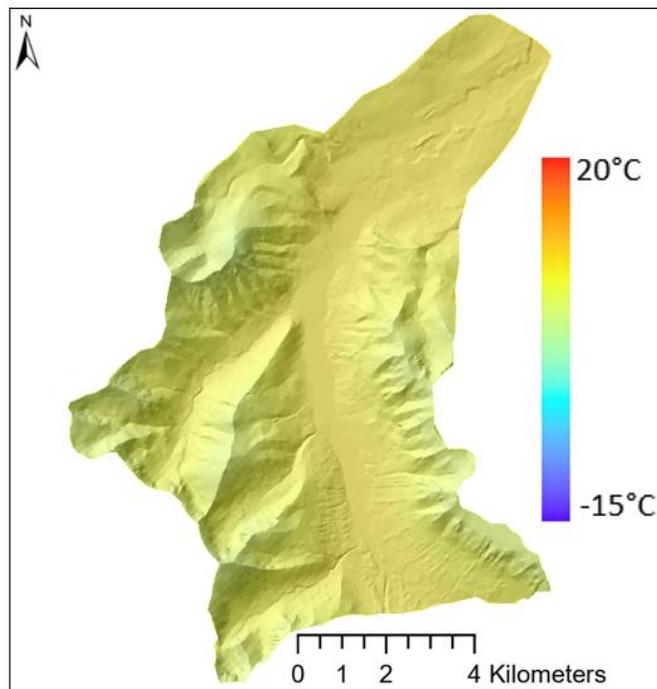
Appendix C:6. Average air temperature model for the month of June displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



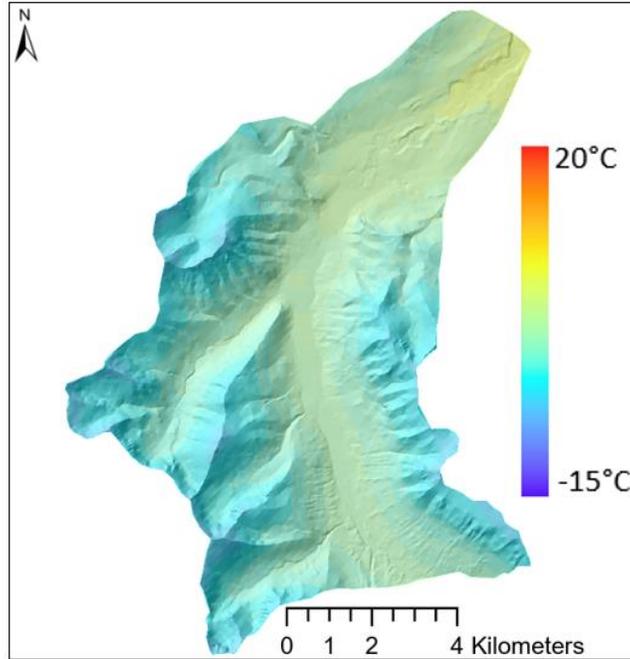
Appendix C:7. Average air temperature model for the month of July displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



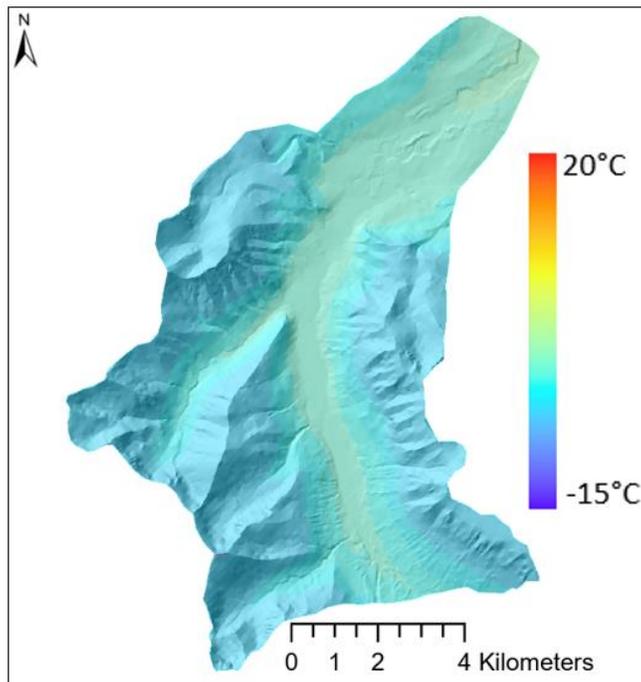
Appendix C:8. Average air temperature model for the month of August displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



