

Air and surface temperature modelling across a temperate mountain landscape: An investigation of microclimatic influences on surface offsets viewed within the context of epigaeic arthropod thermal habitat

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Funding information / Financement de la recherche
Natural Sciences and Engineering Research Council of Canada

Abstract

Development of high-resolution temperature models in mountain environments must include consideration of the influence of complex topography and seasonality on thermal distribution across horizontal and vertical scales. Small-bodied organisms, including arthropods, in montane and alpine ecosystems inhabit environments for which local microclimate and heat transfer is especially important. We developed and applied high-resolution air and surface temperature models for a remote mountain environment using in-situ data for interpolation procedures in ArcGIS Pro. This approach requires recording directional and time-period specific lapse rates to aid in the development of air temperature models. Also examined is the offset between air temperature and surface temperature and to what extent air temperature alone is a reliable indicator of ground-level thermal conditions. We describe an environmentally inclusive surface temperature modelling method that allows for the addition of explanatory layers (landcover, elevation, aspect, slope, and topographic position index) aiding in the interpolation process. These models are used to delineate thermally defined ecological zones and model unique thermal properties of relevance to arthropods across the southern Alberta study area.

Résumé

Le développement de modèles de haute résolution de température dans les environnements montagneux doit inclure une considération de l'influence de la topographie complexe et de la saisonnalité sur la distribution thermique à travers les échelles horizontales et verticales. Les organismes de petite taille dans les écosystèmes montagneux et alpins, y compris les arthropodes, vivent dans des environnements pour lesquels le microclimat local et le transfert de chaleur sont particulièrement importants. Nous avons développé et appliqué des modèles de haute résolution de températures de l'air et de la surface pour un environnement montagneux isolé en utilisant des données in situ pour les procédures d'interpolation dans ArcGIS Pro. Cette approche nécessite l'enregistrement de taux de déphasage directionnels et temporels spécifiques pour aider au développement de modèles.

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Le décalage entre la température de l'air et la température de la surface est également étudié afin de comprendre dans quelle mesure la température de l'air constitue à elle seule un indicateur fiable des conditions thermiques au niveau du sol. Par ailleurs, nous décrivons une méthode de modélisation de la température de surface qui tient compte de l'environnement et qui permet l'addition de couches explicatives (couverture du sol, élévation, etc.) aidant au processus d'interpolation. Ces modèles sont utilisés pour délimiter les zones écologiques définies thermiquement et pour modéliser les propriétés thermiques uniques pertinentes aux arthropodes dans le sud de l'Alberta.

KEYWORDS

basal temperature of snow, castle provincial park, epigeic arthropod, surface lapse rate, thermal modelling

Key messages

- The study is based on the collection of in-situ field thermal data over the course of one year in mountainous southern Alberta to examine potential arthropod habitat.
- Development of directional specific surface lapse rates aid in the development of air temperature models capable of accounting for the topographic influences on temperature in these regions.
- Air temperature alone in temperate mountain environments is often not a reliable indicator of surface temperature due to the offsetting properties of vegetation, snow cover, and small-scale topographic features.

INTRODUCTION

The development of high-resolution temperature models can provide useful insights into conditions experienced by local taxa (Fand et al., 2014; Kearney et al., 2021; Lactin et al., 1997). Elements of the thermal environment that predictive models should aim to describe in this context include the severity, duration, and frequency of thermal events experienced within an ecosystem (Bale, 1996; Ma et al., 2021; Sømme, 1996). Such information is crucial for understanding and predicting the emergence timing, distribution, growth, activity, fecundity, and survival of ectothermic taxa such as terrestrial arthropods (Dahlhoff et al., 2019; Delatte et al., 2009; Forrest & Thompson, 2011). Impacts of temperature on arthropods have been extensively tested, documented, and summarized in experimental studies and reviews (Bale & Hayward, 2010; Ohyama & Asahina, 1972; Wellington et al., 1999). However, much of this work has been based on controlled laboratory settings. Thus, they are possibly poor representations of the natural world as they fail to account for behavioural adaptations of arthropods to influence body temperature (Lactin et al., 1995; Lactin & Johnson, 1997, 1998a, 1998b).

The availability of environmental heat has the potential to profoundly impact the life history traits, behaviour, physiology, and survival of poikilothermic taxa (Bale & Hayward, 2010; Lactin & Johnson, 1998a; Ma et al., 2021; Sinclair & Chown, 2005). Several biophysical and mathematical models have been developed to describe the non-linear response of arthropod development rates to increasing temperatures (Lactin et al., 1995; Logan et al., 1976; Rebaudo & Rabhi, 2018; Sharpe & DeMichele, 1977). This relationship between arthropods and heat becomes more complex when discussed in the context of mountain environments. Here additional variation in environmentally available heat is greatly influenced by the inherent heterogeneity of regional topographic and ecosystem composition that exists across short horizontal distances (Dahlhoff et al., 2019; Sømme et al., 1996). Furthermore, when discussing the relationship between arthropods and heat, it is important to be mindful of scale. Individual arthropods interact with their environment uniquely; thus, it is imperative to understand the role that microclimate formation can play on individual organisms' experiences (Wellington et al., 1999).

Recent advances have been made with regard to modelling microclimatic impacts (including temperature) on ectothermic taxa (Briscoe et al., 2023). For example, NicheMapR (Kearney et al., 2021) is a quasi-mechanistic program capable of creating high resolution spatial models of microclimatic forcings (e.g., temperature, moisture). A useful feature of this tool is that it can also be paired with known physiological attribute data for desired species to determine habitat suitability. NicheMapR was originally developed to investigate temperature influences on reptiles in Australia. The model, however, has been further refined to be compatible with a variety of organisms including epigeic arthropods (Tomlinson, 2020). However, NicheMapR can require robust input datasets and a well-defined, predictable set of parameters (Kearney et al., 2021).

