Stream Thermalscape Scenarios for British Columbia, Canada

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Keywords: stream temperature, British Columbia, thermalscape, August mean temperature, freshwater habitat

Abstract

Water temperature is a key feature of freshwater ecosystems but comprehensive datasets are severely lacking, a limiting factor in research and management of freshwater species and habitats. An existing statistical stream temperature model developed for British Columbia, Canada, was refit to predict August mean stream temperatures, a common index of stream thermal regime also used in thermalscapes developed for the western US. Thermalscapes of predicted August mean stream temperature were produced for 680,000 km of stream network at approximately 400 m intervals. Temperature predictions were averaged for 20-year periods from 1981-2100 to produce 86 scenarios: one for each historical period (i.e., 1981-2000, 2001-2020), and 21 for each future period (i.e., six global climate models and an ensemble average under three representative concentration pathways). The final model performance was consistent with other published regional-scale statistical models (R^2 = 0.79, RMSE = 1.53°C, MAE = 1.18°C), particularly given the relative paucity of data, large geographic extent, and range of climatic and physiographic conditions. Model results suggested an average increase of August mean stream temperature of 2.9 ± 1.0°C (RCP 4.5 ensemble mean ± SD) by end of century, with significant heterogeneity in predicted temperatures and warming rates across the province. Compared to stream temperature predictions from the western US, the predictions for BC showed good agreement at cross-border streams (Pearson's r = 0.91), suggesting the possible integration of both products for a full western North America thermalscape. These stream thermalscapes for British Columbia address a major data deficiency in freshwater ecosystems and have potential applications to stream ecology, species distribution modelling, and evaluation of climate change impacts.

Introduction

Water temperature is a key factor in aquatic environments, affecting ecological, biological, and chemical processes (Angilletta 2009; Kingslover 2009), but available datasets are sparse, especially for entire stream networks. This situation represents a major data deficit in freshwater ecosystems, where the complexity inherent in freshwater systems (Ward 1989), and the accompanying heterogeneity of habitats (Poole 2002; Ward 1998), requires data at a large enough spatial extent to capture relevant catchment-scale processes and of a sufficiently high resolution for the scale of investigation (Torgersen et al. 2022). Stream temperature models (see reviews in Benyahya et al. 2007; Dugdale et al. 2017) can potentially address this deficit.

Stream temperature models generally fall along a spectrum spanning two distinct approaches: process-based and empirical (statistical/stochastic). Process-based models have the potential to account explicitly for the complex sets of catchment- and reach-scale hydrological and thermal processes that drive stream temperature variability in both time and space, including lateral and longitudinal advection and vertical energy exchanges at the stream and bed surfaces (e.g., Bosmans et al. 2022; Khorsandi et al. 2022; Larabi et al. 2022). However, process-based models require a substantial investment in model set-up and are computationally intensive, especially at regional and larger scales. Further, when applied over large regions, process-based models may lack the resolution for more fine-grained applications, especially in headwater reaches, where lateral advection via hillslope runoff can exert a major influence (Gallice et al. 2016; Leach and Moore 2017). Large-scale models typically parameterize rather than simulate headwater thermal dynamics (e.g., Sun et al. 2015), which can lead to inaccurate simulation at those scales (Leach and Moore 2015). This issue is important given that headwater reaches constitute a significant portion of the total channel length in stream networks (e.g., Gomi et al. 2002).

Empirical approaches include a range of model types, including site-specific regression models that relate stream temperature time series to air temperature (e.g., Mohseni et al. 1998), multiple regression models that relate the spatial patterns of a static stream temperature metric to catchment attributes and climatic variables (e.g., Moore 2006; Wehrly et al., 2009), and more complex models that simulate spatio-temporal variability at a regional scale (e.g., Jackson et al., 2018). In North America, the Northwest Stream Temperature (NorWeST) project (Isaak et al. 2017) is the gold standard for stream temperature monitoring and empirical modelling (https://www.fs.usda.gov/rm/boise/AWAE/projects/NorWeST.html). It consists of a large, centralized, quality-controlled database of stream temperature summaries collected from organizations and individuals across the western United States (US) (Chandler et al. 2016). Those data were then used to predict stream temperatures using spatial statistical network models that account for the unique spatial autocorrelation structure of hydrologic networks (Ver Hoef et al. 2006). Thermalscapes, which are continuous maps of mean August water temperature (AugTw) across the stream network, were produced for a range of historical and future time periods and climate scenarios (Isaak et al. 2016a). The model performance (R^2 = 0.91, RMSE = 1.10°C, MAE = 0.72°C; Isaak et al. 2017), spatial extent (western US), and resolution of the thermalscapes (1:100,000 scale stream network) has made them a useful tool for a wide range of user groups (Isaak et al. 2017). The broad use of NorWeST products underscores the value of this type of stream temperature dataset and the need for comparable products in other regions.

British Columbia (BC), Canada, does not have a province-wide dataset of continuous historic or future stream temperature predictions that is comparable to the NorWeST thermalscape scenarios (Isaak et al. 2016a). This lack is a major data deficit given the province's freshwater resources, which includes 2 million km of streams and rivers and over 700,000 lakes and wetlands (BC Freshwater Atlas), and the pressures of a warming climate (IPCC 2021), land use changes (e.g., deforestation), and human uses (e.g., water abstraction, hydro power generation) on the freshwater systems and species that they support. In addition to within-province applications, BC stream temperature predictions that are directly comparable to NorWeST could facilitate production of a thermalscape for much of western North America's stream network, overcoming the issues of (1) freshwater datasets restricted by political boundaries (Domisch et al. 2015a; Domisch et al. 2015b), and (2) artificially-bounded ranges used to assess and model species-environment relationships (Barbet-Massin et al. 2010; Domisch et al. 2015a).

Following the example of the NorWeST project to produce comparable thermalscapes for BC, while ideal, is not an expedient solution to the current lack of stream temperature predictions for the province. Stream temperature data in BC have typically been collected and maintained by individual user-groups (e.g., government agencies, professionals, community groups), and there is currently no central data repository for stream temperature observations in BC. Further, the necessary spatial datasets to run spatial statistical network models are lacking for BC, including both topologically conditioned stream network layers (Isaak et al. 2013) and important model covariates used in NorWeST, like groundwater influence and stream discharge. An alternative approach would be to use existing BC-specific stream temperature models to produce thermalscapes (e.g., Moore 2006; Moore et al. 2013); however, the thermal metrics predicted by these models are not directly comparable to NorWeST.

In light of current data limitations and the pressing need for stream temperature predictions, a previously developed statistical model for maximum weekly average temperature (MWAT; Moore et al. 2013) was refit to cover the provincial stream network and provide a full suite of projections under different climate change scenarios. Further, the model was updated to predict a different thermal metric, AugTw, to align with the NorWeST stream temperature predictions (Isaak et al. 2016a) and evaluate the potential of an integrated thermalscape product for western North America. The thermalscapes presented here for BC's stream network are the first in Canada and represent a major step forward for application in aquatic research and management.

Methods

Study area

The province of BC covers approximately 950,000 km^2, spanning 12° of latitude and a diverse range of climates, physiographic features, and ecological zones (Eaton and Moore 2010; Moore et al. 2010) (Figure 1, Table S1). Land elevations range from sea level to over 4,000 m, and include drainages for some of the largest rivers on the continent (e.g., Fraser, Columbia, and Mackenzie).

General overview

The MWAT statistical stream temperature model (Moore et al. 2013), hereafter referred to as the 'BC MWAT model', was selected as the foundation for developing BC thermalscapes for a number of reasons. First, the model was regionally appropriate; it was developed for BC using stream temperature observations from 418 stations across the province. Second, the *in situ* daily observations used to calculate MWATs were of sufficient duration and temporal resolution to calculate AugTw values and refit the model, hereafter referred to as the 'BC AugTw model'. Refitting the model to predict AugTw was necessary so predictions could be directly compared to the NorWeST thermalscapes (Isaak et al. 2016a). Finally, the spatial data layers required as inputs for the model and necessary to predict stream temperatures under future climate scenarios were available with sufficient temporal coverage and resolution for the study area.

Besides using a different thermal metric, the approach to refitting the BC MWAT model deviated from the original methods (Moore et al. 2013) in several notable ways. First, an expanded dataset of *in situ* stream temperature observations was used. Second, the model predictions were made at the stream reach scale (i.e., an uninterrupted section of the stream between two stream junctions, or between a junction and an origin or outlet), instead of for specific stations, to better align with the spatial data framework (detailed in following sections). Finally, a limited set of additional covariates was considered when refitting the model to improve fit and better facilitate climate projections (see Table 1 for a comparison of NorWeST and BC stream temperature model covariates).

Spatial data framework

The BC Freshwater Atlas (FWA) was used as the spatial framework for this project. The FWA is a geospatial database describing BC's freshwater features (e.g., streams, lakes, watersheds) at a 1:20,000 scale that serves as a standardized dataset for mapping and analyses of freshwater systems within the province (Province of BC 2010). The FWA uses a hierarchical coding scheme that describes the relative position of features within the hydrologic network; this facilitates catchment delineation and analyses of network connectivity. The 'fundamental watershed' is the base sampling unit of the FWA. Fundamental watersheds are the smallest areal unit in the FWA and represent the surface area that drains directly into a stream reach. Within the FWA, there are > 3.2 million fundamental watersheds with a median area of 13 ha. The median length of a stream reach associated with a fundamental watershed is approximately 400 m. Hereafter, the term 'watershed' is used in reference to fundamental watersheds; a 'watershed' is the areal unit that directly corresponds to a linear stream 'reach'. The term 'catchment' is used to refer the entire upstream area that drains into a specific point along a reach. Within the spatial framework of the FWA, a catchment consists of all watersheds upstream of a specific point, inclusive of the watershed that contains the point. Since the FWA does not resolve to a finer scale than a watershed, this means that all catchments are defined relative to the most downstream point within a particular reach/watershed. All data used in this project, including model covariates and *in situ* stream temperature observations, were initially summarized by watershed. Catchment-scale covariates (e.g., fractional lake cover) were subsequently calculated by identifying all watersheds within a catchment, then aggregating the relevant watershed-scale values.

The watersheds dataset was expanded so the catchment-scale covariates could be calculated appropriately. Most spatial data layers in the FWA are limited to the BC provincial boundary, so the watersheds dataset does not include areas that drain into BC from neighbouring provinces, territories, or states. To address this deficiency, additional watersheds were delineated to capture all areas outside of BC that drained into the province's stream network and create a revised fundamental watersheds dataset that included the entire catchment area for all of BC (Figure 1). Watersheds that intersected the BC boundary were identified, then their respective catchment areas were delineated using the Hydrology toolset in ArcGIS Pro and a digital elevation model (DEM). The DEM was compiled using data from the Canadian Digital Elevation Model (CDEM 2015; ¾ arc second resolution) for all areas in Canada and data from the National Elevation Dataset (NED 2019; ⅓ arc second resolution) for all areas in the US. Both elevation datasets were resampled to a 25-m resolution using a shared coordinate system (BC Albers: https://epsg.io/3005) then mosaicked together. The FWA's hierarchical coding scheme was used to assign each of the new watersheds a position within the hydrologic network and to maintain the functionality of the original FWA database. Where necessary, the hierarchical codes of existing watersheds within BC were revised to accommodate the new watersheds and maintain the correct drainage patterns.

All statistical analyses were conducted in R 4.1.2 (R Core Team 2021). All spatial analyses, data manipulation, and mapping were done in ArcGIS Pro v 2.7 (ESRI, Redlands, California).

Stream temperature data

In situ stream temperature data from 562 unique stations and 1,544 station-years were used to refit the model. Stations included in the BC MWAT model were limited to catchments with areas between 1 – 10,000 km^2, but the upper limit on catchment size was removed for this study to capture a greater portion of the BC stream network. This allowed for inclusion of some stations that had been excluded from the original project dataset, as well as more recent observations (~ 2010 – 2020) available from Water Survey of Canada hydrometric monitoring stations within BC that record water temperature data. All additional data were quality controlled according to the same protocols as the original project (see Appendix A in Lewis et al. 2000).

Static covariates

Catchment area for each watershed was calculated by summing the areas of all upstream watersheds, including the target watershed. Watershed elevation was calculated from the 25-m study area DEM as the average value of all raster cells within each fundamental watershed (i.e., a zonal mean). Mean catchment elevation was calculated as the area-weighted average of all upstream watersheds. The FWA contains a provincial lakes dataset that was used to calculate total lake area within each watershed in BC. Lake areas in transboundary drainages within Canada were derived from the National Hydro Network (NHN 2016), and from the National Hydrography Dataset (USGS 2017) in the US. Lake areas for all watersheds within each catchment were summed then divided by catchment area to calculate fractional lake cover within the catchment. Latitude was derived from the centroid of each watershed. Slope was calculated as the gradient (rise:run) of the stream reach flowing through a watershed. Reach length was calculated from the FWA's linear stream network layer, and total elevation change was derived from the study area DEM.