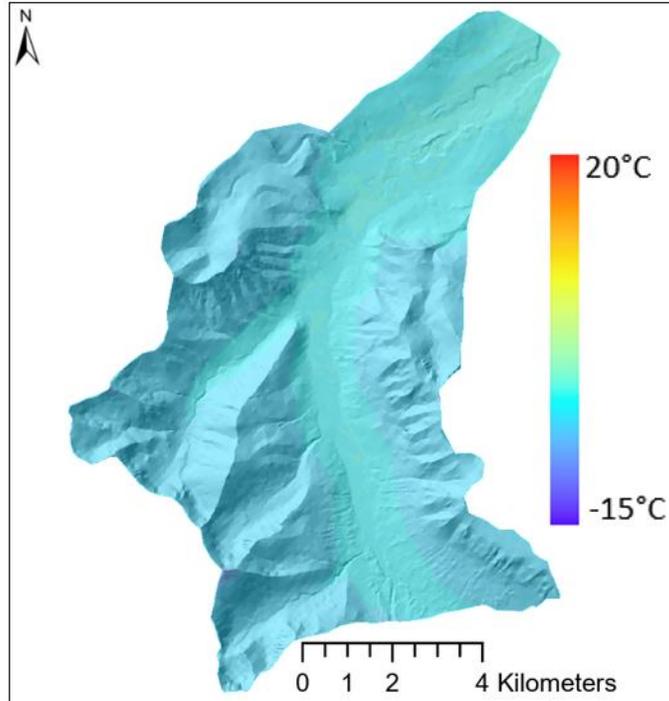
Appendix C:9. Average air temperature model for the month of September displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



Appendix C:10. Average air temperature model for the month of October displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