Unfortunately, in the context of arthropods in mountain environments, much of this spatial and biological input data is largely unavailable or difficult to collect on a meaningful spatial scale. Additionally, the impact of specific environmental parameters (e.g., elevation, aspect, topographic position index) on surface temperatures is difficult to define due to insulative surface offsets from snow, vegetation, and local topography (Goodrich, 1982; Haeberli, 1973; Sinclair et al., 2001).

In the context of modelling temperature in remote mountain environments, software options (e.g., Climate NA, Globesim, MT-CLIM) have been developed which can create estimates of temperature in data limited regions (Cao et al., 2019; Hirata et al., 2020; Wang et al., 2016). This is done either by estimating the amount of incoming shortwave solar radiation received at a location over a specified period (Hirata et al., 2020; Kienzle, 2011) or by using a simulation-based modelling approach to produce estimates of expected atmospheric conditions (Cao et al., 2019; Wang et al., 2016). However, these products are again limited in their ability to account for surface offsets which can provide shelter for epigeic invertebrates (Goodrich, 1982; Ma et al., 2021; Sinclair et al., 2001; Sømme et al., 1996). The influence of vegetation and topography on microclimate formation in Alberta was recently investigated by Estevo et al. (2022), although this study excluded Alberta's mountainous regions from their analysis due to the inherent complexities.

The purpose of this study was to investigate the spatiotemporal distribution of thermal profiles across a temperate mountain range in southern Alberta, which allowed the data to be contextualized in a manner relevant for local populations of epigeic arthropods. This required developing high resolution temperature models on both horizontal and vertical scales to account for the influences of vegetation, substrate, topography, and snowpack on surface offsets (Cartwright et al., 2020; Goodrich, 1982; Ma et al., 2021; Shur & Jorgenson, 2007). As a result, our model served as an alternative method for modelling surface-level thermal events and interactions with greater accuracy compared to existing practices which heavily rely on air temperature measurements (Lembrechts et al., 2019). This was accomplished via the development of a new interpolation-based modelling procedure in ArcGIS Pro v. 2.9.1 from *in-situ* temperature measurements. This methodology produced six thermally defined ecoregions with unique thermal conditions relevant for epigeic arthropods.

STUDY AREA

Castle Provincial Park and Castle Wildlands Provincial Park include a 1,050 km² protected area in the southwestern portion of Alberta (Alberta Environment & Parks, 2018). Fieldwork and analysis for this project was confined to an 87-km² subsection of the West Castle Watershed where weather data recording stations could be installed and accessed via local hiking routes (Figure 1). The unique topography of the park includes steep mountainous peaks and glacially carved valleys that span an elevational gradient from 1,332 m to 2,632 m asl (Alberta Environment & Parks, 2018). Foothill regions are scattered throughout the lowlands of the park, forming intact grassland corridors that connect to the prairies east of the park boundary. Lower elevation woodlands provide a moist, cooler environment compared to the foothills which then extend upward to elevations near 2,200 m before giving way to loose shale where bryophytes and varieties of alpine wildflowers serve as the dominant forms of vegetation. Meteorological conditions within the park are influenced by the region's continental location, northern latitude, and mountainous topography, which is indicative of the eastern slopes of the Canadian Rockies (Cullen & Marshall, 2011; Forbes et al., 2011). Atmospheric temperatures at the lower elevations range from 37.2°C to -38.2°C annually, and average annual precipitation is 679.8 mm/year. (Alberta Climate Information Service, 2020; Environment and Natural Resources, 2024).

METHODS

Air and surface temperature data collection

Hourly air and surface temperature data were recorded using Onset HOB0 MX2301 or MX2305 wireless temperature data loggers ($\pm 0.2^\circ\text{C}$ accuracy between -40°C and 70°C) apart from six surface temperature sensors (manufactured by Maxim Integrated), which are part of a long-standing network of iButton loggers ($\pm 1^\circ\text{C}$ accuracy between -40°C and 85°C). The iButton temperature loggers had not been serviced for several years and data was rolling over, but these units were able to be used to opportunistically bolster sensor locations chosen to capture heterogeneity across elevation, aspect, and ecoregion (Figure 1). Air temperature loggers were all secured within radiation shields (Onset Hobo RS1) to protect them from direct sunlight and weather. Air temperature recording units were fastened to the downslope side of trees at a height of ~ 2 m to ensure the units would not be buried under snow during the winter. In the absence of trees, radiation shields were fixed to T-bar posts secured using cables and metal spikes. Weather recording infrastructure used for this project was operational for one year (from summer of 2020 to summer of 2021). Hourly air temperature data during this time was also exported from two Alberta Climate Information Service (ACIS) weather stations, Castle Auto and West Castle (Alberta Climate Information Service, 2020) (Figure 1).