Temporal Covariates

Temporal covariates considered in the model refitting included: August mean air temperature (°C), total annual precipitation (mm), and fractional glacier cover of the catchment. Data for temporal covariates were split into two general time periods: a 'historical period' (1981-2020) and a 'future period' (2021-2100). The historical period captured all *in situ* stream temperature observations that were used in model refitting and evaluation, and was used to represent baseline conditions for the temporal covariates. Covariate data for the historical period were derived from historical climate reanalysis products or observational datasets. Covariate data for the future period were derived from the outputs of global climate models (GCMs). All temporal covariates required complete datasets for a shared set of historical and future conditions and time periods. Projected air temperature and precipitation datasets are both widely available, so the selection of future climate scenarios was dictated by those available in the projected glacier dataset (Clarke et al. 2015). Datasets for temporal covariates under future conditions were driven by six CMIP5-era global climate models forced under three representative concentration pathways (RCPs): RCP 2.6 ('best case'), RCP 4.5 ('middle of the road'), RCP 8.5 ('worst case') (Table S2).

ClimateNA v7.30 (Wang et al. 2016) was used to produce monthly gridded climate layers, downscaled to a 1-km resolution, for both August mean air temperature (°C) and total annual precipitation (mm). Each climate covariate was represented by two model terms: a baseline value to represent the broad-scale geographic pattern and an anomaly value to represent the temporal variability. Baseline values were calculated as the 40-year average of mean August air temperature or annual precipitation from the 1981-2020 period. The air temperature anomaly was calculated as the difference between the mean August air temperature in a given year and the respective baseline value. The precipitation anomaly was calculated as the ratio of annual precipitation in a given year to the respective baseline value. Air temperature and precipitation covariates, both the baseline and anomaly values, were calculated for each watershed as zonal means.

The Randolph Glacier Inventory Version 6.0 was used to derive the baseline glacier area for the historical period (RGI; RGI Consortium 2017a). The RGI was developed as a global inventory of glacier footprints, approximating conditions at the start of the 21st century (RGI Consortium 2017b). The RGI footprints were considered to be representative of our entire historical period (i.e., 1981-2020). The majority of RGI glacier outlines in BC were dated from 2004-2010, but there is no glacier inventory of comparable coverage and resolution that aligned with the earlier half of the historical period. Glacier loss in western Canada has been documented during the late 20th century (Bevington and Menounos 2022; Hugonnet et al. 2021; Menounos et al. 2019), so use of the RGI for the entire historical period may have resulted in some underestimation of baseline glacier area. For each watershed, the fraction of the catchment area covered by glaciers was calculated (same approach as fractional lake area). Glacier projections from the Clarke et al. (2015) regional glaciation model (data accessed from accessed from https://couplet.unbc.ca/data/RGM_archive/) were used to quantify glacier cover for future climate scenarios. Clarke et al. (2015) developed a high-resolution (200-m grid) model to predict changes in glacier volume and area in western Canada under a range of future climate scenarios. Delta-change values derived from the projected glacier layers were applied to the baseline glacier values to produce fractional glacier cover estimates for each future scenario (see Supplemental Materials for full details of glacier layer processing).

Stream temperature predictions for the thermalscape scenarios were produced in 20-year increments from 1981-2100. Twenty-year periods were used, instead of 30-year normal periods, to provide finer temporal resolution for the thermalscape products that would be more useful in a conservation and resource management context. Projected air temperature and precipitation layers for all future periods (2021-2100) were bias corrected using a delta-change method; the most recent of the 20-year historical periods (i.e., 2001-2020) was used as the reference period to anchor future climate projections. The model terms for baseline air temperature and precipitation remained static under all scenarios, and the annual anomaly terms for each watershed were averaged within each 20-year period. Fractional glacier cover in each watershed was summarized as a 20-year average for each future scenario, and baseline glacier cover from the RGI was used for both historical 20-year periods.

Model fitting and evaluation

A notable development in the modelling process was the shift from a station-specific to a reach- or watershed-specific approach to better align with the FWA framework. For the BC MWAT model, unique static covariates were calculated for each monitoring station while observed thermal metrics and temporal covariates were averaged by station when more than one year of data were available. This maintained the assumption of independence for each observation while using all available information. That approach was adapted to watersheds, averaging the AugTw observations and all temporal covariates for each station-year by watersheds. For example, two *in* situ stations along the same reach (i.e., within the same watershed) with a combined total of three station-years of AugTw observations and associated covariates would be averaged to produce a single AugTw value and set of covariate values for that watershed. The *in situ* observations from 562 stations were thus aggregated into 534 unique watersheds.

A limited suite of candidate covariates were considered during the model fitting process informed by the BC MWAT model as the starting point. Given the high correlation between MWAT and other metrics of summer thermal maxima (Dunham et al. 2005; Isaak and Hubert 2001; Nelitz et al. 2007; Sullivan et al. 2000), it was expected that the original suite of covariates in the BC MWAT model would have been sufficient if the model were simply refit to predict AugTw as an alternate thermal metric. However, replacing the static *k2* term with precipitation terms (i.e., baseline and annual anomaly) was necessary so hydroclimatic conditions could be captured by a temporal covariate that reflected the future climate scenarios. Of the potential covariates from other regionally similar stream temperature models, most lacked available datasets with sufficient spatial and temporal coverage (e.g., groundwater, discharge, flow regulation) (Table 1). Latitude and precipitation terms were the only additional covariates considered beyond those in the original model. Multi-collinearity was assessed using variance inflation factors; values for all candidate covariates were less than 3.5.

The global model included all of the covariates from the BC MWAT model except *k2*, as well as the precipitation terms and latitude. All covariates included in the global model had well-established relationships with physical processes known to affect stream temperature and have been widely used in other modelling efforts (e.g., Table 1). Multiple linear regression was used to fit a model to each unique subset of candidate covariates in the global model (MuMIn package in R, Bartoń 2022). The best model was determined using the lowest ranked AIC score. Of the models with ΔAIC score < 2, the best model was determined by the lowest ranked BIC score that penalises more complex models. A 10-fold cross-validation was used to assess the predictive accuracy of the best-fit model (Moore et al. 2013; Jackson et al. 2018). Data were randomly split into 10 groups of approximately equal size. Each group was used as a test dataset for the model fit to the other nine groups. Observations and predictions from each test group were merged and a suite of performance metrics were calculated (i.e., R^2, RMSE, and MAE).

The degree of extrapolation for the stream temperature predictions was characterized using the dsmextra package in R (Bouchet et al. 2020). The Extrapolation Detection tool was used to quantify the total length of stream network where predictions were analogous to the reference dataset (i.e., no extrapolation), and identify which covariate most contributed to extrapolation in the non-analogous sections of stream network. Predictions were also characterized using the Percent Nearby tool that estimates how 'well-informed' a prediction is based on its similarity to the reference data. Extrapolation assessments were completed for the 2001-2020 historical period, and for each of the three end-of-century (i.e., 2081-2100) RCP ensembles to capture a range of environmental conditions.

A main objective of this study was to produce a thermalscape product for BC that could justifiably be combined with the NorWeST thermalscape to produce a layer of stream temperature estimates for the majority of western North America. In addition to a comparison of standard performance metrics between the NorWeST and BC AugTw models, predictions from the respective models were compared along shared stream reaches. All cross-border (i.e., BC-US) stream reaches with associated temperature predictions from each model were identified. Since the FWA and NorWeST stream networks were derived from different data sources (FWA and NHDPlus, respectively) and at different spatial resolutions (FWA = 1:20,000; NHDPlus = 1:100,000), they did not align seamlessly. Therefore, only cross-border reaches where segments on each side of the border could be confidently assigned to the same reach were included; decisions were supported by analysis of basemap imagery and the study area DEM. A total of 76 cross-border streams reaches were identified, two of which were excluded because they were approximately 1-2 km downstream of major dams. Unlike the NorWeST models, there was no covariate in the BC AugTw model that captured the effect of flow regulation structures, so direct comparison of temperature predictions for those reaches was not appropriate. Predictions from NorWeST were for a 1993-2011 baseline period, and were compared with the 1981-2020 period for BC (average of 1981-2000 and 2001-2020 periods).

Thermalscapes

The BC AugTw model was used to predict August mean stream temperature in each watershed. Predictions were made for all six 20-year periods spanning 1981-2100; this included the two historical periods and each unique future scenario between 2021 and 2100 for a total of 86 unique temperature predictions (Table S2). For all future periods, predictions from the six GCMs were used to calculate an ensemble mean for each 20-year period and RCP scenario. All temperature predictions were transferred from the watersheds to the corresponding reach in the FWA's linear stream network that served as the template for the thermalscapes. Model predictions below 0°C were possible, especially in catchments with high glacier cover. Sub-zero predictions were rounded up to 0°C, but retained in the thermalscape so a baseline comparison was available if stream segments warmed above 0°C under future scenarios. The final thermalscape was produced by filtering the network to exclude secondary flow paths (e.g., braided channels, isolated wetlands, connecting lines), lakes, and all reaches with catchment areas less than 1 km^2 (the minimum catchment size of the *in situ* stations). All analyses were performed on this final version of the thermalscape.

To further characterize the thermal conditions, we calculated the predicted thermal sensitivity for each stream reach. Thermal sensitivity describes the expected change in water temperature for a given change in air temperature (Kelleher et al. 2012; Mohseni et al. 1998), and can highlight regions more vulnerable to temperature shifts. For each stream reach, AugTw predictions were paired with the corresponding air temperature covariate (74 pairs total – ensemble means were not considered) and a simple linear regression was fit for each reach. The coefficient of the slope parameter was taken as the sensitivity value (e.g., Leach and Moore 2019, Isaak et al. 2016b, Luce et al. 2014, Mayer 2012).

Results

Model re-fitting and evaluation

The best model from the re-fitting process is summarized in Table 2 (see Table S3 for comparison of top-ranked models). The directionality of the coefficients was consistent with the assumed effects represented by each covariate. The scatterplot of observed versus predicted values showed good agreement through the majority of observed temperature range, but greater scatter at the extremes (adjusted $R^2 = 0.79$) (Figure 2). Residuals appeared normally distributed with a RMSE of 1.53°C and a MAE of 1.18°C (Figure 3). There was no apparent spatial pattern in the distribution of the prediction errors throughout BC (Figure 4).

The range of environmental conditions represented by the model development data captured much of the variation across the prediction scenarios with extrapolation limited to 4.2 – 23.2% of the total network length (Table 3). High elevation areas in the Columbia and Fraser drainage regions were a persistent source of extrapolation under all considered scenarios (mean catchment elevation > 2,100 m; Figure S5-S8). Extrapolation attributed to low mean August air temperatures (< 8.8°C) in northern BC during the 2001-2020 period largely resolved under warming temperatures predicted for the end-of-century RCP 2.6 and RCP 4.5 scenarios (Figure S5-S7). Extrapolation attributed to high mean August air temperatures (> 23.1°C) was limited to select low elevation valleys in the southern Fraser and Columbia drainages under the end-of-century RCP 4.5 scenario, but expanded dramatically under RCP 8.5 to include most low elevation regions of the Columbia drainage, the southern Fraser drainage, and most of the Fraser River mainstem (Figure S7-S8).

The cross-border comparison of our model predictions to NorWeST yielded good agreement (Figure 5). Predictions between the two models were highly correlated (Pearson's r = 0.91), and the slope coefficient from a simple linear regression fit between the two sets of temperature predictions was 1.03 (Figure 5). The BC AugTw predictions averaged 1.1°C warmer than the predictions from NorWeST.

Thermalscapes

The final thermalscape product consisted of 681,142 km of linear stream network across the entire province (Figure 6). For the 2001-2020 historical period, AugTw averaged 8.6°C (SD = 3.3°C), with a maximum value of 21.0°C and a minimum value of 0°C. A total of 8,941 km of stream network (~1% of total) were assigned a 0°C temperature prediction during the 2001-2020 period; that value dropped to < 0.1% of network length under end-of-century climate scenarios, with 0°C stream reaches only persisting in the most high-elevation, glacier-dominated catchments. The spatial distribution of stream temperatures across BC followed expected trends: warmer temperatures at low elevations and in larger streams and river systems, and cooler temperatures in lower-order, high-elevation streams (Figure 6). Due to the high resolution of the thermalscape stream network, smaller catchments made up a relatively high proportion of the total network length. For example, third order streams and smaller (as defined using the FWA's stream order attributes) accounted for 76% of the total thermalscape length. Therefore, high-level summaries of thermalscape characteristics were largely driven by the characteristics of those smaller streams.

Between the two historical periods, average AugTw in BC was predicted to have increased by 0.28°C (SD = 0.27°C). By end-of-century (2081-2100), province-wide increases in stream temperature were predicted under all three RCP scenarios (reported values are ensemble means). Under RCP 4.5, average AugTw rose by 2.9°C (SD = 1.02°C) from 2001-2020, increasing at approximately 0.36°C/decade through mid-century before stabilizing in the 2061-2080 period. While the average increases in AugTw were generally representative of the degree of warming at the provincial scale, local influences on stream temperature had great effects: end-of-century warming was predicted in all stream reaches with ΔAugTw (i.e., change in AugTw) ranging from 0.7 – 10.5°C. Predicted stream temperature increases under RCP 2.6 averaged 1.9°C by end-of-century, with projected temperatures generally stabilizing by mid-century. As expected, predicted temperature changes under the RCP 8.5 scenario were most extreme, with warming rates approaching 0.76°C/decade and average AugTw increasing 6.1°C by the 2081-2100 period.