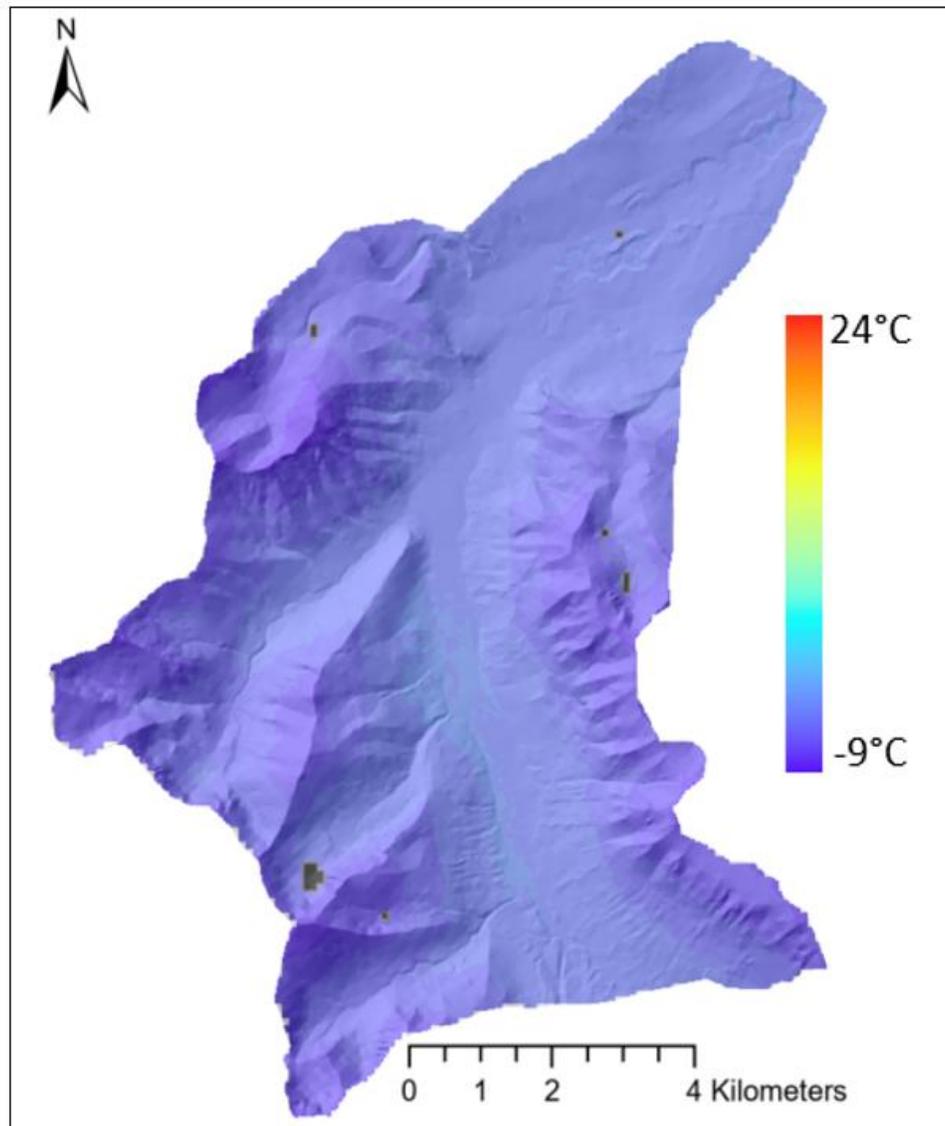
Appendix C:11. Average air temperature model for the month of November displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



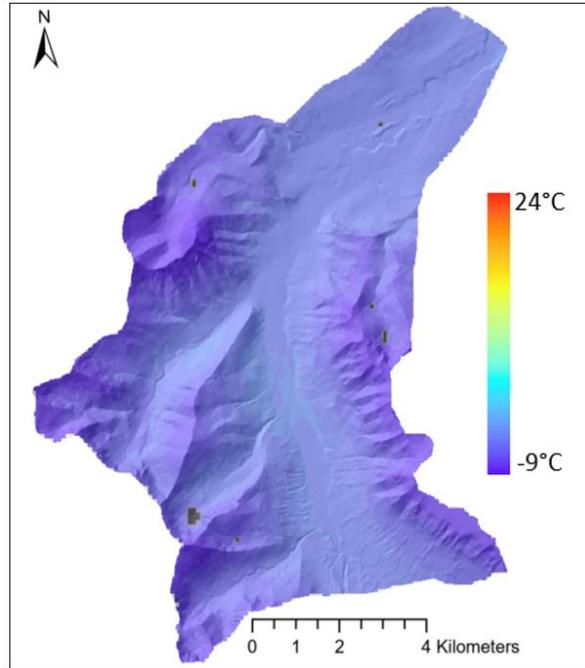
Appendix C:12. Average air temperature model for the month of December displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.