Surface temperature loggers were placed directly underneath corresponding air temperature loggers at 13 locations to measure surface offsets. A surface offset is the temperature of the ground surface minus the temperature in the air (Smith & Riseborough, 2002). This metric is

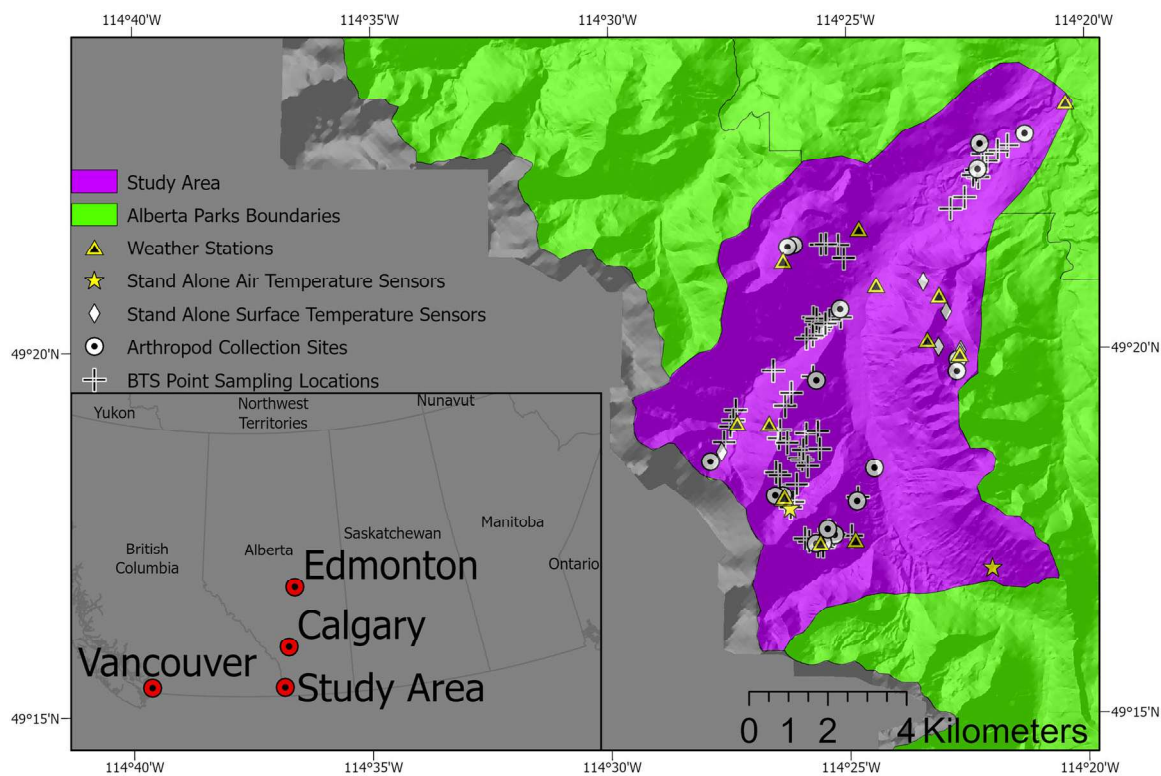


FIGURE 1 The location of the 87-km² study area which bridges Castle Provincial Park and Castle Wildlands Provincial Park. The map is displayed underneath a hill shade layer at 70% transparency to highlight regional topography.

widely used to understand the seasonal insulating properties of snow and vegetation on variable areas (Goodrich, 1982; Way and Lewkowicz, 2018). Surface offsets were measured in various different ecosystem types (forested, grassland, alpine) situated within different topographic position indices, aspects, and elevations. Accompanying these paired air and surface temperature recording sites were an additional set of 23 stand-alone surface temperature loggers to increase the spatial resolution of the network. This allowed for surface offsets to be determined using either measured air temperatures or modelled air temperatures at locations where surface loggers were installed. All surface loggers were buried under the soil at a depth of 2–5 cm and marked with an orange stake to ensure they could be found the following year (Garibaldi et al., 2021; Vegter et al., 2024).

Winter surface temperature measurements recorded by HOBO loggers were further supplemented by the collection of Basal Temperature of Snow (BTS) point measurements (e.g., Bonnaventure et al., 2012). BTS point sampling was employed at locations accessible by snowshoeing trails, cross-country skiing routes, and terrain accessible via chairlifts operated by Castle Mountain Resort. BTS point sampling methodology followed established protocols described by Bonnaventure and Lewkowicz (2008) and Bonnaventure et al. (2012). A total of 59 BTS point measurements were taken at representative locations throughout Castle Provincial Park during the late winter months of 2020 and 2021, respectively. Spacing of at least 200 horizontal meters between sampling was maintained to avoid spatial autocorrelation (Brenning et al., 2005).

Data processing and analysis

Creation of average air temperature models

Hourly air temperature readings from weather stations were used to calculate thermal attribute values at each respective site. The lowest elevation air temperature recording station in the study area was the ACIS site, Castle Auto. This site was located at 1,351 m asl in an open region of the park that made for an ideal base location for calculating Surface Lapse Rates (SLRs) as it is near the bottom of the elevational range of the study area and the impacts of microclimatic forcings are limited (Bonnaventure et al., 2012). SLRs were calculated for North (SLR_N), East (SLR_E), South (SLR_S), and West (SLR_W) vertical rises based on the differences in recorded air temperatures at upper-elevation stations compared to Castle Auto over specified time periods. SLRs for Northeast, Southeast, Southwest, and Northwest orientations were calculated by averaging the measured lapse rates recorded by stations facing primary cardinal directions (e.g., Northeast, SLR_{NE}, was determined from the average

TABLE 1 Average surface lapse rates measured in Castle Provincial Park from summer 2020 to summer 2021. Results are broken down by slope orientation and month and are reported in °C km⁻¹.

Aspect	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
SLR _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
SLR _{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
SLR _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
SLR _{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
SLR _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
SLR _{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
SLR _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
SLR _{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
SLR _{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

between SLR_N and SLR_E). SLRs for areas with flat orientations (mountain peaks, valley bottoms, and alpine benchlands) were calculated by averaging the lapse rate values across all eight possible orientations (Table 1).