A finer-scale analysis of the thermalscapes illustrated the effects of the key model covariates and the spatial heterogeneity in AugTw. The thermalscape for the 2001-2020 period in the Fraser Valley region of southwestern BC (Figure 7A) showed the warmest temperatures in the mainstem of the Fraser River and streams in the low-lying valley floor. In the Coast Mountains to the north, the effects of elevation and glacier cover were evident in the cooler temperature predictions in streams draining to the coast or the Fraser mainstem. The variation in stream temperature change was evident in the ΔAugTw between 2001-2020 and the end-of-century RCP 4.5 scenario (Figure 7B). The greatest predicted increases in temperature (> 4.5°C) occurred in the headwaters of glacier-dominated streams, whereas other high-elevation streams in the Coast Mountains that were not glacier-fed exhibited the least amount of change (< 2.5°C). Predicted temperature changes in the Fraser River and other low-elevation catchments were in an intermediate range (2.5-3.5°C).

Predicted thermal sensitivity values ranged from 0 to 1.9 with a median value of 0.75; nearly 90% of the network had predicted sensitivity values between 0.7 and 0.8. The spatial distribution of thermal sensitivity values across the province was consistent with the relative influences of the temporal covariates in the BC AugTw model (Figure 8). Specifically, province-wide increases in August mean air temperature were the main driver of warming stream temperatures. Predicted increases in annual precipitation resulted in lower thermal sensitivity values across much of the province, particularly along the coast where the greatest increases in precipitation were predicted. The geographically broad, but modest, effect of precipitation on predicted sensitivity was evident from the median sensitivity value being slightly lower than the coefficient for the air temperature anomaly term (0.75 and 0.77, respectively). Higher-sensitivity streams were associated with glacier-influenced catchments. The influence of thermal sensitivity was evident at a finer-scale in the predicted ΔAugTw in the Fraser Valley region where the most warming was predicted in reaches with higher thermal sensitives (Figure 7B). Site-specific plots of predicted ΔAugTw further illustrated the effect of thermal sensitivity on predicted future warming (Figure 8). The site-specific responses of AugTw in each sensitivity group (i.e., High, Intermediate, Low) were broadly illustrative of the amount and rate of warming expected under each RCP scenario based on predicted thermal sensitivity. The predicted ΔAugTw at intermediate sensitivities was approximately 2.9°C by end-of-century under RCP 4.5, while ΔAugTw was roughly 2.2°C and 4.7°C for low and high sensitivity sites, respectively.

Discussion

The BC AugTw stream temperature model provides thermalscapes for the entire province under a range of past and future scenarios, with prediction error in the range of 1-2°C. This is the first dataset of continuous stream temperature predictions of this extent and resolution in Canada, bridging a gap between site- or catchment-specific monitoring and global-scale water temperature products (e.g., Bosmans et al. 2022). This work addresses a major environmental data deficit in BC's freshwater ecosystems and can benefit myriad research and management applications. As exemplified by the use of thermalscape products developed elsewhere, especially NorWeST (Isaak et al. 2017), the thermalscapes that we developed can contribute to: investigations of thermal heterogeneity across stream networks and projected changes under future climate scenarios (e.g., Ficklin et al. 2014; Isaak et al. 2017; Jackson et al. 2018); projected changes in species distributions (e.g., Al-Chokhachy et al. 2016; Bell et al. 2021) or community assemblages under future climate scenarios (Kirk and Rahel 2022; Walters et al. 2018); and identification and prioritization of habitat for conservation or restoration. The refit of an existing model to allow more direct comparisons of predictions with an existing, neighbouring dataset represent a somewhat novel approach to mosaicking stream temperature datasets to leverage existing products and expand spatial coverage. In this case, the mosaicked thermalscape produced from NorWeST and the BC AugTw thermalscapes covers most of western North America.

The main benchmark for the BC AugTw model's performance was the BC MWAT model that was used as a template. The BC AugTw model showed some improvement over the original with a lower RMSE (1.53°C vs. 2.1°C), which was consistent with the modifications to the model. While removing the upper catchment size limit may have generalized some scale-dependent processes (Jones and Schmidt 2017), improved model performance was primarily attributed to the longer averaging period of AugTw relative to MWAT (Stefan and Preud'homme 1993). Similar to the BC MWAT model, the precision of the BC AugTw model was in line with other regional-scale statistical stream temperature models (reviewed in Gallice et al. 2015). All covariates included in the model were consistent with expected physical processes. The precipitation terms had a cooling effect, as was found by Moore (2006) and Isaak et al. (2017), and were an effective substitute for the k2 variable included in the BC MWAT model. Latitude, a term not in the original model, had a cooling effect consistent with the geographic variation in solar radiation. Slope was not included in the final model (Table S3); including slope did not improve model performance and it was predicted to have a warming effect in alternative models, contrary to its expected cooling effect (Webb et al. 2008). The lack of importance of slope in the BC AugTw model may be attributed to the addition of sites in larger, typically lower-gradient catchments, and the shift to a coarser measurement scale for stream gradient (i.e., reach vs. station).

The use of the FWA as the spatial framework for this project was a notable departure from the original methods and was a potential source of prediction uncertainty in the model. Whereas covariate values used in the BC MWAT model were calculated for specific stations (i.e., points), in this project data were only resolved to the scale of watersheds. The use of the FWA a spatial framework for organizing data was similar to Isaak et al.'s (2017) use of the

NHDPlus dataset in developing the NorWeST thermalscapes. With respect to the catchment-scale covariates in the FWA framework, this means that the values for a given watershed are in fact representative of only the most downstream point in the watershed. Using the most downstream point to represent the entire watershed is a source of uncertainty in the BC AugTw model since the 'true' covariate values would depend on the exact position of a monitoring station within a watershed. The effect of this uncertainty is expected to be minor given that the typically small area of the FWA's watersheds (median ≈ 13 ha) and associated reaches (median ≈ 400 m). Each watershed typically constitutes a small fraction of the total catchment area in all but the most headwater streams, so the variation in covariate values within a watershed is usually small. For example, in > 90% of the watersheds with *in situ* temperature data, catchment-scale covariate values differ by less than 5% when calculated at the most upstream point in the watershed instead of the most downstream point. Of the *in* situ stations in more headwater systems, where position within the watershed would have a greater effect on covariate measures, most were towards the downstream end of watershed and should be reasonably well represented by the watershed-scale covariate data.

A main driver of this work was a need for stream temperature predictions under future climate scenarios. Operationally, we followed the recommendation to use the BC MWAT model for first-order estimates of the effects of climate change on stream temperature (Moore et al. 2013), albeit with the refit model. The applicability of stream temperatures predicted with statistical models to future periods, as done here, has been questioned due to potential non-stationarity in the statistical relationships (Arismendi et al. 2014; Leach and Moore 2019). We echo Isaak et al.'s (2017) defence of the NorWeST scenarios: (1) the BC AugTw model better captures the physical processes involved in stream heat budgets than simple air temperature to water temperature models, and (2) the range in values from the static and temporal covariates in the model development data covered much of the predicted range in future conditions for the majority of the province. This position was supported by the extrapolation assessment (Table 3, Figures S5-S12), which demonstrated an approach to detect and characterize the uncertainty introduced by extrapolation (Isaak and Luce 2023). Further, assessment of climate change impacts will continue to be a priority in both freshwater research and management contexts, necessitating the need for this type of product. Our thermalscapes represent an improvement over commonly used alternatives to existing water temperature observations or predictions: direct use of air temperature as a proxy for water temperature (e.g., Rieman et al. 2007; Wenger et al. 2011; Wenger et al. 2013) or simple air temperature-water temperature relationships (e.g., Al-Chokhachy et al. 2013; Mantua et al. 2010; Mohseni et al. 1998). These approaches often lead to over-prediction of warming, especially in mountainous regions (Kirk and Rahel 2022).

The projected changes in BC stream temperatures under future climate scenarios were consistent with the forecasted changes in the model's temporal covariates, broadly including increasing air temperature, increasing coastal precipitation, and declining glacier cover. The BC AugTw model predicted overall warming rates during the historical periods of approximately 0.14°C/decade (1981-2020), similar to NorWeST's estimate of 0.17°C/decade from a similar 40-year period (1976-2015), or Ferrari et al.'s (2007) estimate of 0.12°C/decade in the lower Fraser River, BC. Predicted thermal sensitivities from the BC AugTw model were in good agreement with simulated sensitivity values in the Fraser Basin (0.43-1.01; Islam et al. 2019), and western Canada (0.25-0.75; Shrestha and Pesklevits 2023). Ficklin et al.'s (2014) predicted warming in the Columbia basin of 4.1-5.0°C stream temperature warming for an end-of-century RCP 8.5 scenario was in line with BC AugTw predictions, but predictions by Morrison et al. (2002) and

Ferrari et al. (2007) of approximately 2°C in the lower Fraser River were markedly lower than the BC AugTw predictions for end-of-century warming of 2.8°C or 6.5°C (RCP 4.5 and RCP 8.5, respectively). NorWeST projected changes in stream temperatures of approximately 2°C by end-of-century under an A1B emission scenario for the processing units bordering southern BC (Isaak et al. 2017), compared to the BC AugTw predictions of roughly 3°C warming under the RCP 4.5 scenarios (A1B roughly corresponds to RCP 6.0). Differences between the predicted warming could be attributed to climate forcings from different model eras (CMIP5 vs. CMIP3) and a different set of temporal covariates. For instance, glacier cover and annual precipitation were treated as static variables in NorWeST models, whereas discharge was included as a temporal covariate that we were unable to consider.

Glacier cover is a common covariate considered in stream temperature models (e.g., Isaak et al. 2017; Moore et al. 2013), although it has been typically treated as a static variable (Isaak et al. 2017) or climate change projections were not explicitly considered (Moore 2006, Moore et al. 2013). Declining glacier cover in western North America is expected to result in warmer summer stream temperatures due to reduced contribution of glacier meltwater to total streamflow (Moore et al. 2009), which is consistent with the BC AugTw model's predicted warming from reduced glacier cover. Warming-induced increases in glacial discharge, and correspondingly cooler stream temperatures, are expected during the initial phase of a climatic warming period (Moore et al. 2009); however, declining streamflow attributed to glacier retreat has been documented through much of the study region (Moore et al. 2020; Stahl and Moore 2006), suggesting that most of BC has past this initial warming period. Therefore, the BC AugTw model should provide good first-order estimates of the effects of glacier retreat on stream temperature for most of the province.

The precipitation terms in the BC AugTw model had a cooling effect as expected, with more precipitation associated with higher discharge and more groundwater (Isaak and Hubert 2001). We based our precipitation terms on watershed-specific estimates of total annual precipitation (similar to the station-specific approach by Moore 2006); however, potential changes in the type of precipitation (i.e., rain or snow) and its intra-annual distribution should be considered, particularly when interpreting future stream temperature projections. The consensus among considered GCMs was for increased precipitation across the study area, especially along the coast. The more recent generation of GCMs from CMIP6 similarly predict increased precipitation, as well as higher likelihood of high intensity precipitation events (IPCC 2021). Islam et al. (2017) predicted increased precipitation for the Fraser basin under RCP 4.5 and RCP 8.5 scenarios, but with the fraction of annual precipitation as snow predicted to decline nearly 50% by mid-century. The combination of intense precipitation events and less snowpack is expected to result in lower summer discharge in streams, which would be expected to offset some of cooling predicted by the BC AugTw model based on increased annual precipitation.

There are limitations inherent to statistical models of stream temperatures, and required precision is an important consideration depending on the application of the thermalscapes. Regional-scale status and trends appear represented, but more fine-grained applications may warrant further scrutiny. In a more localized setting, validation of stream temperature predictions against external datasets may be a useful approach to quantify, and potentially correct for, model bias. Lakes were removed from the thermalscapes, but stream temperature predictions immediately downstream should be interpreted with caution due to the potential influence of the lake outflow temperature. Similarly, flow regulation structures were not explicitly considered, and the outflow temperature from reservoirs is dependent on the height of the dam and the point of discharge (Hamblin and McAdam 2003; Olden and Naiman 2010; West and Moore 2020). Stream predictions in the headwaters of glaciated streams also warrant caution where fractional glacier cover exceeds the range of the model development data. The most extreme of these are reaches where sub-freezing predictions of AugTw were truncated to 0°C. Lastly, landscape activities such as logging can increase stream temperatures (Moore et al. 2005). Land cover or land use were not considered due to the lack of a consistent spatial dataset for the entire study area with sufficient spatial and temporal resolution to align with the *in situ* observations.

Conclusions

A regression model was developed to predict August mean stream temperatures for British Columbia, Canada from land cover, physiographic, and climatic characteristics. A 10-fold cross-validation suggested the model's performance is in line with similar statistical stream temperature models (R^2 = 0.79, RMSE = 1.53°C, MAE = 1.18°C). The model was used to create thermalscapes, continuous predictions of stream temperatures, for the provincial stream network. Thermalscapes were produced for a total of 86 scenarios, spanning the period of 1981-2100 and a range of future climate scenarios. Predicted stream temperature warming averaged 2.9°C by end-of-century under an intermediate climate forcing scenario, with significant spatial heterogeneity in warming rates across the province. Predicted stream temperatures for BC under baseline conditions were well-correlated with stream temperature predictions from the NorWeST thermalscape product that spans much of the western United States (Pearson's r = 0.91). The thermalscapes provided through this modelling effort address a significant data gap for freshwater systems within BC. More broadly, the potential applications extend beyond BC through the integration of BC and NorWeST thermalscapes, providing continuous, high-resolution stream temperature predictions across western North America, and marking a major step forward for applications in aquatic research and management.