Appendix D

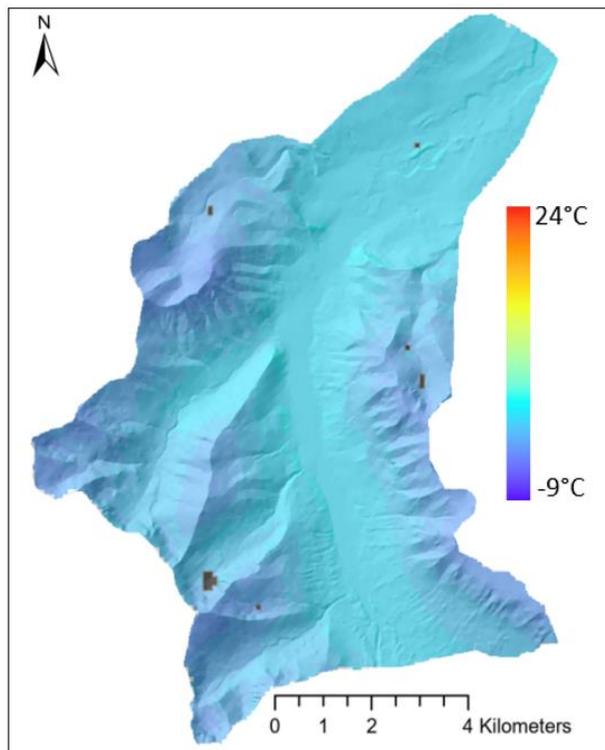
Average monthly ground surface temperature models produced for an 87 km² study area located within the West Castle region of Castle Provincial Park.



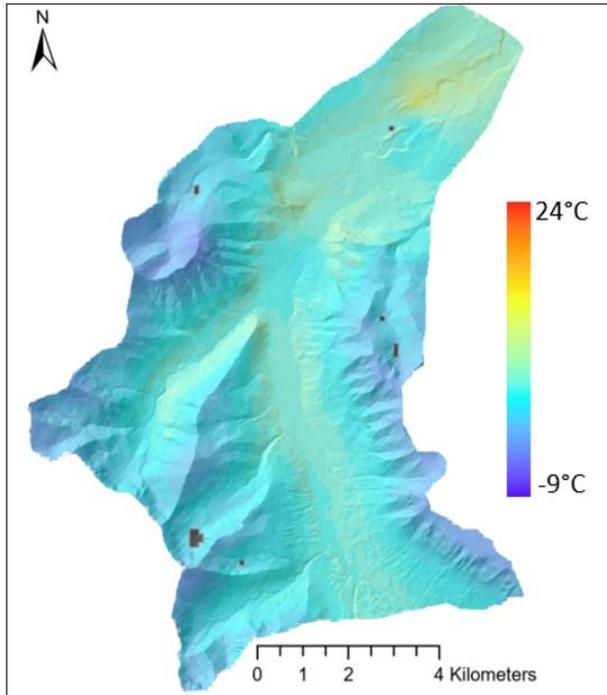
Appendix D:1. Average ground surface temperature model for the month of January displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



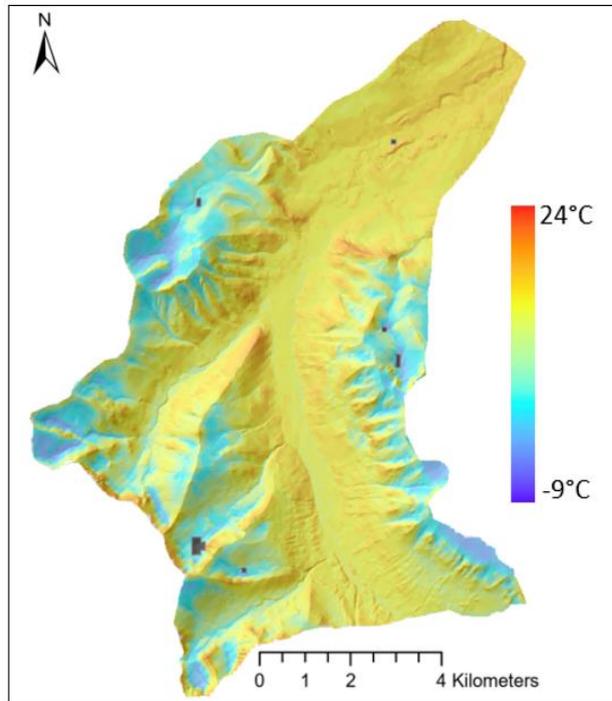
Appendix D:2. Average ground surface temperature model for the month of February displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