The development of these aspect-specific and time-period-specific SLRs allowed for the creation of an adjusted elevational air temperature model (e.g., Lewkowicz et al., 2012). This was achieved as average recorded temperatures at high mountain weather stations were altered using SLRs to mimic that of a uniformly flat environment existing at 1,337 m asl (Lewkowicz & Bonnaventure, 2011). SLR-adjusted temperature readings then served as the basis for the creation of various interpolated surfaces along this flat plane, allowing for temperature estimations to be made across the entire study area. Once interpolated air temperature surfaces had been created, influences of topography on modelled air temperatures were then re-introduced (e.g., Etzelmüller et al., 2007; Lewkowicz et al., 2012) by applying geo-specific SLRs in the digital elevation model (DEM).

Interpolation procedures and the subsequent creation of average air temperature models via the application geo-specific SLRs in the DEM was achieved in ArcGIS Pro. A variety of interpolation methods (Nearest Neighbor, Inverse Distance Weighting, Kriging, Empirical Bayesian Kriging, and Spline) were tested to see how they impacted the accuracy of final model outputs for every period of interest. This was done by extracting temperature values generated by the model for locations where air temperature sensors were present and calculating the Root Mean Squared Error (RMSE) between modeled and measured temperatures across the logger network (Chai & Draxler, 2014). Errors (measured temperature - modeled temperature) at locations of logger stations were squared, then summed, and the square root value of the summed product was reported. Inverse Distance Weighting (utilizing an optimized power function calculated by the Geostatistical Wizard) provided the most accurate results in finalized average air temperature models for most months of the year as well as the Annual Mean Air Temperature (AMAT) model. Empirical Bayesian Kriging, however, produced more accurate results for air temperature models in February, March, April, and November.

Creation of surface temperature models and delineation of thermally defined environments

Average surface temperature models are the product of interpolated surfaces derived from *in-situ* data recorded at logger stations. The input point measurement data for January, February, March, and December models was bolstered via the inclusion of 59 BTS point measurements. The interpolation method used to create these models was Empirical Bayesian Kriging (EBK) Regression, in the Geostatistical Wizard. EBK Regression provided more accurate estimates (verified by calculating RMSE between modelled values vs measured values) than Inverse Distance Weighting, Kriging, or 3D Kriging. EBK Regression, which allows for the inclusion of other layers in the GIS as explanatory layers to aid interpolation process, can be thought of as a hybrid between EBK Regression and linear regression (Krivoruchko & Gribov, 2019). The explanatory variables included in our interpolation analysis were elevation, aspect, slope, topographic position index (TPI), as well as a landcover classification. All these variables are DEM-derived, apart from landcover which was sourced from a 100 m × 100 m landcover classification file provided by Agriculture and Agri-Food Canada (Agriculture and Agri-Food Canada, 2008). Landcover values were simplified using "Reclassify" in Arc GIS Pro to match classifications observed in the field. These categories included values for water bodies, grassland and alpine, forest, or exposed rock.

The creation of surface temperature models allowed for the delineation of thermally defined environments based on modelled annual mean ground surface temperature (AMGST) and landcover classification. Grassland regions below 1,700 m asl were classified as lower elevation

grasslands (LEG). Likewise, forested regions below 1,700 m asl were classified as lower elevation woodlands (LEW). Forested regions above 1,700 m asl with an AMGST above 4.0°C were classified as upper-elevation forested – warm (UEFW). Areas with an AMGST below 4.0°C were classified as upper-elevation forested – cold (UEFC). Alpine areas above treeline with an AMGST above 4.7°C were classified as upper-elevation alpine – warm (UEAW), while areas with an AMGST below 4.7°C were classified as upper-elevation alpine – cold (UEAC). Threshold temperatures of 4.0°C and 4.7°C were chosen as these values evenly distributed upper-elevation surface temperature loggers between warm and cold habitat types. This allowed for a suitable number of replicate sites (minimum six sites) to be used to assess thermal properties of high mountain habitat as they relate to epigeic arthropods.

Relevant climatic conditions for epigeic 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 epigeic arthropods. Statistics originate from field-recorded measurements and are reported based on environment type. Minimum estimated days without snow cover was calculated based on the determination of snowpack establishment and a snowpack melt date. 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.

The effect of temperature on epigeic arthropods during the growing season was based on the relationship between temperature and arthropod development rate as described by Lactin et al. (1995). Assuming development rate had a linear response to temperature, a growing degree day model was employed to quantify suitability of habitat for lifecycle progression. The “(max + min)/2 – threshold” method was utilized to calculate growing degree days in conjunction with threshold temperatures of 5°C, 8°C, and 10°C (Herms, 2004). Additionally, average surface-level offset within each environment type was established.

RESULTS

Air temperature analysis and modelling

Recorded average SLRs at every cardinal direction from summer 2020 to summer 2021 can be found in Table 1. Average SLRs ranged from $-9.44^{\circ}\text{C km}^{-1}$ to $-0.20^{\circ}\text{C km}^{-1}$. The strongest average SLRs were observed in November ($-8.63^{\circ}\text{C km}^{-1}$ average across all aspects), while the weakest occurred in July ($-2.34^{\circ}\text{C km}^{-1}$ average across all aspects). The greatest average SLRs were recorded along north-facing slopes ($-6.26^{\circ}\text{C km}^{-1}$ annual average), while the weakest were recorded along south-facing slopes ($-5.13^{\circ}\text{C km}^{-1}$ annual average). Finally, the average SLR recorded across eight cardinal directions for the annual sample period was $-5.76^{\circ}\text{C km}^{-1}$.