Acknowledgements

This project was funded by Department of Fisheries and Oceans. Access to stream temperature datasets was provided by: Albert Chirico, Tony Botica, Dave Maloney, Deb Epps, Liz Freyman, Kym Keough, Ed Quilty, Erl MacIsaac, Gerry Leering, Greg Henderson, Herb Herunter, Ian Sharpe, Jeff Burrows, Marc Shrimpton, Hydrologic Inc, Dianne Sutherland, Brian Menounos, Tracy Cone, Warren Warttig, Dave Hutchinson, Marc Nelitz, and Matthew Bailey.

Data Availability

Thermalscape scenarios will be made available for download (data repository to be determined).

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Tables

Table 1: Covariates from regional-scale stream temperature models developed for BC and Western US (i.e., NorWeST) that were considered as templates for this modelling effort. Listed covariate terms are representative of an accepted mechanism of influence on stream temperature, but data type, naming conventions, and calculation methods (e.g., data transformations, spatial and temporal resolution) vary between models. Modelled stream temperature metrics were Maximum Weekly Average Temperature (MWAT), August median temperature, and August mean temperature.

Covariate	BC, Moore 2006	BC, Moore et al. 2013	NorWeST, Isaak et al. 2017	BC, this paper
Catchment Area	X	X	X	X
Elevation	X	X	X	X
Slope		X	X	
Latitude			X	X
Groundwater			X	
Flow Regulation	X		X	
Riparian Cover			X	
Lakes	X	X	X	X
Glaciers	X	X	X	X
Air Temperature	X	X	X	X
Precipitation	X		X	X
Discharge		X*	X	
Temperature Metric	Aug. Median	MWAT	Aug. Mean	Aug. Mean
Application	Catchments > 100 km^2	Catchments 1 – 10,000 km^2	All catchments	Catchments > 1 km^2

* Moore et al. (2013) used a *k2* term from Eaton et al. (2002) that is used to calculate two-year floods and bankfull width.

Table 2: Details of the best-fit model. *CATCH_A* = catchment area (ha); *CATCH_Z* = mean catchment elevation (m); *LAT* = latitude (decimal degrees, NAD 1983); *GLC* = fractional glacier cover of catchment; *LAKE* = fractional lake cover of catchment; *TaAug_baseline* (°C) = mean August air temperature over 1981-2020 historical period; *TaAug_anom* (°C) = difference between mean August air temperature in a given year and *TaAug_baseline*; *PPT_baseline* (mm) = mean annual precipitation over 1981-2020 historical period; *PPT_anom* = annual precipitation in a given year expressed as a ratio relative to *PPT_baseline*.

Term	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	2.73e+1	3.34	8.16	2.45e-15
$\log(CATCH\_A + 1)$	1.51	8.52e-2	1.78e+1	< 2.00e-16
CATCH_Z	-3.65e-3	2.49e-4	-1.47e+1	< 2.00e-16
LAT	-3.42e-1	5.00e-2	-6.84	2.24e-11
$\sqrt{GLC}$	-8.09	1.02	-7.94	1.20e-14
$\sqrt{LAKE}$	9.73	1.09	8.90	< 2.00e-16
TaAug_baseline	1.93e-1	5.06e-2	3.82	1.49e-4
TaAug_anom	7.68e-1	1.01e-1	7.60	1.41e-13
PPT_baseline	-8.49e-4	1.71e-4	-4.97	8.94e-7
PPT_anom	-1.54	6.11e-1	-2.52	1.19e-2

Table 3: Percentage of BC stream network where environmental covariates were not extrapolated beyond environmental conditions at the *in situ* stream temperature stations. Historical and end-of-century scenarios were used to illustrate the degree of extrapolation under a range of environmental conditions.

Region	Historical (2001-2020)	RCP 2.6 (2081-2100)	RCP 4.5 (2081-2100)	RCP 8.5 (2081-2100)
Mackenzie	85.6	98.9	99.0	82.7
Fraser	95.1	96.3	95.5	69.0
Columbia	82.4	82.2	79.6	35.6
Coastal	89.3	96.3	96.6	81.8
Skeena	88.6	99.7	99.7	96.8
Stikine	61.7	97.8	99.2	99.2
Yukon	82.0	96.2	97.3	95.8
Nass	86.7	99.4	99.5	97.8
Taku	84.1	97.5	98.6	98.2
All	87.0	96.0	95.8	76.8

Figures

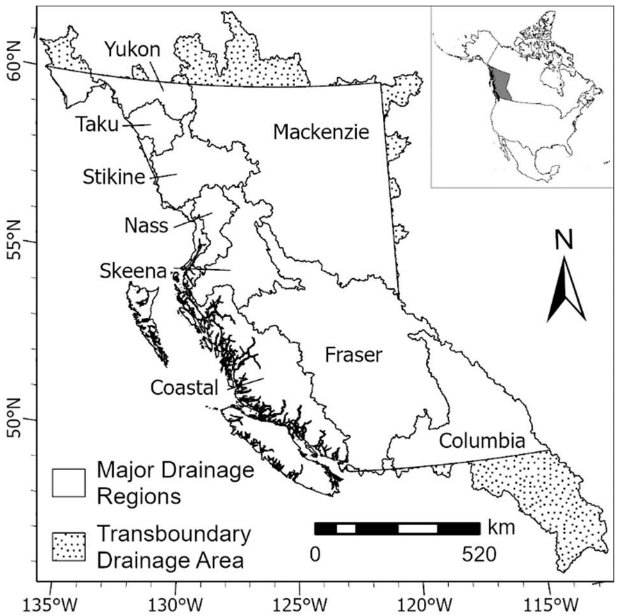

Figure 1: Major drainage regions within British Columbia, Canada (inset: dark gray). Transboundary drainage area was included to capture the entire catchment area for all stream reaches within the province.

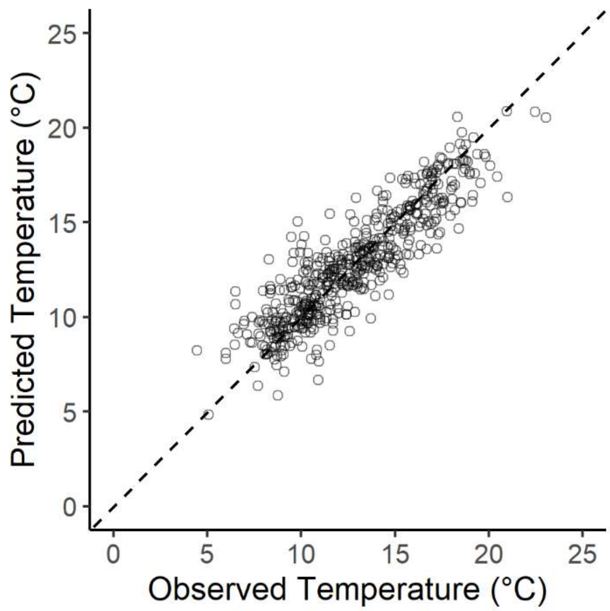

Figure 2: Observed vs. predicted August mean stream temperatures from the cross-validation with a 1:1 reference line (dashed line).

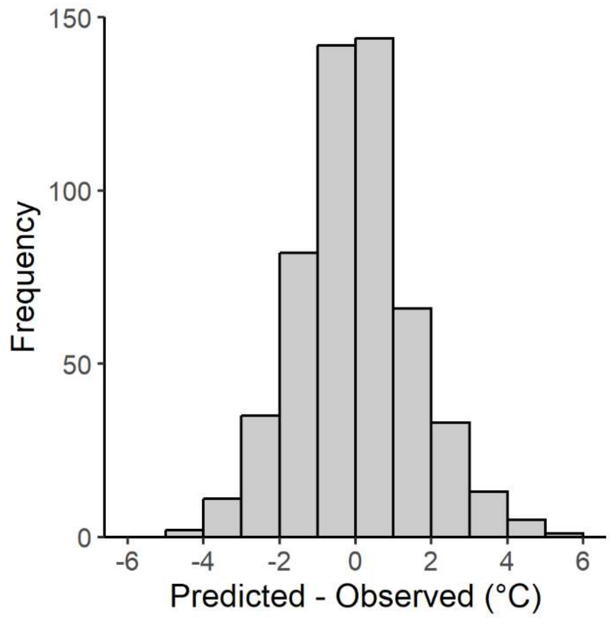

Figure 3: Histogram of prediction errors from the cross-validation. Standard deviation of prediction errors is 1.53°C.

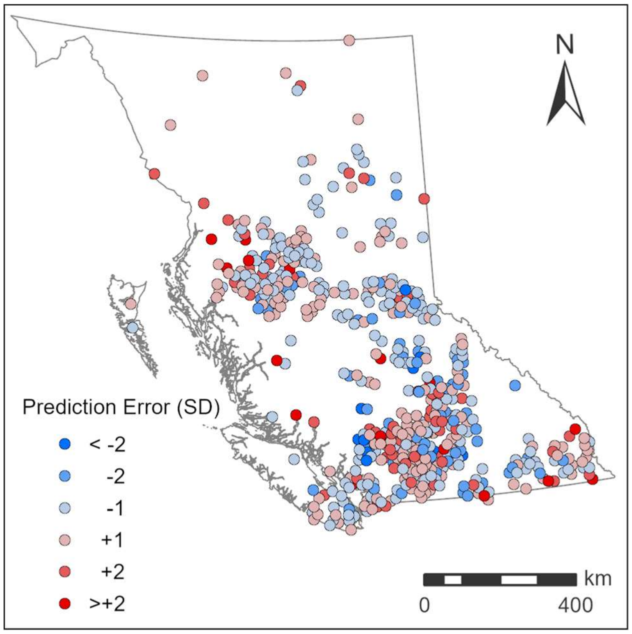

Figure 4: Mapped prediction errors from BC AugTw model, binned by standard deviation (SD = 1.53°C). Spatial offset applied to error points for display purposes.

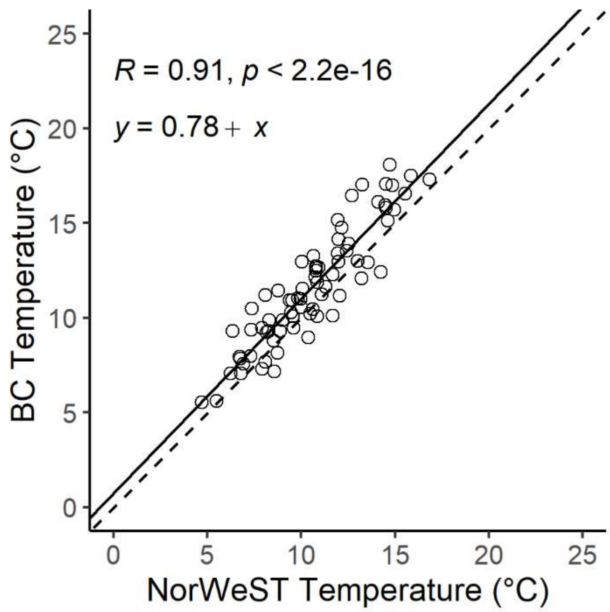

Figure 5: NorWeST vs. BC predictions of August mean stream temperature for transboundary stream segments (n = 74) along the BC-US border. NorWeST predictions were for a 1993-2011 reference period and BC predictions were averaged from the 1981-2000 and 2001-2020 predictions. Solid line is a simple linear regression between NorWeST and BC temperature predictions. Dashed line is a 1:1 reference.