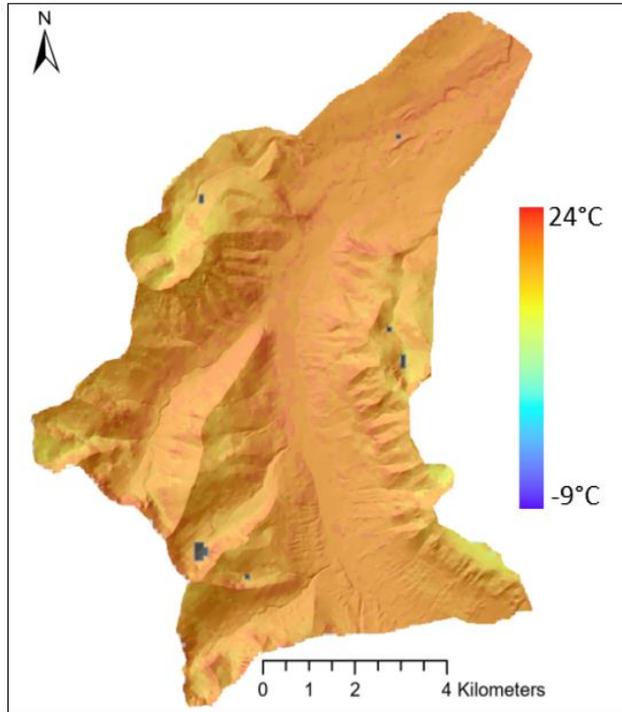
Appendix D:3. Average ground surface temperature model for the month of March displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



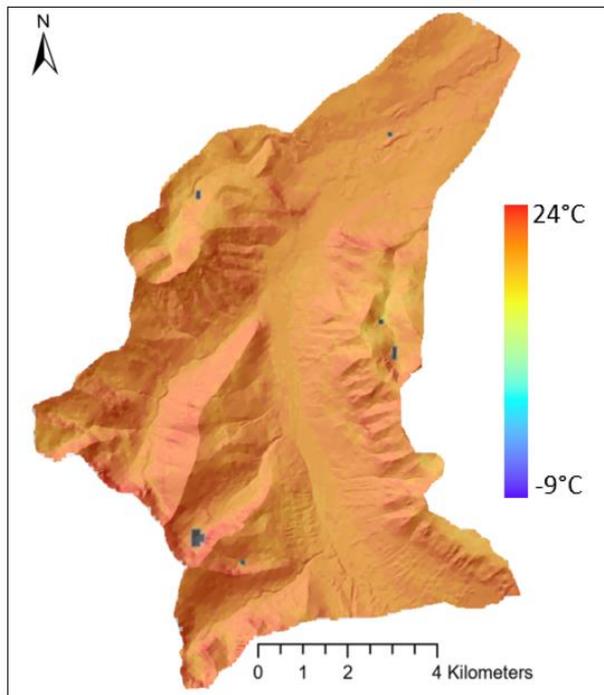
Appendix D:4. Average ground surface temperature model for the month of April displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



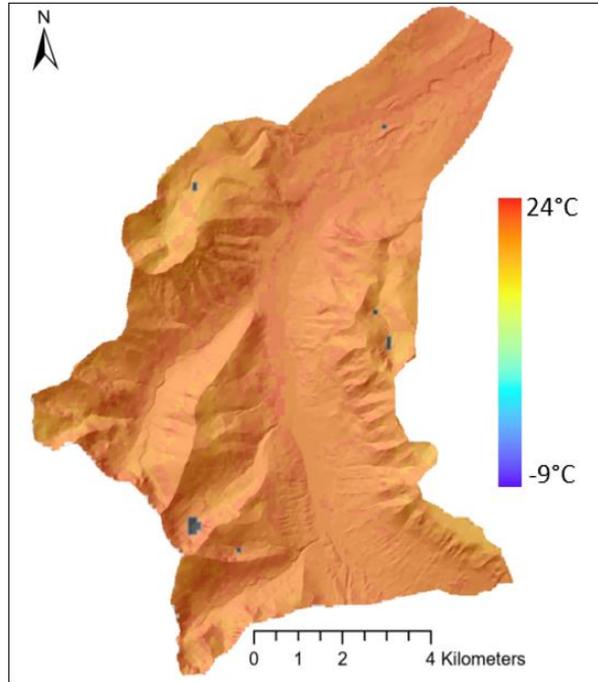
Appendix D:5. Average ground surface temperature model for the month of May displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