Modelled average monthly air temperature values ranged from -15.00°C in February to 19.40°C in July, while modelled AMAT values ranged from -2.34°C to 5.74°C , respectively (Figure 2). The average AMAT for the entire study area was 3.05°C , and the AMAT model yielded a RMSE value of 0.14°C . Average RMSE for monthly air temperature models was 0.21°C as the month with the largest RMSE value was November with a value of 0.68°C , while August saw the smallest RMSE value of 0.07°C . When viewed over the course of the entire year, monthly air temperature models did not statistically differ from field measured values (T-Test $(179) = 2.07$, $p = 0.0005$).

Surface temperature modelling

AMGST values at 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 the coldest station (WS 5) averaged -12.16°C . Conversely, the warmest month at the surface was July as the mean average surface temperature across all stations was 14.61°C , while the warmest station (WS 9) averaged 21.15°C . 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 on monthly as well as annual time scales. Results from February, July, and the annual model are displayed in Figure 3. Modelled average monthly surface temperature values ranged 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 and the AMGST model yielded an 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.

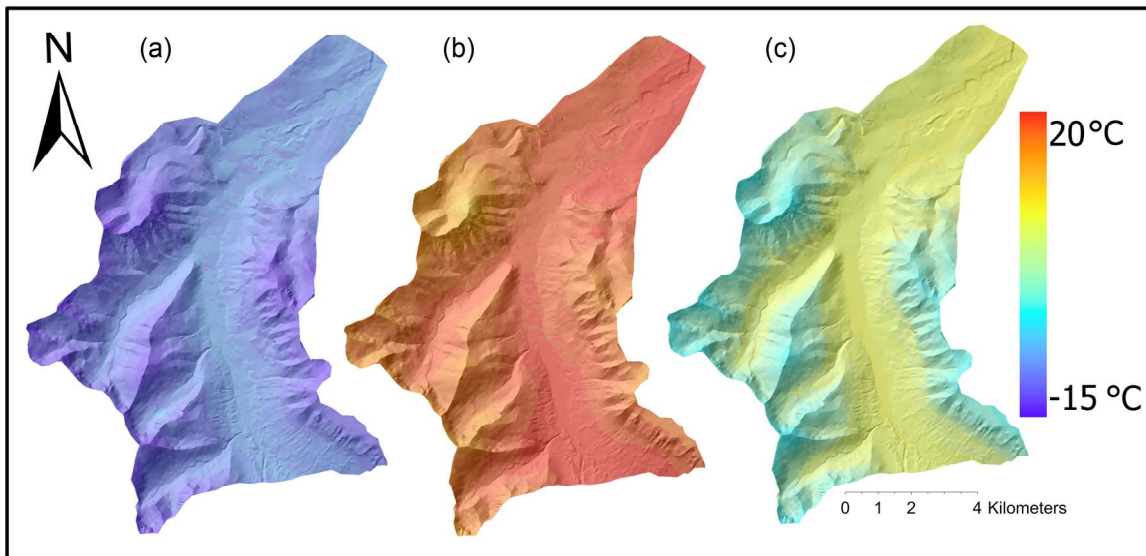


FIGURE 2 Average air temperature models viewed underneath a Hillshade layer at 50% transparency: a) the coldest month (February); b) the warmest month (July); c) the annual model.

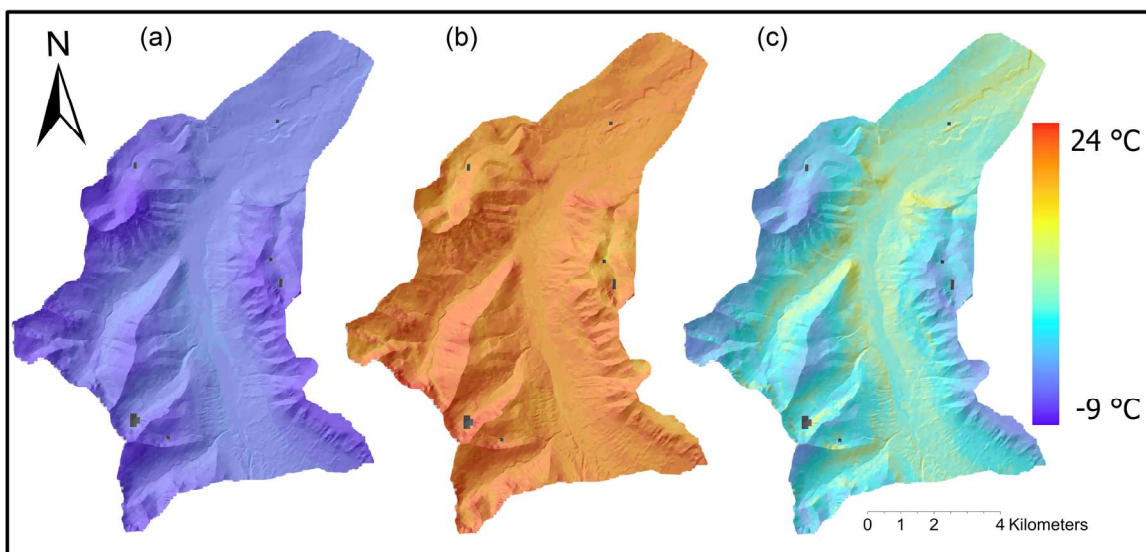


FIGURE 3 Average surface temperature models viewed underneath a Hillshade layer at 50% transparency: a) February; b) July; c) the annual model. Black cells represent bodies of water.

Overall average RMSE for monthly surface temperature models was 1.34°C. When viewed over the course of the entire year, monthly surface temperature models did not statistically differ from field measured values (T-Test₍₆₆₇₎ = 0.05, $p = 0.03$).