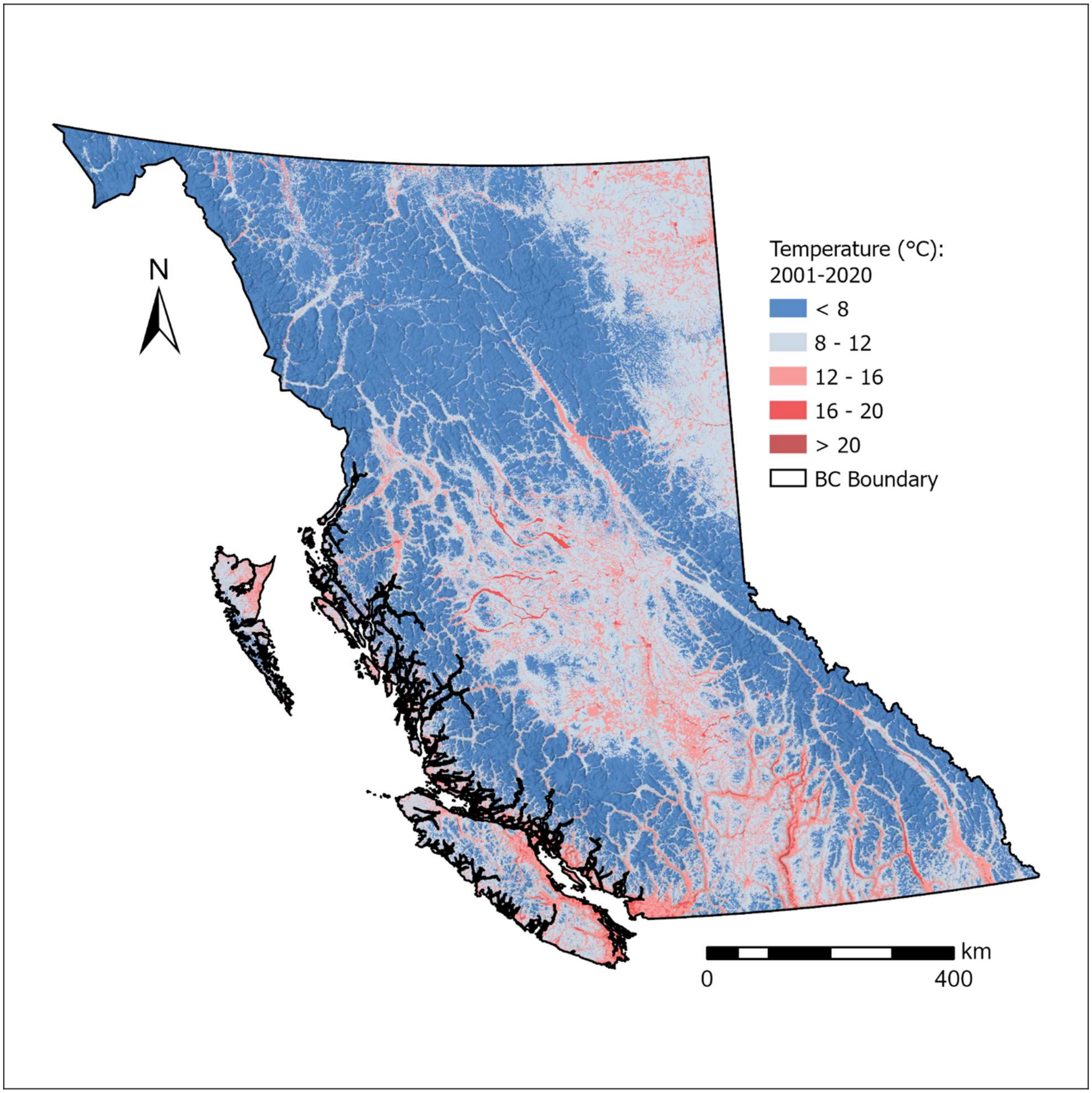

Figure 6: Predicted August mean stream temperatures for all of BC for the 2001-2020 period (for display purposes, temperature predictions are mapped to watersheds instead of stream reaches).

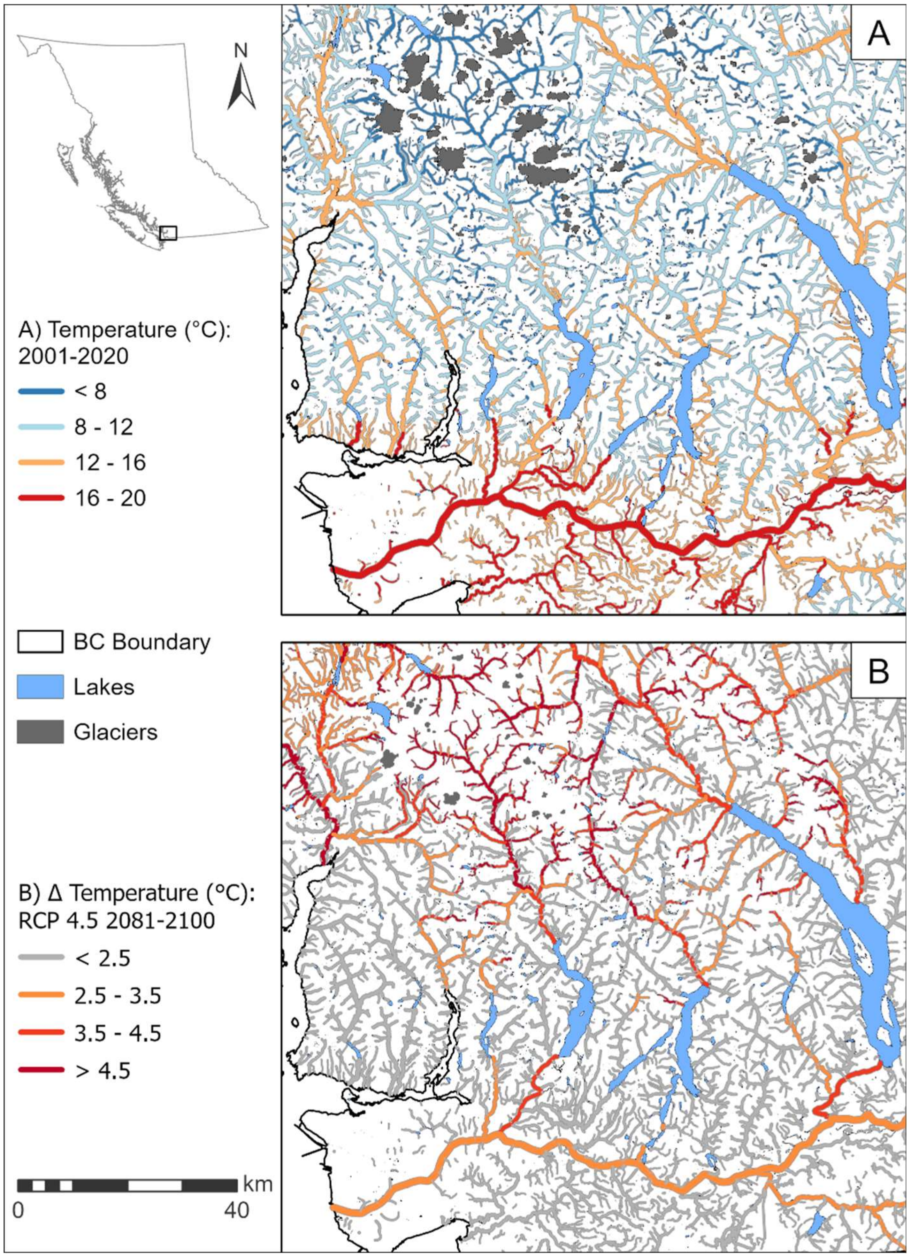

Figure 7: Thermalscape near the Fraser River outlet in southwestern BC (inset map) for the 2001-2020 baseline period (Panel A), and predicted changes (Δ Temperature) from baseline to 2081-2100 under the RCP 4.5 climate scenario (Panel B). Fraser River Valley at south of panel; Coast Mountains to the north. Mapped stream widths are based on stream order. Modelled glacier extents from a single global climate model used to illustrate projected change in cover.

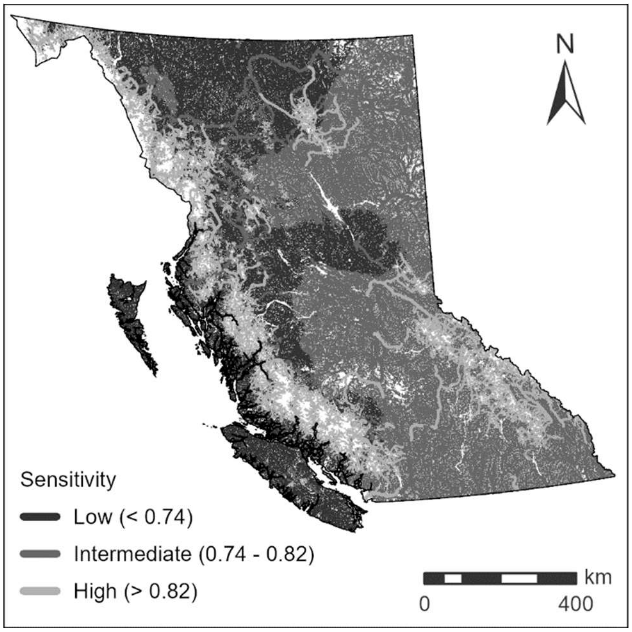

Figure 8: Predicted thermal sensitivity of BC stream reaches.

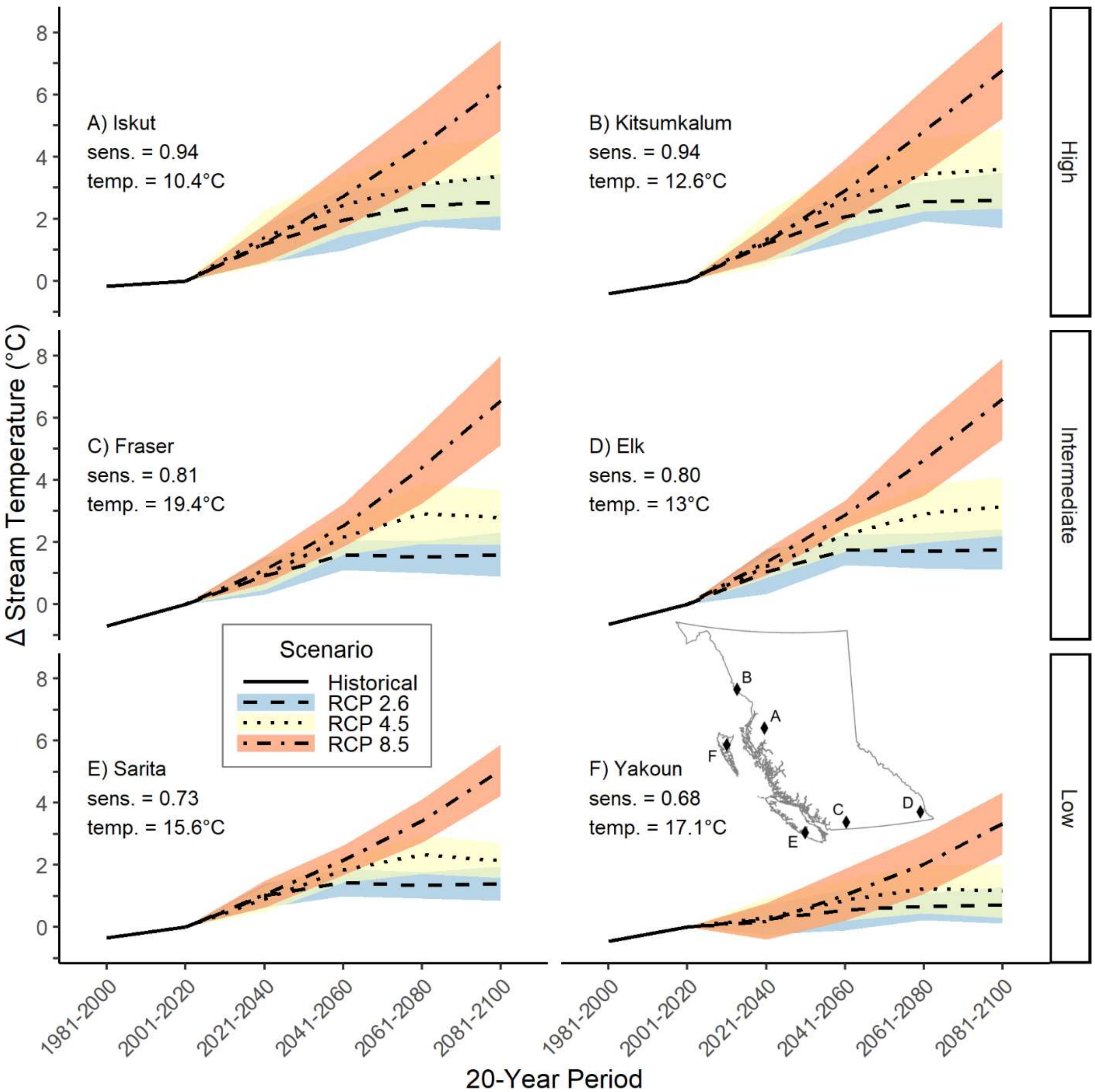

Figure 9: Predicted change in August mean stream temperature at individual sites (inset map bottom right) with different thermal sensitivities (High, Intermediate, Low). Change in stream temperatures were calculated relative to the 2001-2020 baseline period. Lines are the mean of a 6-member GCM ensemble for each RCP scenario and shaded error bars are ± 1 SD. River name, thermal sensitivity (sens.), and baseline temperature (temp.) included in each panel. Sites correspond with Water Survey of Canada gauge locations for hydrometric monitoring (Table S4).

Supporting Information

Supplemental Tables

Table S1: Summary statistics of major terrain and climate covariates by drainage region (inclusive of transboundary catchment area). Air temperature and precipitation values are averages for 2001-2020 period. Min, mean, max values calculated from watershed-scale summaries.

Region	Catchment Area (km^2)	Glacier Cover (km^2)	Lake Cover (km^2)	Elevation (m)			August Air Temperature (°C)			Annual Precipitation (mm)		
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Mackenzie	346,203	545	5,655	224	1,026	2,666	2.4	10.4	15.8	367	720	2,030
Fraser	232,153	2,524	8,245	0	1,188	3,420	3.5	13.2	22.0	259	939	4,597
Columbia	181,972	1,782	4,274	279	1,506	3,344	4.7	13.5	23.0	281	1,077	2,462
Coastal	178,611	16,653	3,565	0	858	3,666	0.4	13.7	19.4	326	2,729	8,070
Skeena	54,403	820	1,173	0	1,061	2,462	5.0	11.4	17.3	374	1,314	6,494
Stikine	50,201	3,522	449	15	1,294	2,660	1.8	9.2	15.5	384	1,189	5,615
Yukon	27,957	1,152	1,851	669	1,188	2,273	4.9	9.7	12.8	259	793	6,163
Nass	21,482	1,263	233	0	1,046	2,566	4.5	10.6	16.6	538	1,307	3,561
Taku	16,870	1,127	192	12	1,138	2,269	4.2	10.2	15.3	298	1,028	6,565
All	1,109,854	29,387	25,637	0	1,131	3,666	0.4	11.9	23.0	259	1,329	8,070

Table S2: All time periods, global climate models (GCMs), and climate forcing pathways considered when developing thermalscapes. Stream temperature thermalscapes were created for 86 scenarios: each unique combination of 20-year period, GCM, and climate forcing. Historical scenarios used data from climate reanalysis or observational datasets.