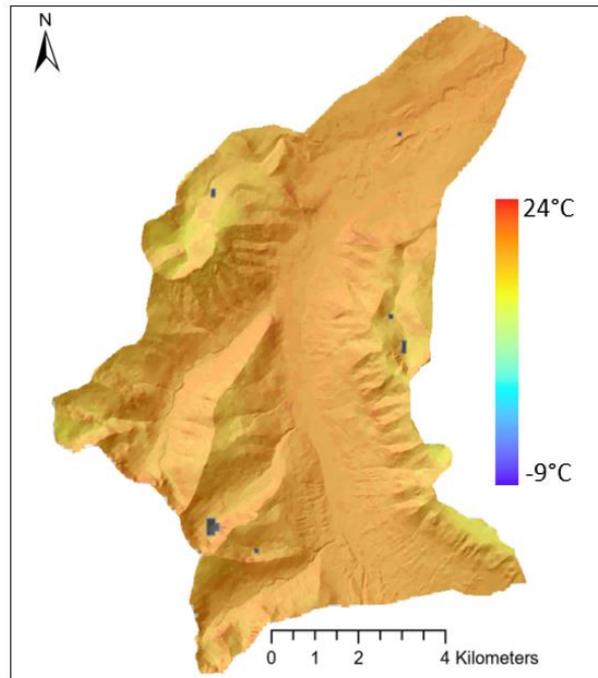
Appendix D:6. Average ground surface temperature model for the month of June displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



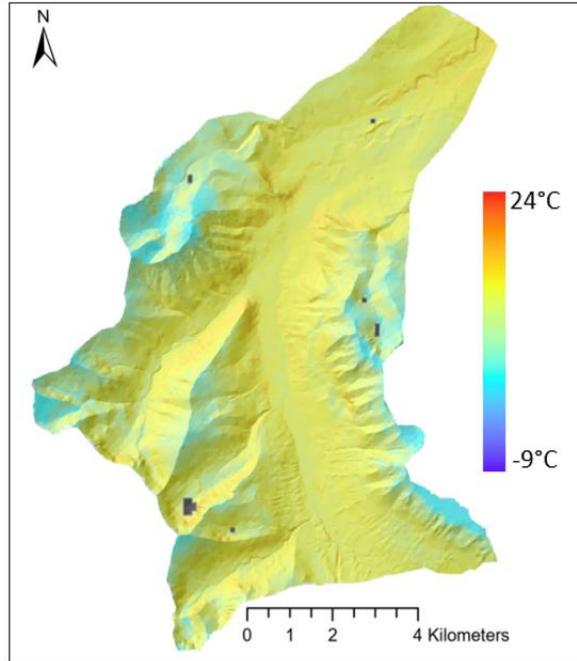
Appendix D:7. Average ground surface temperature model for the month of July displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