Surface offsets

Surface offsets were determined at 36 surface temperature recording locations. Positive offsets indicate colder ground and warmer air while negative offsets indicate warmer ground and colder air. Average monthly surface offsets ranged from 8.55°C to -14.29°C. July had the most positive surface offsets, averaging at 2.50°C across all stations. February had the most negative surface offsets, averaging at -11.03°C across all stations (Figure 4). The month with the least intense surface offsets was August with an average value of 0.28°C. On an annual scale, the average surface offset was -1.42°C across all 36 sites. Average surface offsets within each environment type for every month of the year are reported in Table 2.

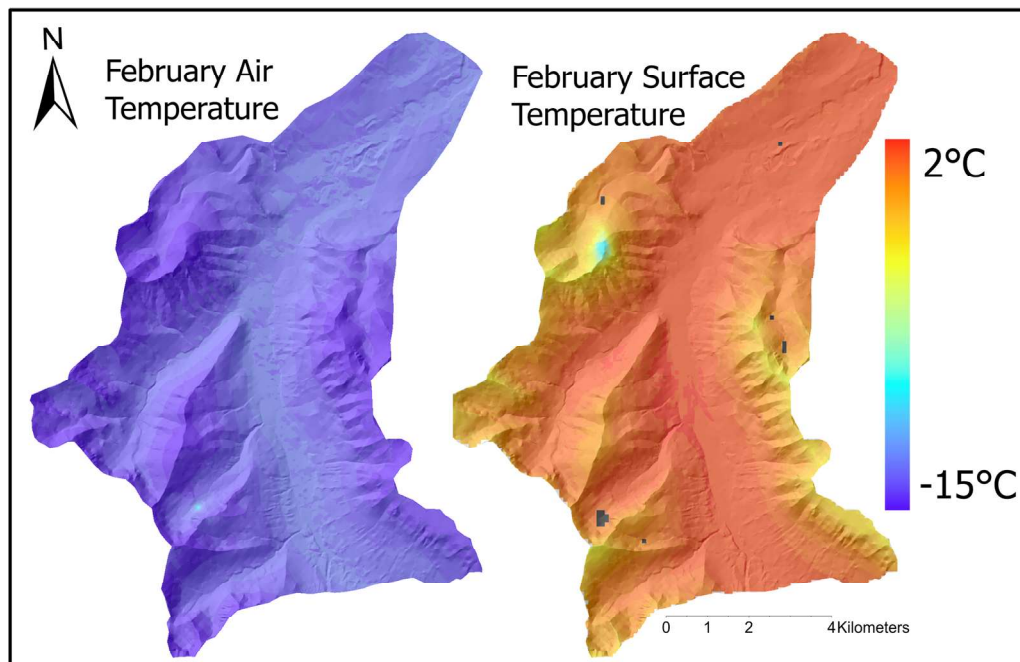


FIGURE 4 Average air and surface temperatures for the month of February underneath a Hillshade layer at 50% transparency. Black cells represent water bodies.

TABLE 2 Average surface offsets recorded within different environment types. Where LEG represents lower elevation grassland environments, LEW represents lower elevation woodland environments, UEFW represents upper-elevation forested – warm environments, UEFC represents upper-elevation forested – cold environments, UEAW represents upper-elevation alpine – warm environments, and UEAC represents upper-elevation alpine – cold environments. UEFW and UEFC environments are categorized based upon mean annual ground surface temperature above or below 4.0°C while UEAW and UEAC environments are categorized based upon mean annual ground surface temperature above or below 4.7°C. All values are average offsets in °C for the respective months.

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

Thermal environment modelling

Maps depicting thermal environment coverage in the study area are shown in Figure 5. Lower elevation (below 1,700 m asl) grasslands (LEG) and woodlands (LEW) covered 49.80% of the study area in Castle Provincial Park (42.69 km²). Upper-elevation environments were distinguished by landcover type and AMGST. As much as 27.61% of the study area was comprised of upper-elevation alpine regions with an AMGST below 4.7°C (UEAC) while regions above this temperature threshold (UEAW) accounted for 8.91% of the area. The smallest environment in the study area was upper-elevation forested sites with an AMGST above 4.0°C (UEFW) which only accounted for 6.52% of the study area (Figure 5).

Thermal distribution relevant to the success of epigeic arthropods

Climate statistics relevant to the overwinter survival and general lifecycle progression of epigeic 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