Time Period		GCM	Climate Forcing	Count
Historical	1981-2000 2001-2020			2
Future	2021-2040 2041-2060 2061-2080 2081-2100	CanESM2 CSIRO-Mk3-6-0 GFDL-CM3 HadGEM2-ES MIROC-ESM MPI-ESM-LR 6-member ensemble	RCP 2.6 RCP 4.5 RCP 8.5	72 (single GCM) 12 (ensemble)

Table S3: Covariates and coefficients from the 10 best-fitting models. Models were ranked by AIC score, with the best-fitting model ranked as 1. Lowest BIC score used to select best model where Δ AIC < 2. Abbreviations for model coefficents are described in Table 2.

Rank	*Intercept*	$log(CATCH + 1)$	*CATCH_Z*	*LAT*	*SLOPE*	$\sqrt{GLC}$	$\sqrt{LAKE}$	*TaAug_baseline*	*TaAug_anom*	*PPT_baseline*	*PPT_anom*	AIC	BIC
1	2.73e+1	1.51	-3.65e-3	-3.42e-1		-8.09	9.73	1.93e-1	7.68e-1	-8.49e-4	-1.54	1984.17	2031.25
2	2.73e+1	1.55	-3.68e-3	-3.43e-1	1.07	-8.16	9.65	1.89e-1	7.67e-1	-8.44e-4	-1.58	1985.77	2037.14
3	2.69e+1	1.54	-3.64e-3	-3.61e-1		-8.17	9.35	1.81e-1	7.43e-1	-8.41e-4		1988.62	2031.43
4	2.69e+1	1.56	-3.66e-3	-3.62e-1	6.37	-8.22	9.30	1.78e-1	7.42e-1	-8.38e-4		1990.48	2037.57
5	3.79e+1	1.68	-4.12e-3	-4.91e-1		-7.61	8.85		7.89e-1	-1.09e-3	-1.31	1996.84	2039.64
6	3.76e+1	1.73	-4.16e-3	-4.87e-1	1.86	-7.75	8.73		7.85e-1	-1.07e-3	-1.39	1997.66	2044.75
7	3.70e+1	1.69	-4.09e-3	-4.98e-1		-7.71	8.57		7.66e-1	-1.07e-3		1999.43	2037.96
8	3.67e+1	1.73	-4.12e-3	-4.96e-1	1.44	-7.83	8.47		7.63e-1	-1.06e-3		2000.73	2043.54
9	1.80e+1	1.50	-2.95e-3	-2.22e-1		-9.58	1.09	2.87e-1	6.61e-1		-1.49	2006.79	2049.60
10	1.81e+1	1.54	-3.00e-3	-2.24e-1	1.49	-9.67	1.07	2.80e-1	6.60e-1		-1.54	2008.07	2055.15

Table S4: Station names and codes for Water Survey of Canada monitoring locations that correspond to site-specific analyses of stream temperature predictions (i.e., Figure 9).

River Name	Station Name	Station Code
Kitsumkalum	Kitsumkalum River below Alice Creek	08EG019
Iskut	Iskut River below Johnson River	08CG001
Fraser	Fraser River at Hope	08MF005
Elk	Elk River at Fernie	08NK002
Sarita	Sarita River near Bamfield	08HB014
Yakoun	Yakoun River near Port Clements	08OA002

Glacier data layer preparation

Following Moore et al. (2013), the glacier covariate in the BC AugTw model was expressed as the fraction of catchment area covered by glaciers. Given the intent to develop thermalscapes for a range of future climate scenarios, it was necessary to treat glacier cover as a temporal covariate since glacier cover has a well-established effect on stream temperature that is expected to change under future climate scenarios. As a catchment-scale covariate, calculation of fractional glacier cover for each fundamental watershed in the study area (> 3 million) was a computationally intensive task, so the temporal resolution of the glacier cover layers was limited to the same 20-year time periods used for air temperature and precipitation climatologies. At this temporal resolution, the calculation of fractional glacier cover layers for each scenario (i.e., each unique combination of GCM, RCP, and 20-year period) was a significant, but manageable process.

The Randolph Glacier Inventory Version 6.0 (RGI; RGI Consortium 2017a) was used to derive the baseline glacier area for the historical period (i.e., 1981-2020). The RGI provided accurate glacier footprints and covered our entire study area, including the transboundary areas that drained into BC (Figure 1). While the RGI was intended to approximate conditions at the start of the 21st century (RGI Consortium 2017b), the RGI footprints were used for both the 1981-2000 and 2001-2020 periods. Baseline glacier area was calculated for each fundamental watershed (Figure S1).

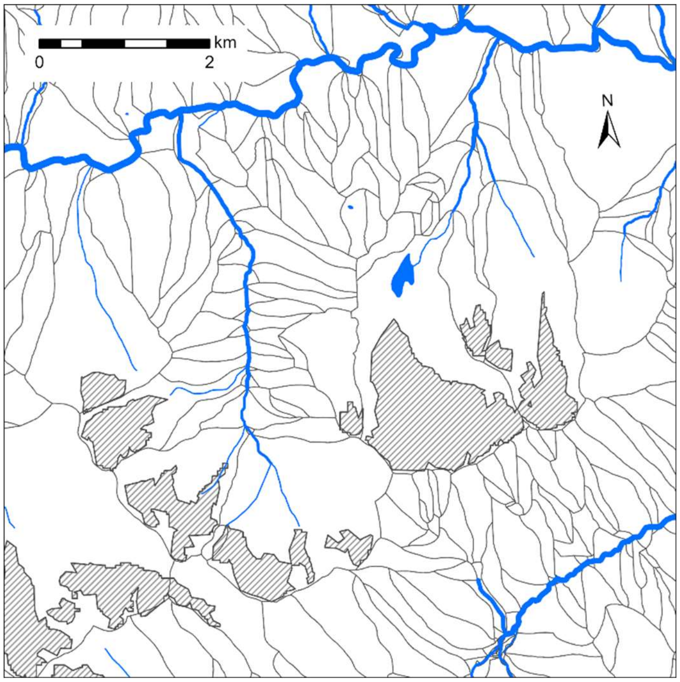

Figure S1: Baseline glacier area for each fundamental watershed (hollow polygons) was calculated as the total area of RGI glacier footprints (hatched gray polygons) within the watershed. Stream network and lakes (blue) included for reference.

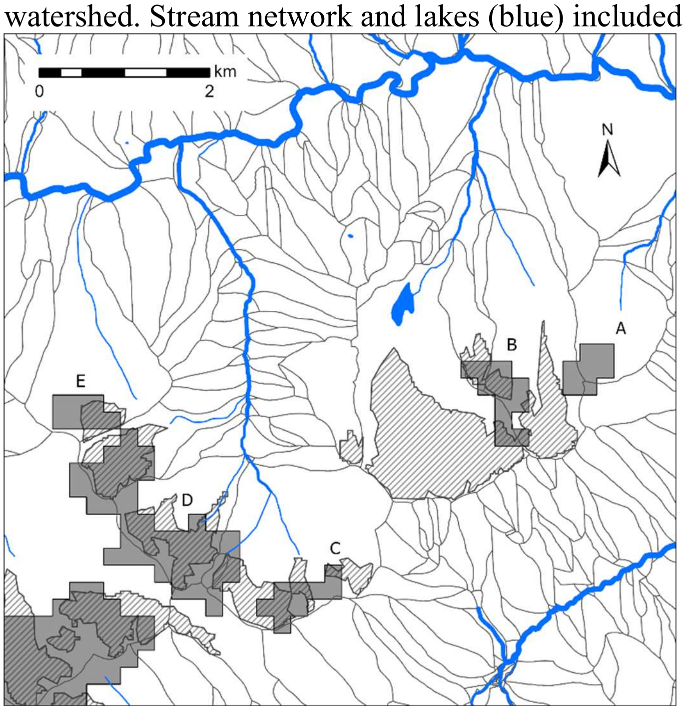

Figure S2: Comparison between RGI polygons (hatched gray polygons) and modelled glacier cover (transparent gray polygons) for the baseline period. For reference, unique ice masses in the modelled glacier cover dataset are labelled A-E. Delta-change values for future climate scenarios were calculated relative to the area of unique ice masses identified in the modelled glacier cover dataset during the baseline period

To quantify glacier cover under future climate scenarios, the glacier projections from Clarke et al.'s (2015) regional glaciation model were used. The authors used the 1980-2008 period to calibrate their model and assess its skill relative to glacier outlines consistent with the RGI (RGI v3.2; Clarke et al. 2015). As such, the modelled glacier cover for that period was considered comparable to the baseline glacier cover from the RGI, and 1980-2008 was used as the reference period from which to calculate the delta change in glacier cover under future climate scenarios. Gridded datasets of predicted annual ice thickness for all years, GCMs, and scenarios produced by Clarke et al. (2015) were accessed from https://couplet.unbc.ca/data/RGM_archive/. To calculate a representative glacier cover for the reference period, annual ice thickness predictions were converted to a binary cover layer (i.e., glacier present = 1, absent = 0) and all years (i.e., 1980-2008) were summarized to a single layer using the median cover value. This same method was used to derive projected glacier cover layers for each of the future scenarios (Table S2).

The 200-m gridded glacier layers derived from Clarke et al. (2015) were comparatively coarse in relation to the baseline RGI polygons (Figure S2). Since there was one not a one-to-one relationship between unique ice masses defined by the respective datasets, delta-change values from ice masses in the projected scenarios could not be directly applied to corresponding ice masses in the baseline dataset. Instead, the relative change in area of the nearest modelled ice mass (i.e., as any contiguous grouping of glacier grid cells; Figure S2) was used as a delta value to adjust the baseline glacier areas. Operationally, we calculated delta values for each unique ice mass modelled in the reference period (i.e., 1980-2008) as the fraction retained area under a future scenario (Figure S3). Delta-change values associated with each ice mass were then assigned to any intersecting fundamental watersheds (Figure S4: watershed 1). If a fundamental watershed intersected two or more ice masses, the intersecting delta values were weighted by the area of each ice mass within the watershed then averaged (Figure S4: watershed 2). If a fundamental watershed contained glacier area from the baseline dataset (i.e., the RGI), but did not intersect any modelled ice masses, it was assigned the delta value from the nearest watershed that intersected a modelled ice mass (Figure S4: watershed 3). Delta-corrected glacier area under each future scenario was calculated for each watershed as the product of the baseline glacier area the scenario-specific delta value. Delta-corrections were applied to glacier area within fundamental watersheds before summarizing to the catchment level and creating the fractional glacier cover layers for future scenarios.

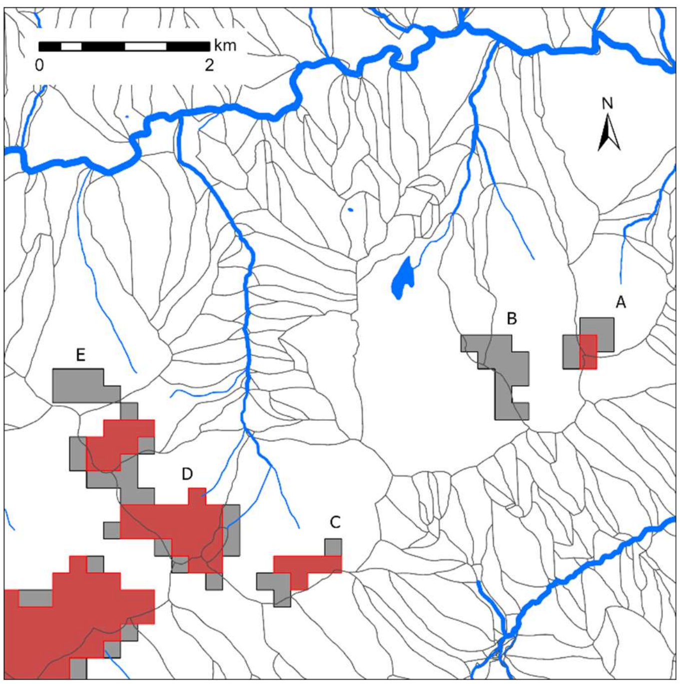

Figure S3: Change in modelled glacier cover from the baseline period (transparent gray polygons) to 2021-2040 (transparent red polygons) with the MIROC-ESM GCM under RCP 4.5. Delta-change values were calculated for each unique ice mass as the fraction of baseline ice mass retained under the future scenario. For example, the delta value for ice masses B and E = 0 (total loss), A = 0.29, C = 0.56, D = 0.60.