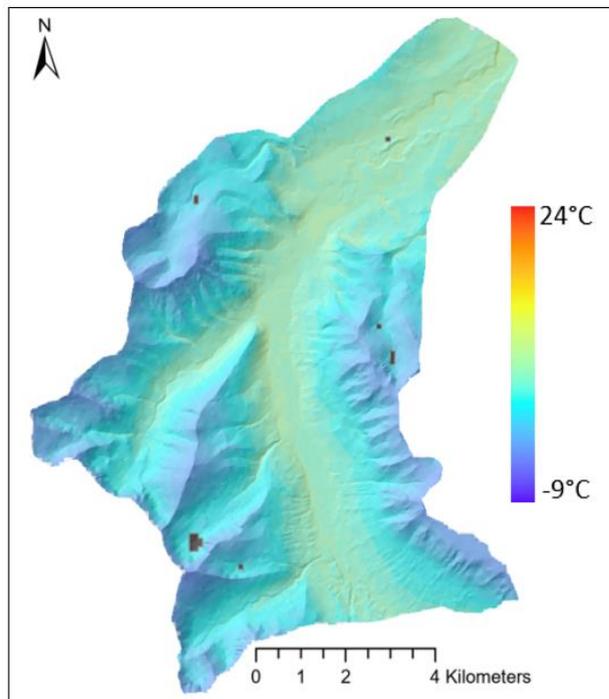
Appendix D:8. Average ground surface temperature model for the month of August displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



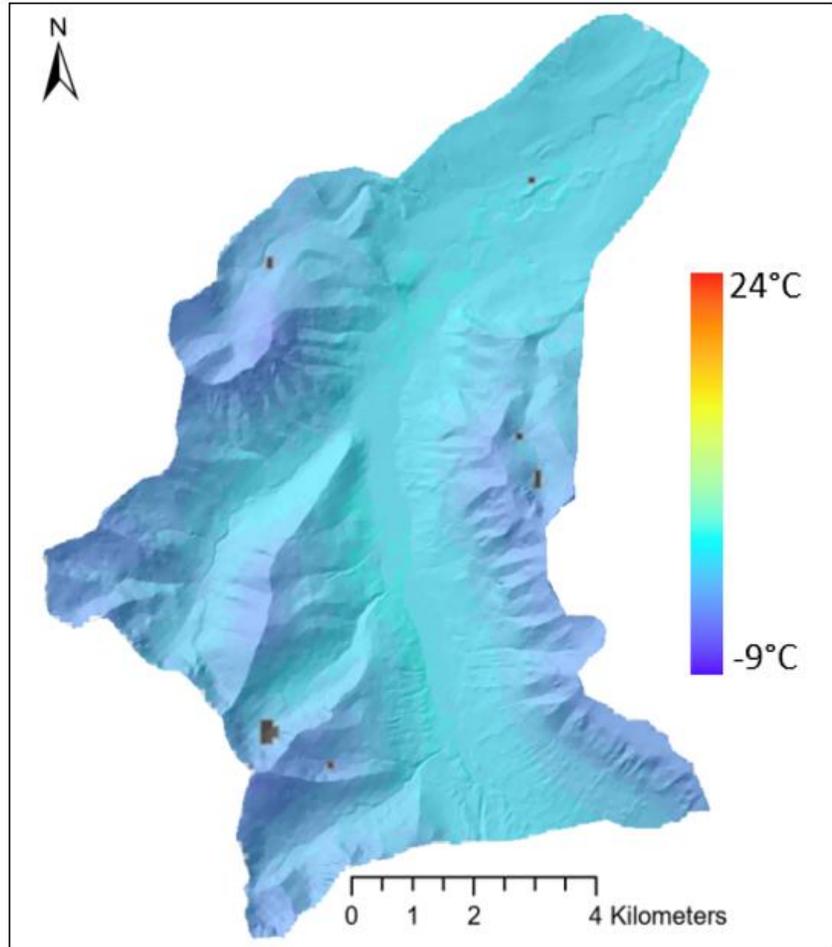
Appendix D:9. Average ground surface temperature model for the month of September displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



Appendix D:10. Average ground surface temperature model for the month of October displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



Appendix D:11. Average ground surface temperature model for the month of November displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.



Appendix D:12. Average ground surface temperature model for the month of December displayed using a universal temperature scale while viewed underneath a Hillshade layer at 50% transparency to highlight topographic features.