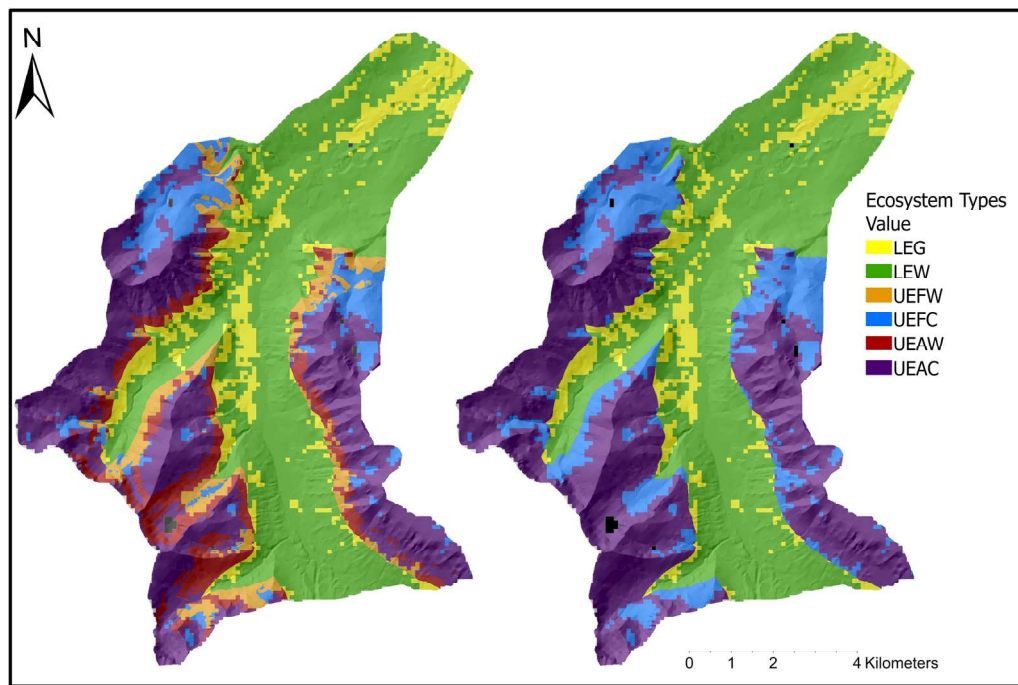


FIGURE 5 Surface-level thermal environment coverage within the defined study. Left represents environment coverage based on annual mean ground surface temperature values. Black cells represent water bodies. Right represents environment coverage based on annual mean air temperature values.

value at 1.9°C. The warmest AMGST recorded in Castle Provincial Park during our sampling period was 7.03°C and the coldest was -0.09°C. Minimum recorded surface temperatures also varied across different environment types, with one UEAC site reaching -21.17°C on 13 February 2021, while the coldest any UEFW site reached was -1.33°C on 20 September 2020. The coldest air temperature readings at these sites both occurred on 11 February 2021. 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 (8 June 2020 to 12 October 2020), which was 67 days shorter than the shortest estimate recorded at any LEG site (26 March 2020 to 13 November 2020). 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 environments, with the most unstable site only registering seven cycles. UEFW and UEAW sites saw much greater fluctuations in surface-level temperature during the shoulder seasons as each environment type has sites recording 45 freeze-thaw cycles within the same 1-year sample period.

The average number of positive growing days recorded over a consecutive 365-day period within each thermal environment classification are reported in Table 4. Similarly, growing-degree days were computed for a weather station in each respective thermal environment classification using both air and surface temperature measurements.

DISCUSSION

The significance of surface offsets in thermal modelling

Recent advancements in climate modelling software (e.g., Climate NA, GlobSim, MT-CLIM, NicheMapR) can require robust input datasets for model development. Those, however, that have been designed to address questions in remote (data-limited) environments largely rely on simulated atmospheric conditions as a metric to establish estimates for surface-level conditions (Cao et al., 2019; Hirata et al., 2020; Wang et al., 2016). Moreover, the bulk of primary literature that addresses high resolution air and surface temperature modelling across mountainous terrain focuses on arctic and sub-arctic regions to address questions related to the persistence of glaciers and permafrost (Bonnaventure et al., 2012; Noad & Bonnaventure, 2024). These methods unfortunately do not translate well in the context of modelling surface temperatures in temperate mountain environments. This is due to the annual thaw of surface components that possess a far greater capacity to store and redistribute heat compared to frozen substrates, contributing to surface offsets that result in a disconnect between atmospheric conditions and surface conditions (Haeberli, 1973; Harris & Pedersen, 1998; Sinclair et al., 2001). Prior thermal modelling work in the province of Alberta has

largely been concerned with agricultural regions. Non-agricultural works are often large-scale products which do not account for the influences of small-scale microclimates or omit the mountainous regions of the province from their analysis due to the inherent complexities associated with modelling temperatures (Estevo et al., 2022; Kienzle, 2017).

Current climate variable modelling products model values for environmental parameters based off defined relationships, such as the impact that a set amount of incoming solar radiation will have on air temperature. However, surface offsets in temperate mountain environments constantly cloud the influence of environmental parameters on surface temperatures (e.g., lapse rates). The magnitude of these offsets (largest recorded offset was 43.03°C) was observed to be in a constant state of flux due to the influences of seasonality and regional topography, making it difficult to accurately define the impact of any one individual environmental parameter (e.g., elevation) on surface temperature. As a result, interpolation of known surface temperatures aided by the incorporation of explanatory layers was the most logical means of creating surface temperature models for the Castle region of Alberta.

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 from summer 2020 to summer 2021. Spatial and temporal variability in air temperature was captured by our models via the incorporation of aspect and time-period specific lapse rates (Lewkowicz et al., 2012; Lewkowicz & Bonnaventure, 2011; Rolland, 1977). This expands on the work by Lewkowicz et al. (2012) and others by demonstrating the utility of this method for developing air temperature models for temperate, non-permafrost environments. While there is a certain causal relationship between air temperature and surface temperature, the reliability of air temperature to serve as an accurate indicator of surface temperature was observed to be highly variable. Surface offsets were frequently observed between paired air and ground temperature sensors because landcover, aspect, slope, and TPI largely determined the capacity for snow retention and exposure to direct sunlight (Cartwright et al., 2020; Goodrich, 1982; Hiemstra et al., 2002). Regions with sufficiently deep snow cover (above 80 cm) and complex vegetation structures largely experienced comparatively more stable and moderate surface conditions due to the insulating properties of snow and the release of latent heat via the freezing of subsurface water (Bonnaventure & Lewkowicz, 2008; Goodrich, 1982; Haeberli, 1973).