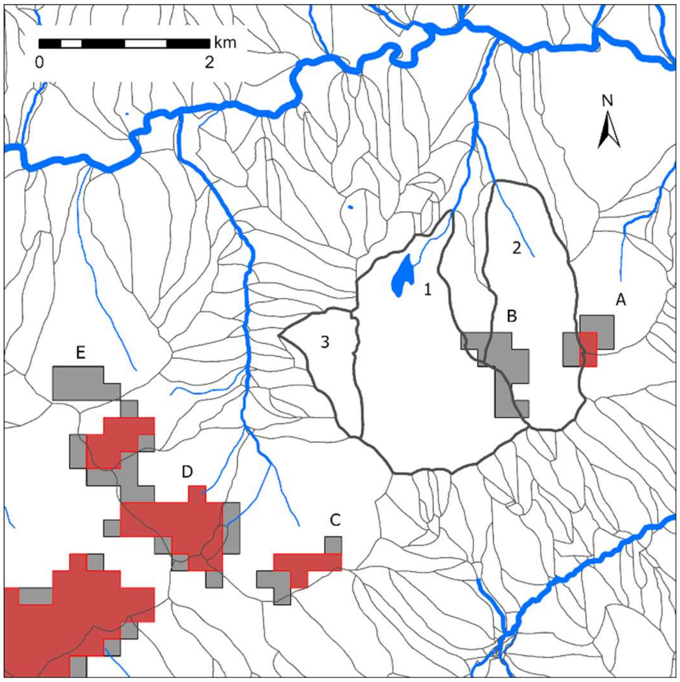

Figure S4. Fundamental watersheds were assigned delta values from intersecting modelled ice masses; example watersheds (1-3, bold outlines) highlight assignment cases. Watershed 1 intersects modelled ice mass B (Δ = 0) so was assigned its delta value (Δ = 0). Watershed 2 intersects A (Δ = 0.29) and B so it was assigned a weighted average of their respective deltas (Δ = 0.08). Watershed 3 does not intersect any modelled ice masses so it was assigned the delta of the nearest ice mass, in this case C (Δ = 0.56).

Extrapolation Assessment

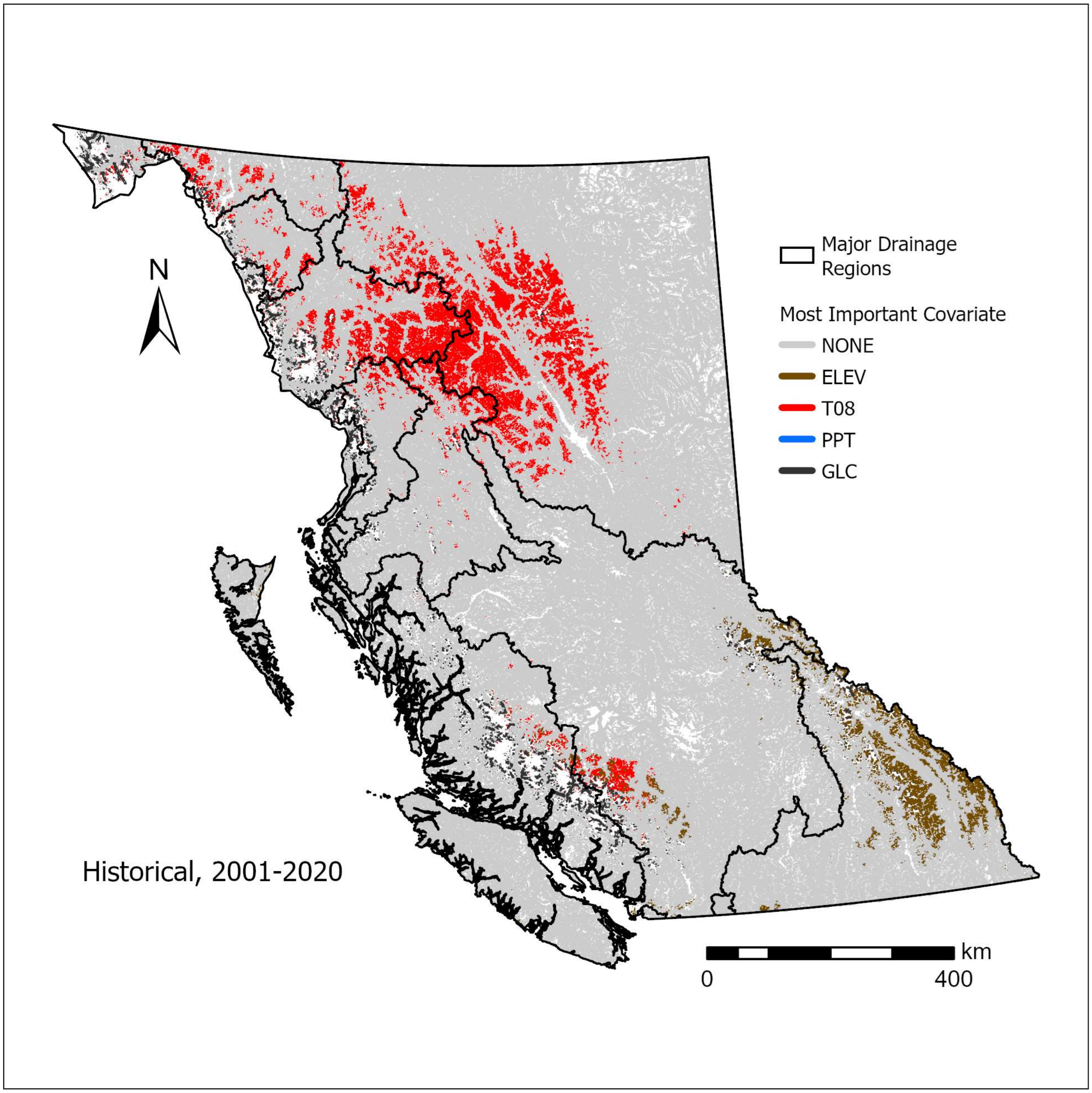

Figure S5: Most important covariates contributing to extrapolation under 2001-2020 historical period: NONE = no extrapolation; ELEV = elevation; T08 = mean August air temperature; PPT = annual precipitation; GLC = fractional glacier cover. Latitude, catchment area, and fractional lake cover were excluded because they were rarely the most important covariate and were not visible at the provincial scale. Univariate and combinatorial extrapolation were not distinguished in this figure.

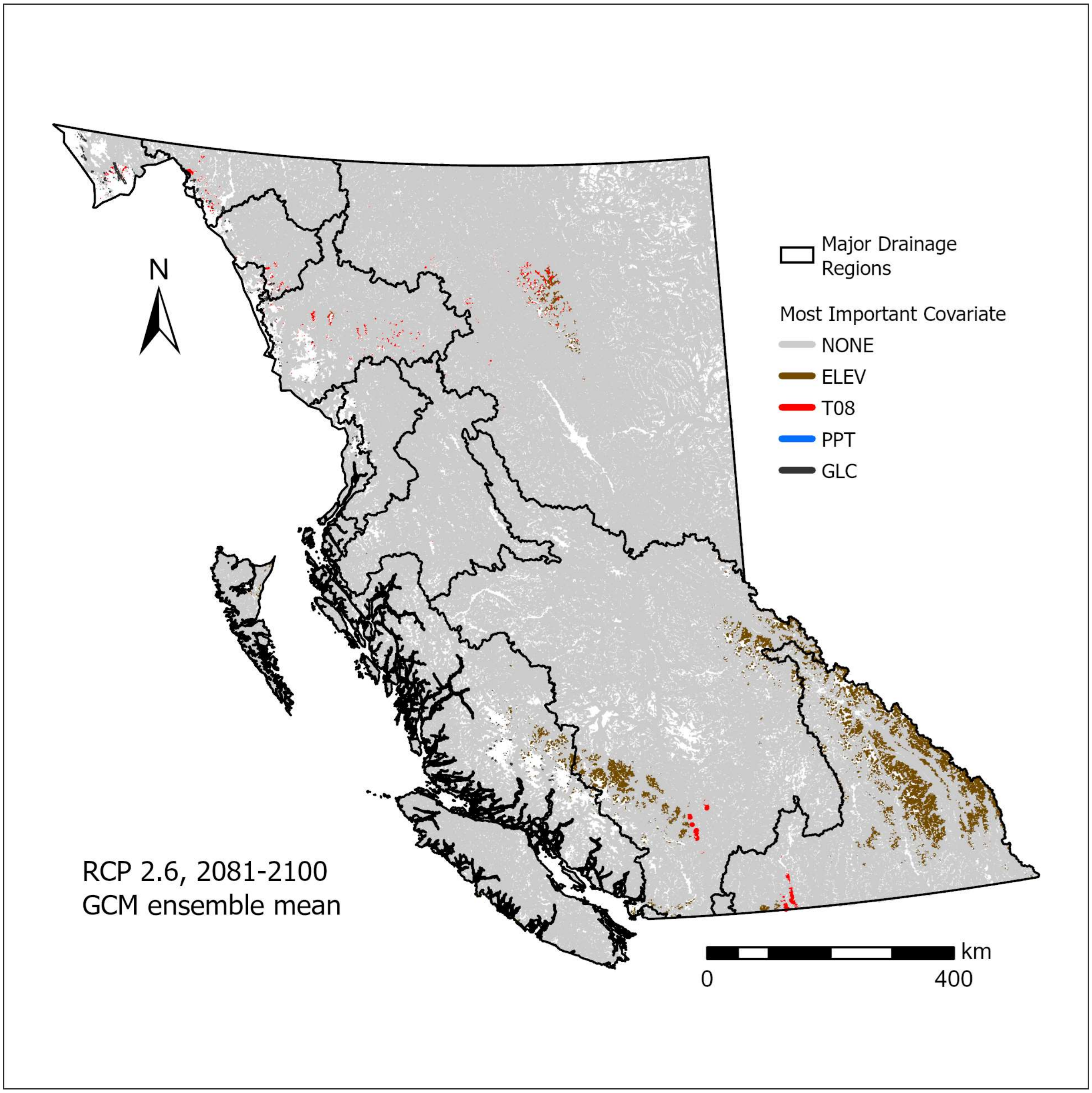

Figure S6: Most important covariates contributing to extrapolation under the RCP 2.6 ensemble scenario for 2081-2100: NONE = no extrapolation; ELEV = elevation; T08 = mean August air temperature; PPT = annual precipitation; GLC = fractional glacier cover. Latitude, catchment area, and fractional lake cover were excluded because they were rarely the most important covariate and were not visible at the provincial scale. Univariate and combinatorial extrapolation were not distinguished in this figure.

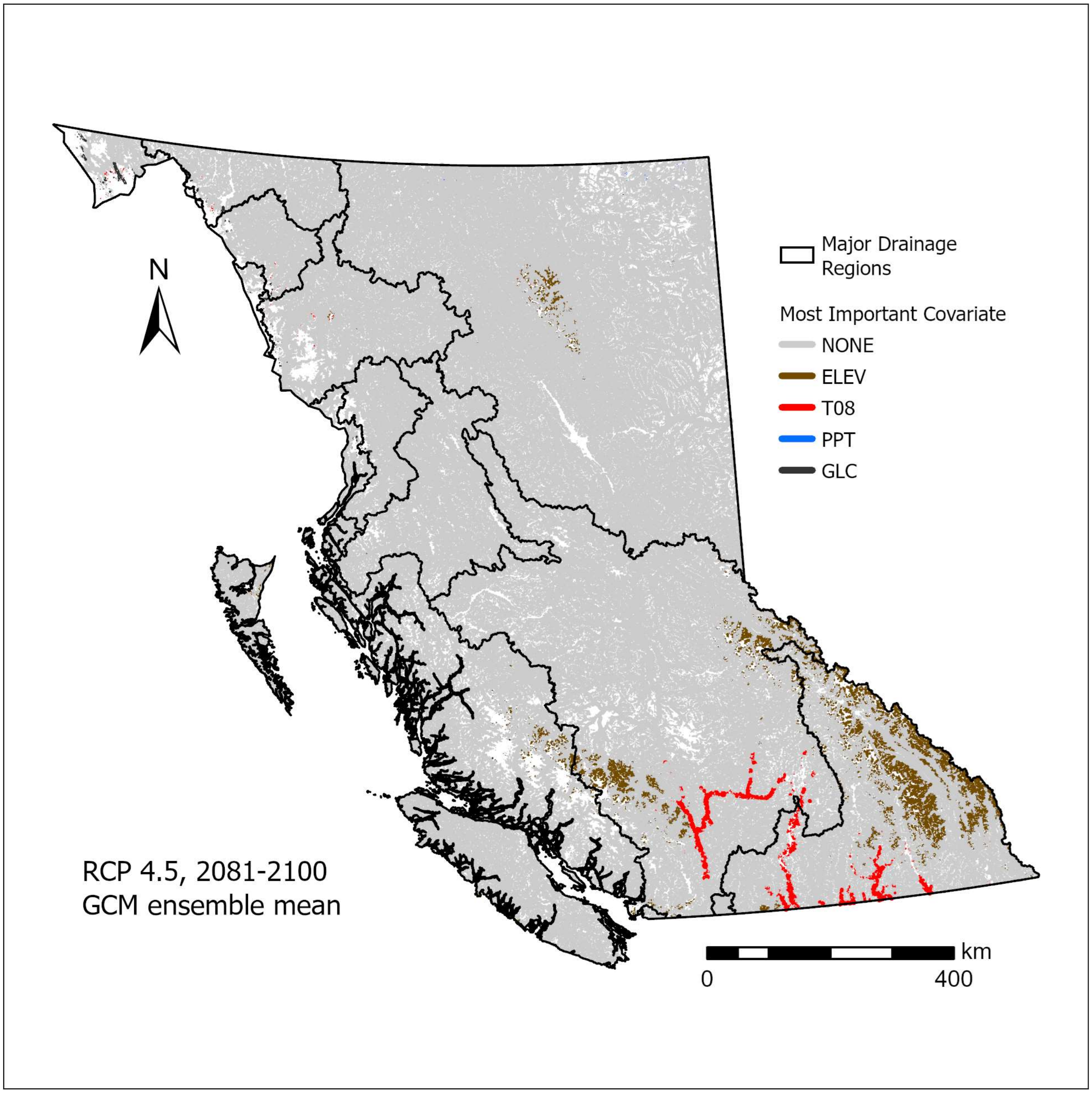

Figure S7: Most important covariates contributing to extrapolation under the RCP 4.5 ensemble scenario for 2081-2100: NONE = no extrapolation; ELEV = elevation; T08 = mean August air temperature; PPT = annual precipitation; GLC = fractional glacier cover. Latitude, catchment area, and fractional lake cover were excluded because they were rarely the most important covariate and were not visible at the provincial scale. Univariate and combinatorial extrapolation were not distinguished in this figure.