Our approach to modelling surface temperatures needed to account for landcover, slope, aspect, and TPI as principal forcings contributing to surface offsets capable of muddying the influence of SLRs. This was achieved in our modelling process by using *in-situ* surface temperature measurements as base data for a regression algorithm (EBK Regression) that incorporated DEM-derived layers and a landcover layer as explanatory variables to aid in interpolation (Krivoruchko & Gribov, 2019). The success of modelling via this method largely hinged upon the locations of loggers and BTS point measurements to provide temperature data at a spatial resolution that was adequate for the study area and captured the heterogeneity present within the natural environment (Bonnaventure & Lewkowicz, 2008; Brenning et al., 2005). Creation of models using this method contributes to the work of Bonnaventure and Lewkowicz (2008), Etzelmüller et al. (2007), and others by demonstrating the utility of BTS sampling and the use of *in-situ* measurement for surface temperature modelling in temperate mountain environments. Though *in-situ* sampling and model development via this method can be more resource-intensive than remote sensing alternatives, access to precise measurements at locations of interest was necessary to develop our understanding of the exact conditions experienced by taxa inhabiting these environments.

Model performance in the context of determining thermal suitability for mountain arthropods

Regional topography and landcover significantly impacted the distribution of heat across our study area. As a result, the thermal biological characteristics required for survival of epigeic arthropods varied across different thermally defined ecoregions as described in Tables 3 and 4

TABLE 3 Climate statistics relevant to the overwinter survival and lifecycle progression of surface-dwelling arthropods broken down by environment classification. Results are reported in °C.

Environment Classification	Average AMGST (°C)	Max AMGST (°C)	Min AMGST (°C)	Min Surface Temp (°C)	Max Surface Temp (°C)	Minimum Estimated Days Without Snow Cover (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
LEW	4.85	5.62	3.90	-4.64	28.00	114.00	56.63	7
UEFW	5.06	6.10	4.09	-1.33	51.18	119.00	101.25	36
UEFC	3.19	3.89	2.11	-5.58	31.49	107.00	156.38	45
UEAW	5.28	6.57	4.82	-10.21	46.00	134.00	126.33	45
UEAC	1.90	4.70	-0.09	-21.17	30.00	125.00	214.83	27

TABLE 4 Average number of net growing days (per year) recorded within each thermal environment type using 5°C, 8°C, and 10°C as threshold temperatures.

Environment 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

(Bale, 1991, 1996; Lactin et al., 1995; Marshall & Sinclair, 2015). This was described as a function of the severity, duration, and frequency of exposure to cold as well as the intensity and stability of thermal conditions during the growing season. It is well known that temperature can determine the success of arthropods as it impacts the emergence timing, growth and development, dispersal, fecundity, and mortality of these poikilothermic taxa (Bale & Hayward, 2010; Nealis, 2020; Wellington et al., 1999). The collection of *in-situ* data allowed us to record these thermal parameters of interest at several locations within thermally defined eco-regions. Through our modelling procedure, it could be determined how heat relevant to the success of epigaeic arthropods was spatially distributed across a temperate mountain environment. Amongst our thermal ecosystem classifications, snow retention varied by as much as 158 days, lowest experienced temperature by 19.84°C, number of freeze-thaw cycles experienced per year by as many as 38 cycles, and the average number of growing degree days (above 5°C) by 65 days. While multiple factors have the capacity to influence the abundance and distribution of arthropods (e.g., soil characteristics, cover, food availability, moisture), in mountain environments, thermal suitability is yet another factor that must be considered when predicting the success and survival of these species (Dahlhoff et al., 2019; Sinclair et al., 2001; Sømme et al., 1996).

Uncertainty and future directions

The thermal models described in this study demonstrate the need to account for the scale at which temperature can fluctuate. This illustrates the importance of accounting for surface offsets when attempting to describe conditions experienced by surface-dwelling taxa (Goodrich, 1982; Sinclair et al., 2001; Tomlinson, 2020). *In-situ* data used to develop temperature models were based on a single year of field-collected data. This was due to a lack of historical weather data available for this region, and a lack of regional climate model development at the spatial resolution required to capture surface-level microclimatological variability (Alberta Climate Information Service, 2020; Ernakovich et al., 2014; Kienzle, 2017). Access to longer record datasets spanning several years would improve the overall accuracy and predictive capability of these models, allowing for better description of the impacts of microclimates on the success of local taxa. Furthermore, the development and incorporation of additional layers that account for environmental variables of consequence for species of interest (e.g., moisture, soil classification, availability of coarse woody debris) provides an opportunity to further refine habitat suitability models for arthropods, amphibians, plants, and other taxa found at the surface level in remote mountain environments.

CONCLUSIONS

Thermal conditions across heterogeneous mountain terrain vary temporally and spatially across both horizontal and vertical scales. The development of directional and time-period specific surface lapse rates can aid in the development of air temperature models capable of accounting for the topographic influences on temperature in these regions. However, air temperature in temperate mountain environments is often an unreliable indicator of surface temperature due to the offsetting properties of vegetation, snow cover, and small-scale topographic features. These surface offsets can result in completely different seasonal or annual temperature regimes at the ground surface compared to the air. Although this is well understood, habitat models for many species do not consider this critical offset for either present or predicted thermal habitat mapping. To account for these insulating properties when modelling surface temperature, our approach details the importance of *in-situ* measurements from a spatially balanced network that is representative of regional heterogeneity as well as the development and incorporation of explanatory layers (elevation, aspect, slope, topographic position index, landcover, and others) to aid in the interpolation process. Development of high-resolution surface temperature models for remote mountainous terrain is important as it

allows us to better define how this critical element of the environment is impacting arthropods, amphibians, and plants which form the basis for these ecosystems.

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How to cite this article: Hassink, N., Bonnaventure, P. P., & Johnson, D. L. (2025). Air and surface temperature modelling across a temperate mountain landscape: An investigation of microclimatic influences on surface offsets viewed within the context of epigeaic arthropod thermal habitat. *Canadian Geographies / Géographies canadiennes* 69 (1): e70003. <https://doi.org/10.1111/cag.70003>