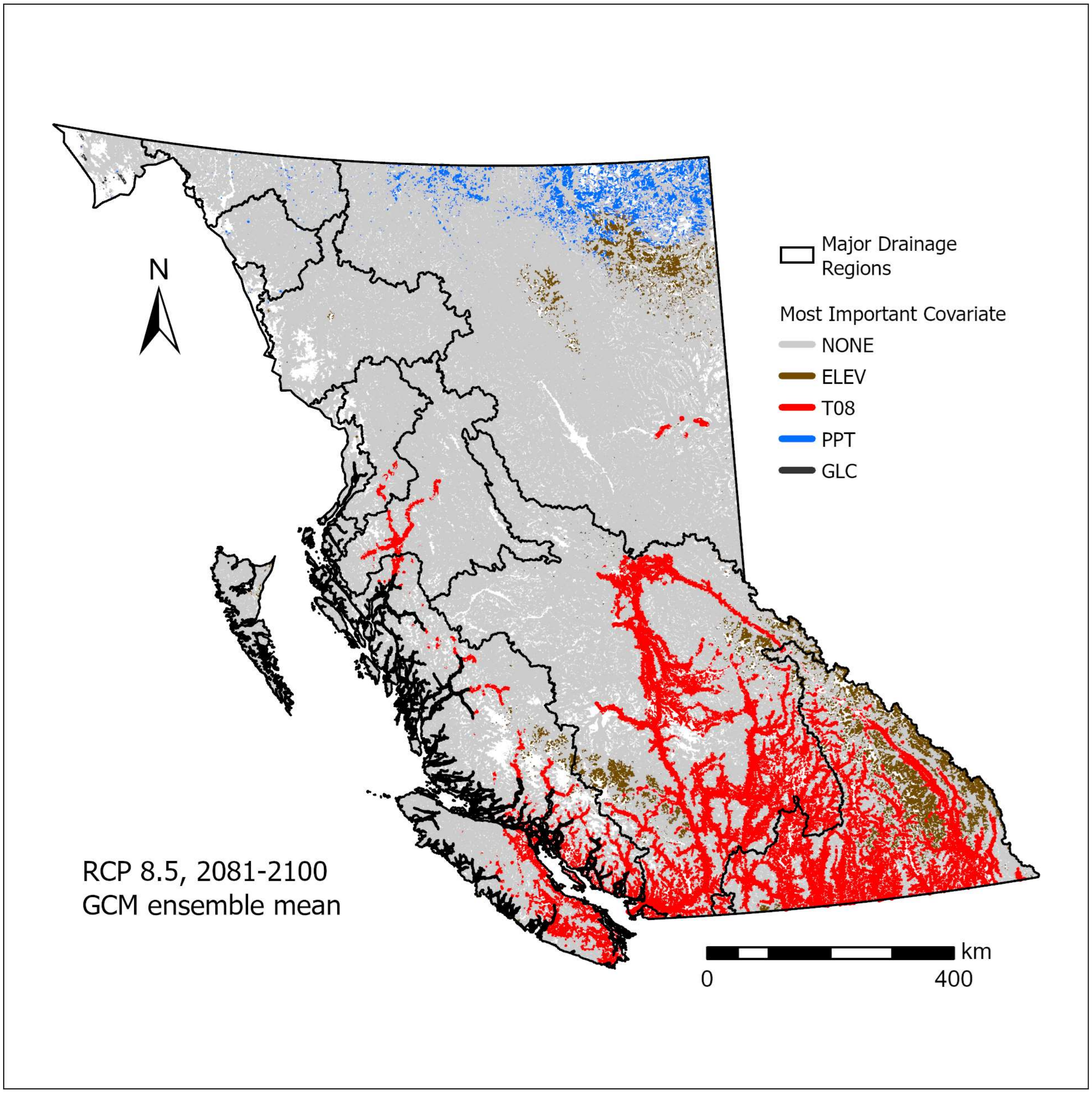

Figure S8: Most important covariates contributing to extrapolation under the RCP 8.5 ensemble scenario for 2081-2100: NONE = no extrapolation; ELEV = elevation; T08 = mean August air temperature; PPT = annual precipitation; GLC = fractional glacier cover. Latitude, catchment area, and fractional lake cover were excluded because they were rarely the most important covariate and were not visible at the provincial scale. Univariate and combinatorial extrapolation were not distinguished in this figure.

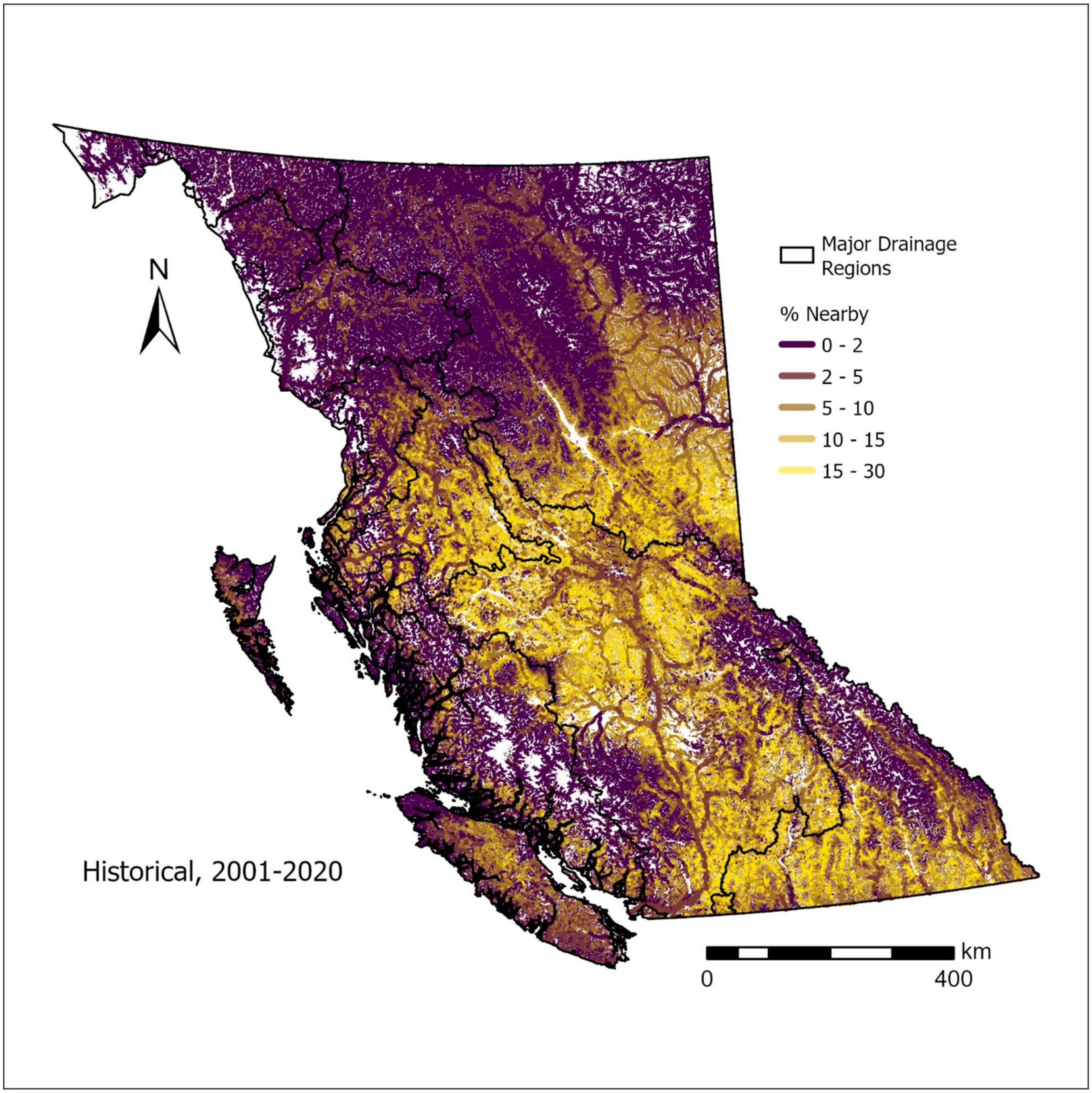

Figure S9: Percentage of *in situ* stream temperature stations that are in the same 'neighbourhood' as a prediction location (i.e., stream reach) under the 2001-2020 historical period. The neighbourhood is defined by the multivariate environmental space of the covariates used to develop the stream temperature model.

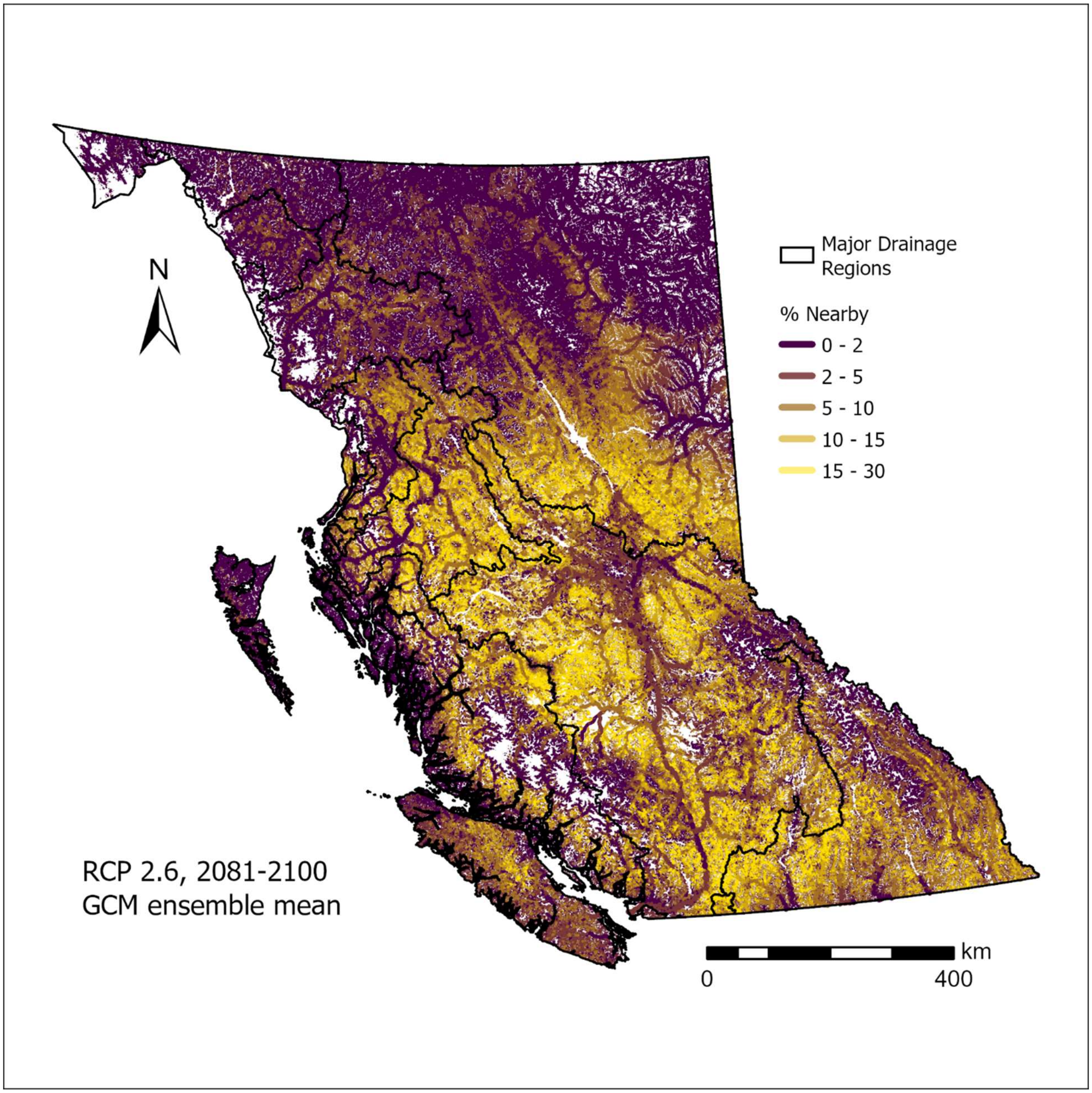

Figure S10: Percentage of *in situ* stream temperature stations that are in the same 'neighbourhood' as a prediction location (i.e., stream reach) under the RCP 2.6 ensemble scenario for 2081-2100. The neighbourhood is defined by the multivariate environmental space of the covariates used to develop the stream temperature model.

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